

THE GLACIAL GEOMORPHOLOGY OF GLASGOW
WITH PARTICULAR REFERENCE TO THE DRUMLINS

Volume 1

(Text)

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UNIVERSITY OF EDINBURGH

1976

In accordance with the University of Edinburgh Postgraduate Study regulation 2.4.15., the following declaration is made:

This thesis was composed by me and is based on my own research, except in those parts of the thesis indicated below.

Dr. R. Thompson, Department of Geophysics, University of Edinburgh, made the necessary measurements of palaeomagnetic properties of till. Dr. A. McGown and Dr. A. M. Radwan, Department of Civil Engineering, University of Strathclyde, while working on the engineering properties of till in Glasgow, allowed me to work with them, supplying me with information on geotechnical properties from samples tested by Dr. Radwan and myself.

The analysis of and conclusions drawn from both the palaeomagnetic and geotechnical data were made by myself.

July 1976.

A B S T R A C T

The events of the last glaciation and deglaciation in Glasgow were studied and the stratigraphic sequence of drift deposits re-examined using borelog records and field mapping. Drumlins and their internal material were studied in order to examine theories of drumlin origin and to develop a broader theory of their formation.

Over 8000 borelogs were collected and analysed in order to study drift stratigraphy, drift thickness and rockhead topography. Cross-sections were drawn to clarify the drift sequence. The Clyde buried channel and its infilling deposits were mapped from borelog records, and both appear to be subglacial in origin.

The characteristics of red and grey till were studied using till fabrics, fissure fabrics, palaeomagnetic and pebble lithology investigations. Till samples were geotechnically analysed, measurements of moisture content, consolidation, shear strength, and particle size distribution being made. Although great variability was found in the tills, they appear to have been deposited contemporaneously.

No relationships could be detected between drumlins and terrain characteristics. Fissure studies suggest drumlin growth by accretion. Till layers and palaeomagnetic work suggested till depositional rates were high. These high depositional rates were possibly due to changes in the subglacial environment resulting from removal of water. Every drumlin does not appear to require a solid core, only a minimum size to withstand ice forces.

Field mapping, fabrics and drumlin orientation indicate ice flow eastwards across the area. The mode of deglaciation appears to

have been unusual since ice apparently remained in Glasgow while adjacent areas, including the Firth of Clyde, became ice free.

A C K N O W L E D G E M E N T S

I would like to express my indebtedness to my supervisor, Dr. J. B. Sissons, for his constant advice and encouragement. I am most grateful to Brian Sissons for the many helpful discussions we have had and for his invaluable constructive criticism. I must also thank my second supervisor, Dr. J. A. T. Young, for his advice and translation of drumlin papers. To my fellow postgraduates I am indebted for their criticism of ideas and interest in my research.

I am extremely grateful to Ian Smalley for our many frank discussions and correspondence on the drumlin problem and for his advice.

In collecting a large number of borelogs scattered in many offices and archives I am grateful to a large number of people for their interest and help. In particular I am deeply grateful to Bill Bradford and to many others in Glasgow City Corporation. I am grateful to the Institute of Geological Sciences, Edinburgh, for permitting access to their borelog files. To Neill McNeill, Willie Anderson, Douglas Burke, Willard Dougall and many others from various firms in Glasgow I am indebted for their help with borelog information and core samples. I would like also to acknowledge the assistance of British Rail, the Clyde Port Authority and the S.S.E.B. for access to their borelog records.

For advice and help in understanding the details of palaeomagnetism I am most grateful to Roy Thompson. I am indebted to him for his interest and laboratory work on till and for our sampling forays to Glasgow.

I am indebted to Amr Radwan and Alan McGown for their advice and

interest in my research and for their help in understanding the complexities of soil mechanics. To several others, J. L. Knill, W. H. Mathews, Bill Ritchie, Ian Stevens, Adrian Thomas, Brian Whalley, I am indebted for their advice and ideas.

For help in computer programming I am grateful to Miss L. Roche, Miss M. Stone and Mr. D. Cooper. I would also like to thank Jerry Dunn for his kind help in xeroxing, to Ralph Morton, Ray Harris and Alex Bradley for drawing several figures and cross-sections and to David Agnew for his assistance in laboratory work.

I am indebted to Dr. R. Glentworth, Macaulay Institute for Soil Research, for allowing me time in which to continue writing my thesis.

I would like to thank the University of Edinburgh for granting me a Studentship and for contributing to research costs.

Finally I am extremely indebted to my wife, Teresa, for her unending encouragement and patience. For her help during many long hours of research and final collation and her constant sacrifice, I am forever grateful.

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CHAPTER 1

I N T R O D U C T I O N

Drumlins are perhaps among the most well documented yet poorly understood glacial landforms. Although considerable research has gone into where drumlins are found and why, the explanation of why and how such a landform is created remains enigmatic. Since any group of drumlins is a product of glaciation within a specific area, to understand how and why these drumlins have formed it is necessary to understand the sequence of glaciation and deglaciation within that area. The aims of this thesis were firstly, to clarify the events of the last glaciation and deglaciation of the Glasgow district and secondly, to attempt to develop a broad theory of drumlin formation.

Drumlins have been often regarded as unique aberrations of the glacial system. Workers have previously investigated the question of drumlin formation largely in an attempt to find a unique formative factor and have been largely unsuccessful. Another method of approaching the problem appears to be required. In this thesis an attempt has been made to find what similarities, if any, exist between drumlin internal material and undrumlinised drift in order to relate present knowledge of subglacial depositional mechanics to drumlin formation. Previously several workers have discussed the relationship of drumlins to one another but very few attempts have been made to relate drumlins to surrounding factors such as bedrock slope and drift thickness. As a consequence in this thesis several factors possibly controlling drumlin formation are statistically correlated in an attempt to find

some other clues as to the mechanism of drumlin formation.

Work on Quaternary events in Glasgow until the mid 1920's was considerable but since then, although several radiocarbon dates obtained from organic remains have been published, little published work on the Glasgow area in relation to Quaternary events in the rest of Scotland exists. In the last few years, as knowledge of the Quaternary events in Scotland has increased, the significance of the lower Clyde valley, in and around Glasgow, appears to have become critical in understanding the final events of Devensian glaciation in west-central Scotland. Within Glasgow several controversial issues exist, namely whether the red till is evidence of a readvance of ice over the grey till; whether the sea first flooded into this area in late-glacial times via the Lochwinnoch Gap or by the present estuary mouth; whether the buried channel of the Clyde is preglacial or subglacial; and whether the infilling deposits in the channel are evidence of a temporary ice-dammed lake or subglacial deposition. To attempt to answer these questions it is necessary that a clearer understanding be had of the distribution and stratigraphic sequence of glacial and non-glacial deposits.

Four main areas of investigation are utilised. Firstly, the internal composition and structure of the drumlins are studied using borelog data gathered from central Glasgow and by examining and analysing drumlin till, using various techniques. The borelog data gives information on the stratigraphic sequence of Quaternary deposits in the Glasgow area. Secondly, the drumlins and all other glacial deposits in the study area are mapped. The Geomorphological map aids in elucidating the Quaternary events in Glasgow. Thirdly, by com-

binning borelog information, in the form of Rockhead and Drift Thickness maps, and the Geomorphological map it is possible to attempt to discover both the relationships that may exist between the factors that appear to control the mechanism of drumlin formation and morphometry and the intercalation and distribution of various glacial deposits. Fourthly, previous literature relevant to the aims of the thesis is examined and reassessed in the light of new findings.

In studying drumlin till various techniques are used in the hope that a better understanding might be had of how the till was deposited and consequently how the drumlins were created. An analysis of the pebble lithology of the till sought to discover the inter-relationship between glacial erosion and deposition within a drumlin field.

In examining the possible relationship between stress fissures and till fabrics at various sites on two drumlins it is hoped that some information might be obtained as to the stress history of till and mode of formation of these drumlins.

In several exposures of drumlin till distinct horizontal layering is detected and measured. These till layers are compared with the findings of other workers and are tentatively related to rates of till deposition.

Palaeomagnetic studies are made on till samples in an attempt to clarify the ages of the red and grey till on the basis of their respective magnetic pole positions. An attempt is made to gather information on the mechanics of till deposition from a knowledge of the anisotropy of the magnetic particles within the till and on the intricate movements of the ice across the drumlin field.

Measurements of the geotechnical properties of drumlin till are

made in order to assess the possible effect of varying stresses applied to till in the subglacial environment.

Throughout the thesis grid references all lie within National Grid Sheet 26 (NS) unless otherwise prefixed. All Plates and Figures are to be found in Volume 2 and the Borelog summary in Volume 3.

LANDSCAPE AND GEOLOGY

In any landscape there exists a delicate balance between the forces of nature and man. This balance may be viewed as a series of gradations or superimpositions of man's created environment on the natural landscape which in its turn is a balance between endogenic and exogenic forces.

Glasgow probably brings into many people's minds an image of a city with heavy industry and tenement slums. This is a somewhat outdated view, for the heavy industry is now almost gone and the slums are disappearing. Yet human domination of the landscape has persisted for so long that only remnants of natural landscape exist. In direct contrast, however, are the agricultural fringe areas to the north and south.

The area studied, lying within the O.S. 1" sheet number 60, extends from the Kilpatrick Hills (395m O.D.) and Milngavie in the north, to Hogganfield Loch (642 674) in the east, crossing south of the River Clyde as far as the Glasgow to Paisley railway line. The southern boundary stretches from Ibrox and Hillington in the west to Rutherglen in the east (Fig. 1). An arbitrary boundary was selected in order to encompass several ideas held when the investigation was initiated:

1. to include agricultural land to facilitate the study of drumlin forms;
2. to include an area from which the drumlins appeared to emanate (i.e. the up-ice part of a drumlin field);
3. to include an area of dense borehole data (i.e. dense urban development).

The boundary, so determined, conforms to these three initial demands. As seen from Figure 1 the area includes the central part of Glasgow, railway stations, docks, universities and many new office blocks, which provided dense borehole evidence.

The River Clyde has a wide alluvial plain but reveals interference from glacial landforms, marine transgressions and man. Drumlins dominate the landscape to the south of the Kilpatrick Hills (Plate 1). The Geological Memoir for the Glasgow District (Clough et al., 1925, p.1) describes the landscape "as a gently undulating central plain of drift-covered Carboniferous rocks". The effect on the urban landscape of these drumlins and undulations is summed up by the fact that Glasgow, at one time, had sixteen "Hill Streets" within its boundary. Names such as Jordanhill, Garrowhill, Ruchill, Maryhill and Downhill are all indicative of the problems of urban development in such a landscape (Plate 2). The drumlin field extends from the Kilpatrick Hills in the west in a broad south-east, then east sweep across the Midland Valley almost to Edinburgh; it straddles the River Clyde and extends south towards the foothills around Eaglesham (575 520). Close to the River Clyde, however, the drumlin field is partly submerged by later raised beach deposits.

The raised beach deposits consist of flat spreads of clays and sands often covered by considerable thicknesses of peat (e.g. Linwood Moss, 435 650, Plate 3). They extend from Dumbarton (375 755) and Bishopton (415 720) in the west to Rutherglen (605 625) in the east. Stretching away from the present river amongst the drumlins, the beaches submerge some drumlins and partly submerge others, leaving the latter with steep lower slopes and nick points where the late-and post-glacial seas have washed around them. The highest beach is traceable to approximately 26m O.D., there being several other lower beaches (Chap. 3). Some beach fragments are almost isolated amongst the drumlins as in Drumchapel (520 707). The best developed beaches are south of the river and in the Yoker/Drumchapel/Jordanhill triangle to the north. In the Linwood Moss/Erskine area large expanses of beach mask previous older deposits (Fig. 1).

In this latter area the flatness has been an added attraction to the development of an airport and to the sprawling nature of light industry. Due to river rejuvenation, after the deposition of the raised beaches, many rivers possess alluvial flats lying below the raised beaches.

The topographic landscape within the city remained virtually untouched up to the eighteenth century, but now it is exceedingly difficult to envisage. The problem of identifying landforms and breaks of slope within the city will be discussed later (Chap. 10), but it is a problem that can only be partially solved.

SOLID GEOLOGY

The masking effect of the thick Quaternary deposits on the solid geology has meant that the relevance of the latter in the landscape is small compared to the Quaternary sequence. When discussing solid geology, its relevance or irrelevance to the landscape and geomorphology is therefore borne in mind.

The geology of the Glasgow area displays considerable variations in lithology and structure (Fig. 2). The Midland Valley of Scotland, the much larger structural unit within which the area of study lies, is a sharply defined rift between rocks of Lower Palaeozoic age to the north and south. The Valley, itself, contains Upper Palaeozoic rocks. The rocks of the study area include contorted and faulted metamorphics, north of the Highland Boundary Fault; varied Coal Measures of Upper Carboniferous Limestone; Clyde Plateau Lavas and soft easily eroded sandstones and mudstones of the synclinal Carboniferous sediments.

Within the confines of the study area, the stratigraphic succession is as follows:

- 4) Quaternary
- 3) Mesozoic-Tertiary interval - no sediments known
- 2) Carboniferous)
-) Upper Palaeozoic
- 1) Devonian)

Several older geological sequences surround the area, namely Dalradian to the north and Ordovician to the south. Other than contributing material such as greywackes, shales and basic volcanics to the till content, these rocks are of little or no relevance to the geomorphology of the area.

1) DEVONIAN

By the close of the Caledonian Orogeny a deep graben or rift appears to have been created between the then two land masses of the Highlands and Southern Uplands. This orogeny manifests itself within Scotland as the distinct north-east to south-west grain of the country (e.g. Lochs Tay and Tummel and the Midland Valley). Semi-arid sediments were deposited within this subsiding graben. The Lower Old Red Sandstone sediments (Fig. 2) of sandstones, marls and conglomerates were deposited in great thicknesses of 3,000 to 4,500m. The red ferruginous colouring of these sediments and subsequently of the tills are its distinctive trait.

Due to the unsettled earth tectonics of the time, outpourings of basalt and other volcanics are common to the south in Lanarkshire but absent in the north.

The Middle Old Red Sandstone phase is not known in the Glasgow area. The Upper Old Red Sandstone because of its bright red colour is sharply distinct from the lower member. These bright red sediments, south-east of the Lower Old Red Sandstone, partly compose the flanks of the Kilpatrick

Hills. They are composed of marls, sandstones and, again due to their ease of erosion, manifest themselves in the red colouring of the till.

As a component of the landscape, the Devonian sediments have a subdued rounded appearance due to intense subaerial and glacial erosion. The volcanics however remain craggy and distinct when uncovered.

2) CARBONIFEROUS

The predominant rocks within the Midland Valley and the most important source of mineral wealth are the Carboniferous strata. Coal, ironstone, oil shale and fireclay were, at one time, the most important minerals. The Carboniferous system is not only the most common series, it is also the most complex in its stratigraphic succession (Fig. 2).

The broad stratigraphic succession is as follows:

Coal Measures	(Barren red Measures ((Productive Measures
Millstone Grit	
Carboniferous Limestone Series	(Upper Limestone Group ((Limestone Coal Group ((Lower Limestone Group
Calciferous Sandstone Series	Upper Sedimentary Group with coals and fireclays

The main sedimentary rock types that form the Carboniferous system are coal, limestone, shale, mudstone and sandstone. They are arranged stratigraphically within a broad syncline in sequences or suites described as rhythms, cycles or cyclotherms (Goodlet, 1960; Wells, 1960). These sequences and the added tectonic movements attributed to the

Variscan orogeny have resulted in a complexity of outcropping. Due to the severity of erosion processes, both subaerial and glacial, related to the ease of weathering and erosion of these sediments, little or no topographic expression can be attributed to the sedimentary Carboniferous rocks. In one instance however at Douglas Muir, west of Milngavie (522 750) a resistant band of Calciferous Sandstone has produced a scarp-like cliff face now 10 to 15m high, which faced the oncoming glacial advance. Although the Carboniferous contributes little in the way of topographic form in the landscape, the sandstones, mudstones and other sedimentary rocks of the series are the major components in both colour, stone content and texture of the common grey tills in Glasgow.

Sedimentation with its rhythmic constancy while occurring in the ever sinking graben was repeatedly interrupted by the occurrence of widespread vulcanicity. The Clyde Plateau Lavas are the best expression of these episodic occurrences. The main outcrop runs in a great curve from Strathaven via Eaglesham to the Renfrew Hills, then across the Clyde to the Kilpatrick Hills (Fig. 2). The dominant rock types are dark black basalts, mugearites and porphyries.

One feature in the landscape is the east-west dykes and sills of quartz-dolerite and teschenite. The geological age of these intrusions is in the region of the Permo-Carboniferous boundary. One of the important characteristics of these dykes is their great width, often 10 to 15m across. Many dykes are known to exist under the drift cover, the evidence largely coming from coal and other mining activities. However only three dykes have any important topographic expression. One runs from Cadder (615 724) to Cawder Cuilt (565 707). Another dyke runs from Crowhill (613 697) to north Lambhill (575 698) with a similar

eastern exposure. The last dyke runs almost north, north-east to south, south-west from Stobhill (608 696) via a railway cutting to Possil (590 688).

There are few quartz-dolerite sills of any topographic importance, the only exception being the Milngavie dolerite sill. This sill intruded into Galfiferous Sandstone series extends from Milngavie (545 739) north-east to the Mugdock and Craigmaddie Reservoirs (558 758).

The teschenite sills running east to west are perhaps more sharply defined within the landscape. The major sill of the Necropolis Hill (655 604) extends from the Necropolis eastwards via Alexandra Parade (654 624) to Ruchazie (646 665). In several places the sill bifurcates especially in the Blackhill area (630 667), resulting in several igneous masses appearing at the surface as at Riddrie (635 661). Between Whiteinch (540 670) and Paisley several other teschenite sills are known to exist, crossing the River Clyde.

3) MESOZOIC-TERTIARY INTERVAL

This interval of geological time, including the Permian period, extended over 270million years approximately. The Carboniferous in comparison only extended over 120 million years. However little or nothing other than conjecture and hypothesis linked with a few scarce facts is known of this huge interval. What is important is that within this interval of time, the skeleton of the present river system developed, much of the rocks were severely and deeply weathered and from the Cretaceous onwards probably no major marine transgressions occurred, the land surface being lowered due to subaerial agencies.

Theories on the development of the river system have remained, through lack of substantial evidence, fairly flimsy notions. Many

theorists believed all the rivers of Scotland flowed initially eastwards or south-eastwards (Mackinder, 1902; Gregory, 1915; Mort, 1918; Peach & Horne, 1930; Linton, 1933, 1940, 1951; Bremner, 1942). Others believed in more localised concentrations of drainage, for example around the Moray Firth, Tay and Forth estuaries (Bremner, 1942; Linton, 1951). Sissons (1967, p.24-7) reviewed these above theories and proposed the theory that a major watershed with short western rivers and much longer eastern river, not too dissimilar from the present river system was initiated during this interval, perhaps on a now totally removed Mesozoic cover. As regards the River Clyde and its tributaries, the theorists have suggested reversed drainage or drainage as it is today. What is important is that in this geological interval, rivers developed with a pattern akin to today's network and have since only undergone subaerial and glacial modification.

Some evidence would suggest that in this protracted interval intense differential physical and chemical weathering of the solid rocks may have occurred, especially in the Tertiary. What appear to be core-stones now close to the surface can be seen near North Queensferry and around Airdrie. Other areas in Scotland, especially the North-East, reveal deeply weathered rocks (Phemister & Simpson, 1949; Godard, 1965; Sissons, 1967, p.22; Fitzpatrick, 1972). Much of this weathered material has presumably been incorporated into the tills (Feininger, 1971; Rosenqvist, 1975) giving rise to the weathered appearance of many stones, clay minerals, and the high clay particle content in many lowland tills (Wilson et al., 1972).

The vast amount of denudation that has taken place in this interval has been remarked upon by various workers (Linton, 1955; George, 1958, 1960, 1965; Godard, 1965; Fitzpatrick, 1965, 1972; Sissons, 1967).

Evidence of this intense subaerial denudation can be detected throughout the landscape. For example, deep river channels cut across Tertiary Dykes, many of the rivers are discordant having superimposed sections and there is a lack of lava flows related to the Tertiary dykes.

With the close of this long interval, the study area entered the Quaternary. The pre-glacial climate seems to have been more humid and warmer than today. Rivers had cut down from once higher surfaces and now existed in deep valleys. The valley sides and interfluves were of moderate relief, probably thickly covered with residual soils. With the oncoming ice advance and the climatic recession the vegetation changed, leaving a periglacial, tundra zone of intense frost shattering, permafrost, solifluction down the valley interfluves and tundra vegetation.

The Quaternary period, although the shortest and most complex, has left a fairly complete and detailed record of its occurrence. Although the Quaternary probably lasted over 2 or 3 million years, the deposits that are left are probably, in the main the work of glaciers that existed during the last few tens of thousands of years. Much of the glacial erosion cannot be dated accurately but sediments with organic inliers can. Due to its importance and complexities in the landscape, a separate chapter deals with the Quaternary.

CHAPTER 3

PREVIOUS LITERATURE ON THE QUATERNARY OF THE GLASGOW AREA

The Quaternary period, although the shortest, has left the most complete record of its occurrence throughout the whole of Scotland. Evidence in the form of tills, moraines, fluvio-glacial sands and gravels and the later raised beaches of Glasgow is well documented. The landscape, as noted in the previous chapter, is totally dominated by Quaternary deposits masking and submerging much of the solid geology.

By the mid-nineteenth century the work and observations of men such as Agassiz, Imrie and Chambers had clearly ascertained the probable origin of the huge spreads of unconsolidated deposits which cover the Glasgow area. While researching into the elevated marine terraces and their fossiliferous beds around the Clyde estuary, J. Smith of Jordanhill had illustrated the arctic nature of the beds. Chambers (1848) noted the extent and heights of many raised shoreline features.

Apart from the fossiliferous raised beaches, scratched boulders and striae, perhaps the most enigmatic problem was the distribution of Highland erratics either as surface boulders or as stones in the till (boulder clay). The distribution of these erratics obviously was contrary to the present drainage routes and was largely from north-west to south-east by east.

Arguments between the Diluvialists and the Glacialists existed even up to the early part of the twentieth century. The Diluvialists believed in "waves of translation", "the flood" and other fluvial processes to

raise boulders up hill summits, shells to over 150m O.D. and to produce till. However even by the 1840's it would appear that a Glacial theory for the above deposits and erratics was becoming acceptable to some workers (Bryce, 1855).

REGIONAL DESCRIPTIONS PRIOR TO 1925

It was in 1855 that Bryce published perhaps the first concise regional description of the Glasgow area, arguing on the basis of erratics and striae for a south-east and easterly movement of glaciers over this area. An interesting observation is that when till was stripped from the underlying rock, the rock exhibited a smoothed, scratched and grooved surface indicative of glacial action (Bryce, 1855, p. 11).

Over the next fifty years (1850-1900) work by the Geological Survey officers, and many enthusiastic amateurs produced such a mass of detail and information, that there is little today that was not observed or commented upon at that period. A. Geikie (1863, 1865), Bennie (1866, 1868, 1891), Bell (1871, 1874, 1894), R. Craig (1874), J. Geikie (1874), Blair (1891) and J. Smith (1893) were the main contributors.

A major glacial phase was recognised in which ice flowing from Loch Long, Gareloch and Cowal was prevented from moving south¹ due to the mass of ice in the lower Firth of Clyde. Bell (1894) calculated a thickness of 1000m for this ice mass. The ice was then directed east and south-east over Glasgow. Another movement, suggested by Campsie Fells erratics in the Stobhill Dock excavations, was from the north-east to south-west (Smith, 1874) (Fig. 3).

EARLY RESEARCH ON THE BURIED CHANNELS

The researches of Bennie and Croll revealed the deep buried valleys of the Clyde, Kelvin and several smaller valleys in the Motherwell and Lanark areas. What was of interest was not the valleys themselves but the infilling deposits. These valleys were presumed to be of pre-glacial origin related to a low sea level in the Tertiary (Bennie, 1868; Croll, 1870, 1875). With the advance of the ice, it was suggested that a lake, caused by the damming back of the Clyde and its tributaries, would have formed (Bell, 1874; Geikie J., 1874). This lake might have had several possible outlets, once specific lake levels were reached, either through the Kilwinning Gap, Cowdon Glen or east via the Kelvin valley to the Forth. J. Geikie and Bell argued that shells found by Bennie in the buried Kelvin valley at Blairdardie (525 709) might well be freshwater and considered the deposits lacustrine, adding weight to their "lake" theory. Croll and Bennie however argued, for a marine origin, using evidence which has since been shown to be suspect, and correlated the marine fossils at Grangemouth with those at Blairdardie (Clough et al., 1925, p.218). Clough et al. (1925) argued that low sea levels in the Tertiary caused deep river downcutting. Subsequent valley infilling resulted from river silting-up and submergence with the depression of the dissected land surface at the advent of the Quaternary.

ORGANIC REMAINS

Prior to the advance of the ice organic remains of fauna and flora were entrapped in either the lake deposits or between them and the overlying till. These deposits, because of their mild climatic constituent remains, were recognised as interglacial deposits (Geikie, J., 1874). Many localities in the area where such organic remains exist were located

in the nineteenth century and their significance will be discussed later.

TILL

With the subsequent ice advance, red till and grey till were deposited either simultaneously or the grey was deposited prior to the red. The drumlins, so characteristic of this area, were "created" simultaneously with the tills. Within the till, shells and foraminifera were often found (Fig. 3). Similarly erratics within the till such as the Glen Fyne granite erratics have led to an awareness of ice transportation and ice direction.

DEPOSITS ABOVE TILL

After the retreat of the ice, sands and gravels, located to the east of Glasgow, around Baillieston and Coatbridge were deposited, it has been suggested, either as a moraine or stillstand of the ice either in recession or readvance. Similarly up to 52m O.D. along the hill slopes bordering the Kelvin valley west of Kilsyth, sands and gravels overlie till. J. Geikie (1874) also reported sands and gravels at Strathaven up to approximately 250m O.D. It has been suggested that these deposits exhibit evidence of the ice-dammed lake, yet other evidence for this lake is lacking. The ice retreat is presumed to have been down valley towards the Kilpatrick Hills and Cowal.

RAISED BEACHES

At the final wastage of the ice sheet, the Midland Valley was invaded fairly rapidly from the east and west by the sea (Jamieson, 1865). Two distinct shell assemblages (collectively known as "the Clyde Beds") were observed, one of cold Arctic waters, the other of warmer waters (Smith, J., 1898). The colder deposits indicate a phase immediately

following ice retreat from the Midland Valley and the latter a subsequent post-glacial phase of climatic amelioration. The number of raised beaches identified in the Glasgow area varies between three and four (Chambers, 1848; Dougall, 1865; Crosskey & Robertson, 1867). Buried peat layers, Neolithic canoes and crannogs were all discovered at different times and places, creating considerable interest (Croll, 1875; Neilson, 1903). These organic and human remains greatly aided the dating of the youngest sediments, the techniques of palynology and radiocarbon dating being unheard of at that time (Murdoch, 1904).

The events, as outlined above, have been largely accepted since the nineteenth century with only minor changes until the 1960's. The Geological Survey Memoir for the district, first published in 1911 and revised in 1925, makes little effort to gather together the threads of Quaternary research for the area but merely reports and makes observations (Clough et al., 1911, 2nd ed. 1925).

PROGRESS AND AREAS OF INVESTIGATION SINCE 1925

Since the publication of the Geological Memoir progress on the Quaternary history of Glasgow has occurred on four levels.

- 1) Work which had already been done, such as the details pertaining to the buried channels, was incorporated into newer writings so that in effect work well known prior to 1900 but left unincorporated was re-utilised.
- 2) With the advent of palynology and radiocarbon dating many organic remains, discovered prior to 1900, have been dated.
- 3) Similarly new discoveries of organic material as at Queen's Park (Macgregor & Ritchie, 1940), Bishopbriggs (Rolfe, 1966) and the dating of mollusca from Cardross, Dumbarton, Wester Fulwood, Linwood, Gallowhill

and Ralston (Peacock, 1971) have enabled a chronology of beach development and till deposition to be constructed.

4) The greatest area of progress has been the development of knowledge on the Quaternary in Scotland, as a whole. Work performed outwith the Midland Valley was limited up to the 1900's. However since then and with the advent of new dating techniques knowledge of the areas surrounding Glasgow has increased. For example, the location of the Perth Re-advance limit (Sissons, 1963, 1964), in the Larbert area east of Glasgow, presumes that ice must have passed over the Glasgow district during this advance, most probably leaving organic, stratigraphic or geomorphic evidence of the passage of the ice. Glasgow's Quaternary history is therefore no longer isolated, as in the nineteenth century, but now its Quaternary evidence or lack of may be seen within the much wider context of Scotland's Quaternary.

Before considering the most recent views on Glasgow it is necessary to first detail the facts and observations that have been recorded yet largely left unused in older works and which often form component parts of these more recent views.

QUATERNARY STRATIGRAPHY IN GLASGOW

Within Glasgow there are four distinct stratigraphic layers:

1. Sands, gravels and clays within the buried channels
2. Till and associated drumlins overlying the channels
3. Sands and gravels of uncertain origin overlying the till
4. Raised beach silts, clays and muds, associated peats and alluvial deposits

BURIED CHANNELS

As previously mentioned Bennie (1868) and Croll (1870, 1875)

argued for a fluvial rejuvenation theory on the basis of low sea-levels, as did Clough et al., (1925). Bell (1871) and J. Geikie (1874) make little mention of their own ideas regarding the buried channels, being only interested in the contained deposits, and accepted a pre-glacial, presumably, fluvial origin. Other deep channels have been described by Dick (1870) and Dron (1915) at Motherwell, by Stark (1902) at Lanark and by A. Geikie (1863) around Chapelhall near Airdrie.

The buried channels vary greatly in depth between different channels and along individual channel profiles (Clough et al., 1925, p.218). The Kelvin valley, as noted by Bennie (1868), is over -95m deep at Duntocher (551 728) and over -108m at Millichen (574 719). In the buried Clyde channel a depth of -30m O.D. at Glasgow Bridge (587 648) was noted (Clough et al., 1925). Dick (1870) recorded depths of 30 to 45m in the infilled sands and gravels of channels in the Motherwell/Wishaw area. Stark (1902) mentioned depths of over 90m of drift in the New Lanark/Bonnington area. Whether or not these channels are part of an integrated system has never been discussed, but some similarity in age and origin does suggest itself.

In 1870 considerable debate between J. Young and J. Geikie developed over whether the deep valley of the Clyde ever reached the Firth of Clyde via Bowling (Croll, 1870, p.341) or whether, as Young suggested, were linked with the deep Kelvin passing east to the Forth. There appears to be no doubt about the existence of a link between the buried channels of the Kelvin and the Clyde, but there is some doubt as to the location or even existence of a western outlet into the Firth of Clyde (Clough et al., 1925). The view adhered to by most workers since 1925 has been that it does join the Firth of Clyde. No firm evidence of this, however, has been found but many workers who accept a fluvial origin for the channels,

do maintain the necessity for a western outlet in order that the deep profiles of the channels may be linked with a pre-Quaternary low sea level. Bennie (1868, p.146) also mentioned a deep channel stretching from Grangemouth to Bowling (cf. Cadell, 1913). This is corroborated by Croll (1875 p.471) in a diagram showing an east - west link. The significance of this link other than in terms of a marine transgression has never been discussed fully,

An origin similar to that adhered to by Clough et al., (1925), that is of river rejuvenation to a much lower pre-glacial sea-level, is accepted by both George (1965) and Steers (1973). In the Memoir on the Economic Geology of the Central Coalfield, Area 5 (1926, p.157), a buried channel running north-east to south-west in the region of the Monkland Colliery (740 670) was described as a "filled-up interglacial river channel". Sissons (1969, p.26) however argues for a subglacial origin for the buried channels especially in their most constricted areas (e.g. the Carron). In the much wider stretches glacial erosion is viewed as the dominant process. The basis of his work is the evidence obtained from deep boreholes in the Grangemouth/Falkirk area and on the stratigraphic evidence found within the deep buried channel of the Carron. Resemblance of the channels to the deep, narrow tunneldale of Denmark and rinnentäler of the North German plain is drawn. As an explanation of the sinuosities and narrowness of the channels, as well as of the infilling sands and gravels interleaved with silts and clay bands, it overcomes the problem of erosion as a result of a "supposed" low sea-level and later marine or estuarine infilling due to submergence.

The origin of the buried channels remains in debate yet the above explanation of glacial and subglacial processes would seem to be the most

likely (Chap. 8). Although the importance of the buried channels within the Quaternary history of Glasgow cannot be underestimated, the surface expression of these channels is limited. Only where present-day rivers such as the Kelvin and Carron follow the channel direction is there any suggestion of a depression.

DEPOSITS WITHIN THE BURIED CHANNELS
AND THOSE UNDERLYING THE TILL

In discussing the deposits that infill the buried channels past workers have largely correlated origin of deposits in some way with origin of channels. The deposits, themselves, are varied and described as thick strata of sands and gravels intercalated with lenses of laminated clays and silts. Occasionally till is found within the deposits, as many as six bands having been mentioned (Bennie, 1868; Clough et al., 1925). In the main the typical stratigraphy in descending sequence is: till, sands and gravels, then bedrock. In the channel near Monkland Colliery however, a second till resting on the rock beneath the sands and gravels was noted (Geikie, A., 1863). This channel is described as being of interglacial origin as are the infilling deposits. A. Geikie (1863, p.65) states that the channels "belong to the boulder clay period". Sand is so dominant in the channels that coalminers in the Lanarkshire coalfield having driven shafts into the sides of these channels referred to them as "sand dykes" (Dick, 1870).

As previously mentioned several workers accepted a marine origin for the deposits, others fluvial and others lacustrine (Bennie, 1868; Croll, 1870, 1875; Bell, 1871; Geikie, J., 1874, p.134; Clough et al., 1925; Sissons, 1964a, p.34, 1967, p.123).

Sissons (1969) has argued for a subglacial origin to be attributed

to the deposits at Grangemouth. Jardine (1973, p.159) suggested an interstadial or interglacial origin for the deposits terming them "water-laid (? fluvioglacial) sands and gravels".

Inspection of the reported stratigraphy reveals that there is no till on bedrock at the base of these channels, other than at Monkland. It is possible that if a fluvioglacial or glacial erosion origin is accepted for the channels that this lower till which might have existed at some time more widely than now known, could have been removed or washed out.

Organic Remains and Sub Till Deposits

Sands and gravels containing remains of reindeer underlying till have been found at Queen's Park (588 619) (Macgregor & Ritchie, 1940) and at Baillieston (670 634) striated teeth of mammoth have been discovered within sands under till (Bethune, 1879, p.291) (Gregory & Currie, 1928). At Kilmaurs (405 397) in Ayrshire bones of mammoth and reindeer were found in beds underlying till. The part tusk of elephas primigenius was radiocarbon dated 13,700 (+1300 -1700) B.P. (Sissons, 1967) but another from Kilmaurs on a reindeer antler (rangifer tarandus) has since been dated as > 40,000 B.P. (Shotton, et al., 1970). This latter date places doubts on the validity of both dates for any chrono-stratigraphic correlation (McKenzie, 1818; Young & Craig, 1871; Gregory & Currie, 1928; Sissons, 1967a, 1974). A similar discovery of reindeer remains occurred within sands and gravels beneath till at Croftamie (NN 480 860), just to the south of Loch Lomond (Smith, J. A., 1850).

In the Airdrie district, at Chapelhall (780 630), peat and wood fragments were discovered in sands, laminated clays and silts beneath

35m of till (Geikie, A., 1863, pp.59-60), while at the same locality bones of mammoth were also found. As further evidence of sub till deposits a shell bed beneath grey till at Paisley was reported (Crosskey & Robertson, 1869, p.337).

Sands and gravels exposed at the Wilderness Plantation, Bishopbriggs (600 720) reveal the considerable depths of sub till deposits that can exist. These deposits have been extensively worked, and in 1964 remains of woolly rhinoceros were discovered (Rolfe, 1966). A date of 27,550 (+1370 -1680) B.P. was obtained for these remains. This date suggests that around 27,500 years B.P. the climate of the Glasgow area must have been relatively mild in comparison to the preceding and subsequent glacial periods.

The significance of these sands and gravels and encased organic remains beneath the till at Bishopbriggs is that they are evidence of an interstadial or interglacial before the advance of the last glacial phase. The sub till deposits may be of similar age to the infilling deposits of the buried channels or they may be younger. One argument for separating these deposits in age from the buried channel deposits is their fossiliferous content. The sands and gravels and related sediments if not of the buried channel deposit age are presumably fluvioglacial deposits over which ice readvanced.

Periglacial Features of Sub Till Deposits

Galloway (1961, pp. 177-79) mentions sites around Glasgow where ice wedges, involutions and faulting due to permafrost action are found in the sub till deposits. An area of permafrost features is found in the sand and gravel pits at Bishopbriggs (590 720; 610 720; 620 710). Sissons (1967, p.220) suggests that these wedges overlain by till, like

those around Edinburgh, must have been formed in the cold period of an interstadial as the ice again readvanced into these areas. Other sites are recorded at Cardross (Rose, 1975), Drumclog and Falkirk.

TILL

As early as 1840 Agassiz when examining till in Glasgow concluded that it was of glacial origin. A. Geikie (1863, p.35) described the character of the till as " ... not merely a clay with a greater or lesser number of boulders scattered through it; it is rather an earth - a mixture of gritty clay, sand, gravel and boulders, heaped together indiscriminantly in constantly varying proportions".

The areal extent of till in the Lowlands of Scotland was described by J. Geikie (1874, p7) as " ... spread in broad somewhat ragged sheets, which are often continuous across wide tracts". A landscape of rolling drumlinised topography has been produced on the more easily eroded Carboniferous sediments of the Lowlands, with reported depths of till to over 30 to 35m while in other areas 15 to 25m are not uncommon (Clough et al., 1925, pp. 223-5).

Till Stone Content

Examination of the till in Glasgow revealed that many of the stones encountered in excavations were not of local origin. The finer fractions were however recognised as being dominantly comminuted local rock. Hopkins (1852) noted that many of the boulders in the till were of West Highland origin. Later he and Bell noted that these boulders were identical to the Garabal granite outcrop in Glen Fyne (Bell, 1894, 1895, p.20). Glen Fyne erratics were traced down the east side of Loch Fyne, down Loch Long, across the Kilpatrick Hills and into Glasgow (Fig. 3).

Several localities were noted where these granite erratics existed in Glasgow: at Jordanhill, Partick, Hamilton Hill and Garscube Road. Bell subdivided the stone content of the till into: 60% shale and sandstone of Carboniferous age; 30% from Kilpatrick Hills and 10% from the highlands of Dunbarton and Argyllshire (cf. Chap. 5). Other workers have made similar stone content subdivisions (Smith, J., 1838; Gregory, 1915a). Clough et al., (1925, p.225) state that the red till has a more exotic stone content than the grey which tends to be composed of local rocks but they give no details.

Analysis of stone contents illustrate the eastward passage of the ice from the Cowal and upper Loch Long areas. Work on the Lennoxton Essexite boulder train has further revealed this eastward trend (Peach, A.M., 1909).

Till Colour and Texture

Texture and colour are closely allied to the stone content of any till. Hugh Miller commented: "The boulder clay, in the majority of cases is both in colour and quality, just such a clay as might be produced from the rocks on which it rests." (Geikie, A., 1863, p.37).

The till in Glasgow has been described by numerous workers as being grey, black, tenacious and stiff where the Carboniferous shales, mudstones and sandstones underlie it (Plate 4). Where the Old Red Sandstone conglomerates, marls and sandstones exist the till tends towards a reddish colour and is less compact and sticky and of a sandier texture (Clough et al., 1925)(Plate 5). It is reported that in several exposures the red till was seen to overlie the grey till particularly along a line roughly north to south from north Maryhill (570 700) to Whiteinch (530 670) on the Clyde (Clough et al., 1925). West of this line red till predominates

and to the east grey till. Sommerville, however, reported an exposure in the Graving Dock at Blawarthill (516 684) approximately 400m east of Yoker in which red till 6m thick was overlain by blue till 7.6m thick (Sommerville, 1905, p.265). The red till, is in many cases, intercalated with sand and gravel lenses and numerous instances of successive deposits of red, brown and blue till, separated by sands, gravels and muds have been noted from many deep bores (Bennie, 1868, p.133). Red till, however, has been reported in several instances east of this boundary line, for example at Parkhead (630 650) and Mount Vernon (655 650).

This difference in colour, texture and stone content between the two tills has been considered by various workers (Clough et al., 1925; Jardine & Moisley, 1967; Sissons, 1967, 1968; Jardine, 1968, 1973; Jardine & Peacock, 1973). This difference manifests itself in three hypotheses: that the two tills belong to different glacial phases, the red being the younger (Jardine & Moisley, 1967; Jardine, 1968, 1973); that the red till is an ablation till on top of the grey till (Jardine, 1968); that the two tills are of identical age only different in appearance due to bedrock sources.

Weathering in Till

Jardine has pointed to what appears to be a distinctly weathered zone in the top horizons of the grey till (Jardine & Moisley, 1967; Jardine, 1968). However evidence of this weathering zone in either red or grey till would seem to be scanty, as Sissons has pointed out (1968, p.187). Jardine (1973, p.163) later suggested that the weathering in the grey till is only observed when it is not overlain by "later" red till, the implication being that this weathering is a product of post-red deposition. However, no evidence is produced to prove this conjecture.

A more detailed examination of the weathering zone in both tills is required before any such pronouncements can be made.

Marine Organisms in Till

A major obstacle to the acceptance of a glacial theory in Scotland was the inclusion, in several places, of shells or marine micro-organisms in the till. Deposits such as at Clava in Inverness-shire (152m O.D.) or at Chapelhall near Airdrie (155m O.D.) (Smith, J., 1850; Crosskey, 1865; Bell, 1893) were usually explained by marine transgressions to well over 150m O.D. However it was realised that ice grounding on the sea bottom could explain the preponderance of shelly till in some areas, such as Ayrshire.

Within Glasgow several localities exist where marine organisms have been found in the till (Fig. 3). Wright and Neilson examined the till for foraminifera and in 11 different localities within the city found an average of one foraminifera to 417g of till. The richest find of fossils was at Giffnock (565 585) where 22 individual foraminifera were found (Neilson, 1896; Wright, 1896, p.273). Shelly clay intercalated between two tills at Chapelhall, Airdrie, was first noted by Smith of Jordanhill (Smith, J., 1850; Geikie, A., 1863; Bell, 1893).

Other Organic Remains in Till

Other fossil remains such as peat, twigs and mosses with included coleoptera have been discovered in two locations close to Airdrie at Burnhead Quarry (783 666) and at Faskine (753 634) (Dunlop, 1888; Bennie, 1896). Coope has since examined the coleoptera from samples taken at Burnhead in the 1890's and concluded that the fauna are representative of more northerly tundra climates (Coope, 1962).

DRUMLINS

Drumlins spread out from the Glasgow area to the east and south-east across the Lowlands representing the only major surface expression of the till. Little detailed information exists on Glasgow's drumlins (Upham, 1898; Clough et al., 1925; Elder et al., 1935), yet it is the drumlins that dominate much of the landscape of this area.

Internal investigations of the drumlins are rare and those that exist are scanty in description. Bennie (1866) reported the almost complete removal of the Bell's Park drumlin (592 656). Exposures at Hamilton Hill (585 675) and at Gilmorehill (575 665) were reported in some detail (Young, 1869; Neilson, 1896, p.276; Smith, J., 1902). Within Glasgow, itself, other than a few teschenite dykes which form crag and tails (e.g. Necropolis Hill, 585 664 and at Riddrie, 635 664), most of the hills are drumlins. At Hamilton Hill over 21m of till is reported with no rock core to the drumlin being noted (Smith, J., 1902). Occasionally drumlins merge into one another side by side producing an undulating drumlin upland (Sissons, 1967, p.85). Reports on drumlin exposures, in the main, centred on discussions of till origin and stone content and not on drumlin genesis. Reade (1882, p.267), however, although not specifically referring to drumlins and without presenting much evidence, mentions the discontinuity between till cover and the underlying rock. He implied that where the till rises and falls in the form of drumlins and inter-drumlin hollows, the rock surface does not necessarily do so.

J. Geikie, however, showed interest in drumlin genesis and in till structures in the drumlins. He noted that in the Midland Valley towards the sides where the till was thinner, the "drums" occasionally had nuclei of solid rock (Geikie, J., 1874, p.17). He formulated in a general manner

a theory of drumlin genesis, one which even now seems highly likely. Geikie undoubtedly had the essence of a theory by 1874 (Geikie, J., 1874, pp.96-7; 1894 p.81), yet his essential ideas were only taken up again in the 1960's (Chap. 4).

Other than indicating directions and orientations, most workers have done little to expand the knowledge of Glasgow's drumlins (Clough et al., 1925; Elder et al., 1935). Gregory (1915a, p.160) with a rather obtuse theory argued that the present-day morphology of a drumlin was not glacially inherited but due to post-glacial weathering and erosion. He suggested that the drumlins were eroded remnants of a once particularly thick irregular till cover. The only evidence put forward was the deep gullying of some streams among the drumlins.

The chronology of drumlin formation is not entirely clear, debate existing as to whether the two tills were deposited at differing times or not. It is reasonably agreed that drumlin formation occurred during the final glacial phase in this area (Clough et al., 1925, p.214; Sissons, 1964, p.29; 1967a, p.134; Jardine, 1973, p.162). However from the remarks of Clough et al. on drumlin distribution and till colour distribution and from the map of Elder et al. (1935, Plate 6) it would appear that many of the more westerly drumlins within Glasgow are probably composed of red till. As with the hypotheses on the two tills, the drumlins, some of which are of red till and others of grey till, may be either of the same age if the tills are contemporaneous or of two different ages if the tills are of two distinct glaciations (Jardine, 1968, 1973).

The effect of the drumlins on the landscape, particularly on the drainage pattern, is considerable. Small streams wander between the drumlins (e.g. the Molendinary, Yoker and Garngad burns)(Fig. 4). South of Killermont (555 705), the Kelvin valley wanders between the drumlins but

has a channel cut in rock.

GLACIAL DEPOSITS OVERLYING TILL

Deposits other than raised beaches known to overlie till in Glasgow are scanty. Such deposits are either ice-contact or pro-glacial, comprising water-sorted sands and gravels with inclusions of laminated silts and clays in surface hollows. East of Shettleston in a belt of country 3km long and 0.8km wide running north to south from Lochwood (695 666) to Calderpark (680 626) there exists an area covered by: "irregular mounds of loamy boulder clay passing down into pebbly sand" (Wright & Clough, 1906, p.95; Clough et al., 1925, p.227). This belt of deposits abuts against the higher ground on the north, passing below the riverine sands and gravels to the south. Clough et al. describe these deposits (due to their position normal to ice flow) as moraines in part similar to the German "stau-moränen". This then implies an ice stillstand in or readvance to this area within the general phase of deglaciation.

Within a few hundred metres of this "moraine" there exists a narrow, linear, east to west, series of ridges of sands and gravels, stretching from Tollcross (648 632) to Broomhouse (670 626). Clough et al. described these deposits as having horizontal and cross-bedded structures and suggested they were laid down in a temporary lake impounded by the retreating ice front. What significance these glacial deposits, as a whole, have in the general glacial history of Glasgow remains vague. Directions of ice retreat may be indicated by these deposits, without a greater distribution of such deposits in the area little can be added to this conclusion.

Organic Remains found in Glacial Deposits Overlying Till

In stratified deposits at Cowdon Glen (445 561) both animal and

plant remains were found overlain by what has controversially been described either as till, marine deposits or as landslip deposits (Craig, 1874; Geikie, J., 1874, pp.102-3; Sissons, 1967). The deposits extend south from Shillford (445 561) to Dunlop (410 500) (Craig, 1874). If a post-glacial theory, as seems most likely, is accepted for the deposits, then the overlying material must either be soliflucted or landslip deposits (Craig, 1874; Sissons, 1967, p.227).

RAISED BEACHES

Raised beach deposits, estuarine muds and alluvial deposits were examined in considerable detail in the nineteenth century (Smith, J., 1838, 1839, 1862; Chambers, 1848; Geikie, A., 1863; Dougall, 1865; Crosskey & Robertson, 1867, 1869, 1874; Crosskey, 1871; Geikie, J., 1874; Robertson, 1877). At several levels along the margins of the lower Clyde valley elevated beaches containing cold water mollusca and fauna exist. Beach heights were recorded up to the "so-called" "100 foot" beach (Geikie, J., 1874, pp.273-4). Dougall (1865) reported beach levels even higher at 34m, 44m, 54m and at 64m O.D. Whether these relict features are beaches or are patches of lacustrine clays or marine fossils in till was never discussed, but subsequent workers identified beaches only up to the 30m level.

Until 1962, it was accepted that the raised beaches of Scotland existed at three levels, namely 25 feet, 50 feet and 100 feet (Clough et al., 1925, p.231; Sissons 1962). Although some indication of the inaccuracy of this classification had occurred, in the main the classification although set-up as a tentative suggestion, was accepted as fact (Wright, 1937; Sissons, 1967, p.162). Sissons has clearly shown, however, that this three-level concept is untenable (Sissons, 1966;

Sissons & Smith, 1965; Sissons et al., 1966).

Raised Beaches in Glasgow

The raised beaches within the Glasgow area have been little investigated since the time of Smith of Jordanhill and Crosskey and Robertson. Clough et al. envisaged the highest beach (100 ft.) as having been formed as ice still stood at the mouth of the Clyde, the fauna of this beach being sub-arctic (late-glacial) in nature. These sub-arctic deposits represented by laminated clays and silts although extending up to 26m O.D. are most fossiliferous below about 21m O.D. (Clough et al., 1925; Sissons, 1967). The next succeeding lower beach (35 ft.) is less arctic in its contained fauna (post-glacial). Clough et al. suggested that this "35 foot" beach was really the "50 foot" beach supposedly represented elsewhere in Scotland. Similarly the "25 foot" beach, it was suggested, has been covered over by later alluvial spreads.

Within the city limits, marine fossils diminish as the deposits are traced eastwards, the most eastern clays being estuarine (Clough et al., 1925; Sissons, 1967, p.151). Similarly the number of erratics in the late-glacial deposits diminishes the farther eastwards the beaches are traced.

Anderson (1947) working on the clays around Paisley, noted that the ostracods he identified did not include arctic species. This led him to point out the non-arctic nature of the clays in contrast to examined beaches on the east coast (cf. Robertson, 1877). This difference of fossil content between Glasgow's beaches and those in the Carse of Stirling and the Forth estuary is further borne out by the difference in surface heights between the beaches in Glasgow at around 26m O.D.

and those at Stirling at 36.6m O.D. and at southern Lochs Long and Fyne and Glendaruel in Cowal at 36 to 40m O.D. (Sissons, 1974, p.329). One theory to account for this height difference is that ice remained over the site of Glasgow while eastern Scotland and the lower Clyde estuary became ice free (Sissons, 1974). This theory suggests that deglaciation in the Glasgow district was more complicated than has been realised in the past. It also allows the observation that as ice stood at limits at Otter Ferry, Lochs Long and Fyne and Stirling, Glasgow remained ice covered. The relationship of raised beaches with deglaciation therefore appears to be highly significant in the Glasgow district (Sissons, 1974, p. 329) (cf. Chap. 13).

Chronology of the Raised Beaches in Glasgow

The chronological sequence of events is, as yet, little known for the Clyde beaches. Late-glacial deposits as at Garscadden Mains (535 713) (Mitchell, 1952) indicate the nature of the fauna and flora at the time the beach was developing up to 26m O.D. The lower beaches by nature of their sub-arctic fauna appear to have been deposited in late-glacial times. No evidence of buried beaches or the buried gravel layer yet exists. Both Jardine and Peacock, separately, suggest an invasion of marine water into the Clyde inner estuary (i.e. Glasgow/Paisley area), depositing late-glacial sequences of lacustrine-like clays and silts while the lower Clyde estuary was ice-dammed (Peacock, 1971, p.45; Jardine, 1973, p.165). Indicating that while the Cardross/Dumbarton area was still ice covered the inner area around Gallowhill and Ralston was inundated by the sea.

The dates in the following table may suffer from a "hard water effect", causing some of them to be too old (Mangerud, 1972; Olsson, 1974)(Fig. 5). The dates therefore can only be said to convey an

indication of the date for ice-sheet decay. The variation within any dated material may be as great as between dates; therefore the theories proposed which demand differing depositional periods may have a rather fragile basis.

T A B L E 1

<u>Sites</u>	<u>Grid. Ref.</u>	<u>Radiocarbon date</u>	<u>Lab. Ref.</u>
Cardross	NS 341 777	11,787 \pm 122	GO 12
"	"	11,900 \pm 205	N-475
Dumbarton	NS 396 752	11,805 \pm 205	C14/6
Renfrew By-pass	NS 495 657	12,408 \pm 85	SRR-62
Wester Fulwood	NS 432 669	12,650 \pm 200	Birm 122
Lochgilphead	NR 863 875	12,360 \pm 85	SRR-63
Gallowhill	NS 491 657	12,615 \pm 230 (i)	C14/68
Ralston	NS 510 641	12,610 \pm 210 (i)	C14/21

(i) - date of inner part of shell

Bishop and Dickson (1970) put forward a suggested chronological sequence of events based on radiocarbon dates indicating a marine transgression to 26m O.D. by about 13,000 B.P. Sea-level, it is then suggested, fell below its maximum before the close of Zone I (c. 12,000 B.P.). This regression continued and by Zone III (c. 10,800-10,300 B.P.) sea-level had reached approximately its present level. A date of 9,231 \pm 96 yr. B.P. for wood at the base of Linwood peat moss (433 654) indicates sea-level rose after this date, subsequently sea-level fell to present level. This sequence of events as compared with that in the Forth valley and carselands seems oversimplified, yet on the evidence collected perhaps it is the most acceptable explanation at this time (Sissons, 1967, 1969;

Sissons et al., 1966; Sissons & Rhind, 1970).

Organic Remains within the Raised Beach and Estuarine Deposits

Organic remains are fairly common ranging from Neolithic canoes to faunal and molluscan remains. Detailed accounts of mollusca are found in several papers (Jamieson, 1865; Crosskey & Robertson, 1867, 1869, 1874; Geikie, J., 1874). Several animal remains (e.g. ox, bos langifrons; elk, cervus alces) were found buried in beach gravels at Rutherglen and Paisley harbour (Bennie, 1867; Blair, 1891). Remains of plants and trees have also been excavated for example, oak fragments at Stobcross Dock (Burns, 1874).

The best known site of late- and post-glacial organic deposits is at Garscadden Mains in Drumchapel (535 713) where Mitchell (1952) uncovered a late-glacial sequence as follows:

- 1) freshwater varved clays up to 33.5m O.D. within a temporary lake, probably of Zone I age
- 2) marine clays up to 26m O.D. deposited in the latter part of Zone I
- 3) freshwater muds containing remains of dwarf birch (betula nana) and other sub-arctic plants, probably of Zone II age
- 4) soliflucted sands and gravels probably of Zone III age
- 5) post-glacial deposits

The evidence from the site accords with the view that the uppermost beaches in the Glasgow area are of late-glacial age. When allied with radiocarbon dates it leads to the conclusion that the Glasgow area was finally ice-free by 13,000 to 12,500 B.P. with a marine transgression flooding fairly rapidly into the inner estuary, presumably via the estuary mouth (Sissons, 1976).

RECENT AREAL DESCRIPTIONS AND INTEGRATIONS

Charlesworth (1955) suggested multiple stillstand and readvance limits in the Highlands but recognised three major readvance phases termed the "Highland" Glaciation, the "Moraine" Glaciation and a readvance called substage "P". It is now generally accepted that the Glasgow area remained ice free from approximately Zone I onwards. Simpson's Perth Readvance limits as described at Perth were extended by Sissons (1963, 1964) to the south, south-west and north. Critical evidence discovered at Larbert showed raised beach merging into pitted outwash thus illustrating a "supposed" ice readvance to this point in Zone I (Sissons, 1964). This readvance limit was traced south-west past Airdrie to the Lanark/Carnwath area. It was observed that west of a line between Larbert and Airdrie well defined kames and dead-ice hollows were numerous whereas to the east such landforms were infrequent or absent (Sissons, 1964, pp.29-30, 1967). The limits drawn by Sissons in this latter area were partly modified and partly substantiated by later work (McLellan, 1969). Mitchell (1960) had previously indicated a limit lying across the Clyde basin in the area of Airdrie and Coatbridge. This was in accord with the limits drawn by Sissons. Sissons (1964) further postulated that the tills and drumlins in Glasgow were also of this Perth Readvance stage. Recently several workers, in various parts of Scotland, have cast doubt on the validity of the Perth Readvance (Francis *et al.*, 1970; Gemmell, 1973, p.27; Paterson, 1974; Sissons, 1974). The most important evidence is that of Paterson, who has re-interpreted the critical section described by Simpson (1933) at Almondbank, near Perth, as being evidence of successive discharges of sediment down the front of an advancing delta. Previously Simpson had argued that this site exhibited evidence of ice readvance due to a sequence of fine texture laminated material being overlain by coarse sands and gravels.

A mammoth tusk found beneath shelly till at Kilmaurs (22km south of Glasgow) has been dated 13,700 (+ 1,300-1,700) B.P. (Sissons, 1967) and much later a reindeer antler from the same site was dated > 40,000 B.P. (Shotton et al., 1970). Before this latter date was obtained it was argued that the 13,700 B.P. date indicated ice readvance over Kilmaurs just after this date. The shelly till at Kilmaurs was correlated with the Glasgow tills, with the ice limit at Larbert and with the interval between the Kilmaurs date and the dates of Loch Droma (12,814 ± 155 B.P.) and Lockerbie (12,900 ± 250 B.P.) both sites being ice-free by around 13,000 B.P. (Sissons, 1967, p.145). However, with the publication of the latter date (> 40,000 B.P.) the significance of the Kilmaurs date is now considerably suspect. It is more probable that the forward movement of ice that produced the final, upper, extensive till cover represents the last ice-sheet that began to build up around 25,000 B.P. (cf. Bishopbriggs, 27,550 (+ 1,370-1,680) B.P. This ice appears to have retreated from central Scotland sometime just prior to 12,500 B.P. (Fig. 6).

Jardine (1968, 1973), as previously mentioned, suggested a readvance of the ice to account for the red till. This red till readvance would have been preceded by the glacial phase which deposited the grey till. Little evidence is presented other than a few sites where red till appears to overlie grey till. Jardine's (1968) suggestion that the grey till represents a major readvance in Zone Ia whereas the red till resulted from a smaller readvance in Zone Ic (12,300-11,950 B.P.) is countered by several arguments, the strongest being that by Zone Ic the Loch Droma site, backed by 1000m high mountains, had been ice-free since 12,814 ± 155 B.P. and the Loch Builg site close to the heart of the eastern Cairngorms was ice free by 11,770 ± 87 B.P. (Jardine, 1968;

Sissons, 1968; Kirk & Godwin, 1963; Clapperton et al., 1975). Other dates which reveal the timing of deglaciation are at Callander (12,750 \pm 120 B.P.), Abernethy Forest (12,710 \pm 270 B.P.), Drymen (12,510 \pm 310 B.P.) and Loch Etteridge (13,151 \pm 390 B.P.), as well as the dates on shell material around the Clyde estuary (Sissons, 1974).

Other than these above ideas which have tended to complicate the history of events without presenting evidence, the most acceptable argument for the age of Glasgow's tills is of a pre- 13,000 B.P. age (Sissons, 1964, 1967; Jardine, 1973; Sissons, 1974).

With the general retreat of this late-glacial phase the final mode of deglaciation of the Glasgow area remains uncertain. Ice would appear to have covered Glasgow, c. 13,000 B.P., while the Firth of Clyde was inundated by the sea (Peacock, 1971; Jardine, 1973; Sissons, 1974, p.330). Whether the ice that remained then decayed in situ or retreated north through the Strathblane gap or south-east up into the higher reaches of the Clyde remains an unanswered question. Evidence in the form of vast areas of ice-contact sands and gravels overlying the till does not exist other than in the small area around the Shettleston and Baillieston district.

The sequence of events that can now be fairly well accepted is:

- 1) After the interstadial that occurred c. 27,000 B.P. (Fitzpatrick, 1965; Rolfe, 1966; Von Weymarn & Edwards, 1973) a general ice advance over the whole of Scotland occurred.
- 2) This advance seems to have extended into England as far south as Yorkshire (Dimlington) (Penny et al., 1969; and Cheshire (Boulton & Worsley 1965) where it reached its maximum limit c. 18,000 B.P.
- 3) The ice retreated from this maximum extension of Devensian ice, rapidly clearing north Lancashire by c. 14,000 B.P. (Penny et al.

1969) and clearing south-west Scotland (Bishop, 1963; Moar, 1969; Jardine, 1973) by c. 13,000 B.P.

- 4) No interstadial would seem to have occurred after 13,000 B.P.
- 5) Some time during this final major glaciation the upper tills and glacial deposits of central Scotland were deposited. In Midlothian, tills of a previous advance or advances may have been recognised (Kirby, 1968) and such tills may occur in other parts of the Lowlands in areas sheltered from the succeeding glacial advances. 7 Of these upper tills the red and grey tills and the drumlins of Glasgow were deposited at this time.
- 6) By c. 13,000 B.P. (Zone I) ice had retreated from the site of Glasgow and the sea began flooding in, thereby creating beaches which now, due to isostatic recovery, are elevated. Of the late-glacial beaches, a level of 26m O.D. was attained in Glasgow. Scotland is presumed to have been totally ice-free by c. 12,500 B.P. (Sissons & Walker, 1974; Sissons, 1974, p.315; Sissons, 1976). The climate, by this time in the late-glacial, is presumed to have been mild in comparison with the forthcoming Zones II and III (Coope et al., 1971).
- 7) By the close of Zone II, the climate was again arctic and a minor readvance of ice occurred during Zone III, the Loch Lomond Readvance. Although the ice front approached Glasgow it did not advance into it (Mitchell, 1952; Sissons, 1967). Solifluction is known to have occurred extensively at this time (Sissons & Grant, 1972; Sissons, 1972, 1974a; Sissons, 1976).
- 8) Following on from Zone III, post-glacial seas occupied the area,

their visible expression being the extensive carse-lands that border the Clyde estuary.

SUMMARY

It is evident from the above that there are few if any final detailed conclusions on the Quaternary in Glasgow. However a broad framework does exist. So many ideas, theories and explanations in the past have appeared to the "the most acceptable" and have been since discredited, that new observations are necessitated. What must be avoided and seems not to have been, is the frequent re-evaluations without the presentation of new facts and evidence, of the Quaternary sequence of events. As Sissons has noted "More facts are needed, not more speculation." (Sissons, 1968, p.187).

New observations are required from every area of the stratigraphic sequence. Whether it be buried channels, tills or raised beaches, each individual topic needs to be examined in greater detail. An integration of all these observations and past work is necessitated. The accepted views and ideas on Glasgow's Quaternary need to be challenged in order that new lines of approach and newer ideas may develop. An example of this is Sissons' suggestion that ice retreat may not have been down the Clyde estuary. If not where else might ice have retreated and how and when? The distribution of the red and grey till must be clarified. The existence or not of drumlins beneath the raised beaches and in the buried channels needs to be ascertained. The routes and size of the buried channels remain to be finally solved. These and other questions are as yet unanswered.

In the following chapters it is hoped that some of these unanswered questions may be at least in part resolved and a new picture in the light of research and recent Quaternary research findings in Scotland be drawn.

P R E V I O U S L I T E R A T U R E
O N T H E
F O R M A T I O N A N D L O C A T I O N O F D R U M L I N S

Drumlins are smooth, oval hills or hillocks of drift variously likened in shape and general configuration to an inverted spoon or to an egg half-buried along its long axis. Where there is a steeper, blunter end, it points in the up-ice direction and the more gently sloping, more pointed end faces in the down-ice direction, these two ends being respectively known as the stoss and lee ends.

The landform, as such, was first recognised and named by M. H. Close in 1867 in Ireland, deriving the name from the Gaelic - druim - a hill. Since then innumerable workers, in many parts of the world, have observed and studied in detail these landforms and yet no satisfactory explanation of their origin exists. In the past many varying theories have been propounded to explain the drumlin but always fresh evidence has appeared to contradict these ideas. Thus after a century of research and writing on drumlins, no totally satisfactory explanation exists of how, where and why drumlins are formed. The several theories that have been proposed appear to be only partially accurate and in the main are more related to specific observations of unique or infrequent occurrences than to a general theory.

Part of the object of this thesis, is to review the previous theories and try to develop a broad-based general theory of drumlin origin in the light of previous work and new observations. This general theory, it is anticipated, will surmount many of the previous problems, often minor, which caused the old theories to falter and

fail. For example, the important question of why some drumlins are rock-cored and others cored by laminated clays or sands must still be answered. Any new theory must be compatible with the known glaciological and subglaciological parameters. It must also be broad enough to allow new problems, when they appear, to be resolved or accommodated. Many past theories have been too restrictive and not easily open to change. This has meant that too often new problems have been solved by the creation of a new theory.

To find the best and most useful parts of past theories, it is necessary to review all previous theories within the context of the observed data that exist on drumlins. Therefore this chapter attempts to combine the known scientific knowledge on drumlins with previous proposed theories and by examination attempt to find where areas of agreement lie, where the major problems remain and in what direction future research and hypotheses need to go.

To put facts and theories on drumlins into perspective, several fundamental questions have been constructed, which would appear to lie at the root of drumlin formation. The reasoning behind this follows the argument proposed by Andrews (1971, p.321) that, "Progress in the understanding of geological processes is largely dependent upon the ability to ask the right questions". These questions, it is argued by the writer, if and when totally answered should provide, as near as scientifically possible, a definitive explanation of the origin of drumlins.

Since each question below is only a subdivision of the much larger question, how, why and where drumlins are formed, no question is in isolation but each is an integral and interrelated part of the major issue; thus some overlap must be expected and does exist.

- 1) Where are drumlins located and why?
- 2) What is the internal composition of a drumlin and what structures does this internal material exhibit and why?
- 3) Why does the constituent material with its inherent structures develop into isolated mounds?
- 4) What relationships exist between drumlins in terms of spacing, distribution, density, morphometry and terrain factors and the relationship of these factors to the flow of the ice?
- 5) Why is a drumlin so shaped?

QUESTION 1 Where are drumlins located and why?

Drumlins have been, until very recently, accepted as more or less unique features of a glaciated landscape. The reason for this has been partly because they have been regarded as fairly uncommon phenomena, occurring in only a few places in the world and because there are few comparable landforms in terms of size and pattern. It is perhaps this uniqueness that has attracted so much attention and so many varied and unique explanations. However as Flint (1971, p.100) has pointed out, any concept of uniqueness tends to produce unique isolated explanations. Flint further argues that drumlins may be more common than previously thought, largely because in the past it has been drumlin fields that have first been noted, rather than distinct drumlins. There would appear to be no apparent reason why drumlins should not occur in smaller numbers in more areas than at first was recognised. However this concept of uniqueness persists almost throughout all the work and theories on drumlins and it does help to explain many of the more unusual theories that have been derived. It is a concept that probably has caused progress towards a final explanation to be retarded. The

effect of this concept on the explanation of the origin of drumlins, will be discussed in the following pages.

It is notable that since observations began at glacier snouts no positively identified drumlins have been seen emerging from the ice. However a few workers have observed what they, themselves, thought were "pseudo-drumlins" emerging from present-day glaciers (de Quervain & Schniffer, 1920; Dyson, 1952; Boulton, 1968; Goldthwait, R.P., 1974). Drumlins are normally regarded as features of the Quaternary Era and the possibility of observing them while forming today apparently does not occur. This fact must be explained.

Drumlins are found in Northern Russia, China, across the North European Plain, in the North Alpine Foreland, in Britain, Canada, North-east and Mid-west U.S.A. and in South America (Flint, 1957, 1971, p.100; Embleton & King, 1968, p.333). Their distribution is as varied within any one major glaciated area. In Britain, for example, they are found in the Midland Valley of Scotland; the lower Tweed Valley; Galloway; the Vale of Eden; Ribblesdale and Wensleydale.

Hoppe (1959, p.204) has pointed out that drumlins reflect, by their orientations, the direction of the last ice movement over an area and therefore they have been of great value in elucidating the movements particularly of the final phases of the Quaternary Ice Sheets (Alden, 1918; Hollingworth, 1931; Virkkala, 1951; Hansen, 1956; Gravenor, 1957; Wright, H. E., 1962; Fyles, 1963; Black, 1966; Repo & Tynni, 1971).

Where they do occur, they often group themselves in "fields" or "swarms" numbering several thousand for example, in New York, 10,000; New England, 3,000; Wisconsin, 5,000; and Nova Scotia, 2,300. They are arranged normally en echelon, each drumlin extending in length from

several metres to several kilometres (Knahan & Close, 1872; Flint, 1957, 1971; Embleton & King, 1968). Drumlins occasionally merge into each other, lee slope into stoss slope or join one with another, giving a coalescent appearance to the drumlin field. This appearance is further emphasised at times by one drumlin apparently "sitting" on top of another.

LOCATION OF DRUMLINS IN RELATION TO ICE MARGINS AND MORAINES

There has been an underlying suggestion of drumlin location with regard to the margins of ice sheets (Alden, 1918; Ebers, 1926; 1937; Crosby, 1934; Thwaites, 1941; Gravenor, 1953; Virkkala, 1963). Drumlins generally occur close to the ice margin and in areas of ice diffusion, invariably low-lying areas on the piedmont fringes of ice-collecting grounds or close to ice-convergence zones from which such diffusion may occur. However, Lundqvist (1970) found drumlins in highland areas of central Sweden at altitudes of 700 to 800m, and considerable distances from the inferred contemporaneous ice-limits.

It has been argued that a spatial relationship exists between end or terminal moraines and drumlin fields. This relationship might appear to be true in parts of North America but not in Britain (Alden, 1911; Taylor, 1931; Charlesworth, 1957; Flint, 1957; Wright, H. E., 1957; Thwaites, 1963; Thornbury, 1969). Authors who have adopted a depositional explanation for drumlins and moraines have utilised this apparent relationship to substantiate their theories (Alden, 1918; Fairchild, 1929; Gravenor, 1953; Charlesworth, 1957; Smalley & Unwin, 1968). However whether or not this relationship is of genetic significance to the drumlins has still to be examined in greater detail. The two separate features may be related only in terms of their ice

sheet marginal location. That drumlins do appear to be able to develop without the necessity of a corresponding contemporaneous moraine suggests that this relationship is not as important as has often been speculated.

LOCATION OF DRUMLINS IN RELATION TO BEDROCK AND DRIFT THICKNESS

Usually fairly thick till in undulating plains surrounds drumlin fields (Hoppe, 1951) but exceptions do exist as Dean (1953) and Lundqvist (1970) observed. Both workers found drumlins in areas of barren scoured bedrock with only thin peat covering the surrounding terrain. However the relationship between drumlin location and the nature of the underlying bedrock and drift thickness has rarely been commented upon (Lotan & Shetron, 1968; Gluckert, 1973; Gravenor, 1974, p.52). Gravenor (1974) notes that drumlins are rarely found in areas underlain by granite. In discussing the relationship of bedrock factors with drift thickness and drumlins certain factors must be taken into account, for example, systems of jointing, depth of weathering, susceptibility to erosion and evidence of shattering and bedding (Jahns, 1943; Virkkala, 1963; Feininger, 1971; Flint, 1971; Trainer, 1973).

LOCATION OF DRUMLINS IN RELATION TO CHANGES IN THEIR DENSITY

Detailed work (Hill, 1968; Miller, 1972; Crozier, 1975; Trenhaile, 1975) has revealed variations in drumlin density with changes in location across the field. Smalley and Unwin (1968) tentatively suggested that drumlins might concentrate close to the marginal end-moraine zone and become more scattered and elongated farther up-ice. Variations in density over a drumlin field are often manifested as changes in the distribution pattern of the drumlins (i.e. whether they are random or non-random) (Heidenreich, 1964; Smalley & Unwin, 1968). Changes of density would appear to be linked to changes

in till availability, bedrock proximity and to subglaciological factors.

LOCATION OF DRUMLINS WITH REGARD TO GLACIOLOGICAL AND SUBGLACIOLOGICAL FACTORS

Mathews (1974) has suggested recently that a relationship might exist between the location of wet based, low gradient, ice tongues and glacially fluted terrain. The evidence for this statement was obtained by calculating ice gradients from ice lobes of the now vanished ice sheets in North Dakota, U.S.A. and New Zealand. This work highlights the major uncertainty that surrounds all drumlin factor relationships. Aronow (1959) recognised this problem of the unknown glacial factors and could not find a method of obtaining a solution to the problem. Drumlin density, shape and size are all linked to glacial conditions that remain obscure. Relationships linked to ice velocity, ice thickness, ice pressure and to subglacial conditions have been suggested but no quantitative and definitive values have ever been placed upon these relationships (cf. Chap. 14). Mathews however does approach this problem, as did Harrison (1958) with his pre-consolidation values, and both suggest methods that may lead to better quantitative understanding of the glacial conditions at the time of till deposition. Similarly Boulton (1967, 1968, 1970, 1971), Mickelson (1971, 1973), Peterson (1970), and Gravenor and Stupavsky (1974), have supplied valuable information in attempts to understand the glacial factor, so insoluble at the time of Aronow's paper.

CONCLUSION

To the question "Why are drumlins located where they are?" must lie the answer to what causes the material to agglomerate into isolated mounds and vice versa. To explain these interrelated questions two

approaches may be adopted, firstly, to seek to understand the mechanism that causes material to agglomerate into these isolated mounds and in doing so to explain the distribution of the mounds; and secondly, to seek to understand the mechanism that explains the random/non-random distribution and lowland ice diffusion locations of the drumlins and thus explain the mechanism of drumlin material deposition.

The method adopted in this thesis has been the former approach: a mechanism that would explain why drumlin material apparently agglomerates in specific locations has been sought, bearing in mind the various relationships that drumlins have to their surrounding locational factors such as ice margins, bedrock and the other possible factors noted above. Certain other unknown locational factors may exist or have existed that influenced drumlin location, but some will have been removed or destroyed and others may never be known because their influence may now appear secondary.

QUESTION 2 What is the internal composition of a drumlin and what structures does this internal material exhibit and why?

TEXTURE

The internal composition of a drumlin varies from sand to unstratified till to solid bedrock, with every possible permutation between. Drumlins may also have rock, sand or laminated clay cores.

Drumlins have been reported totally composed of sand (Lemke, 1958), of very adhesive clay-rich till (Wilson, 1938; Goldthwait, L., 1948) and of washed drift, covered by a thin till (Miller, 1970). Gravenor (1953, 1974) suggested that till drumlins were essentially composed of sandy till of a very low clay content. Other workers have also shared this view (Sproule, 1939; Putnam & Chapman, 1943; Wright, H. E., 1957; Hoppe, 1959; Muller, 1963; Macneill, 1965; Lasca, 1970; Lundqvist, 1970;

Minell, 1973). The converse, however, has also been noted in clay-rich till drumlins in Dakota (Aronow, 1959) and Nova Scotia (Wilson, 1938). Slater (1929), in examining several sections in drumlins in New York, noted a till of low clay content overlying a highly cohesive clay-rich till, the latter acting as a kind of core. Similar observations in other drumlin fields have been recorded (Upham, 1892; Fairchild, 1907, 1929; Wright, 1912; Hill, 1968, 1971). As a factor in itself, texture is of little significance, only revealing the varied origin of drumlin material. However it might be suggested that when linked to other factors, for example till consolidation or drumlin shape, more significant conclusions may well be drawn (cf. Gravenor, 1974).

STRUCTURES

A rough form of banding is occasionally noted in the till and two or more differing tills may lie one on top of another within any one drumlin (Wright, H. E., 1962, p.88; Hill, 1968, 1971). Hill (1968, 1971) describes the internal composition of several drumlins in north Co. Down, Northern Ireland. In roadcuttings through drumlins, he describes sections (Hill, 1971, pp. 19-20) in which he differentiated an upper till from a lower till on the basis of colour, texture, carbonate content, erratic content and till fabric analysis. Within the lower till often a third till was recognised: a compacted core of lower till.

Tectonic structures indicative of the effect of overriding ice and ice pressure causing deformation, and of ice plucking have been noted in Poland (Jewtuchowicz, 1956), in America (Alden, 1905; Slater, 1929; Lemke, 1958) and in Norway (Minell, 1973). Eberl (1930) in Germany noted the existence of recumbent, "pouring-over" beds in the stoss end of drumlins. Slater (1929, pp.9-16) in a detailed account

of drumlin sections in New York State, illustrated in several diagrams the interdigitation of sand and gravel beds in the till, of sand and silt wisps, of boulder lines, of pseudo faulting and folding, and of bedded till. Slater also noted (1929, p.18) that the drumlins had been subjected to what appeared to be differential pressures, especially lateral pressures. Slater (1929, pp. 9,14,16) advocated these pressures after he had examined several transverse cross-sections that revealed a concentration of faulting, warping and consolidation in lateral locations on the drumlin sides.

LAYERS OR BANDS

Banding within the drumlin till led Fairchild (1929) to argue that each band or shell had been deposited successively in a kind of "accretion process". This has since been observed elsewhere (Alden, 1918; Goldthwait, J. W., 1924; Virkkala, 1951; Flint, 1957), and will be later discussed in the light of newer findings (Chap. 9). It might equally be considered that when two or more tills are found in a section a form of banding also exists.

JOINTS AND FISSURES

Another area of investigation has been the size and extent of joint patterns in the drumlin internal material. Kupsch (1955), in Saskatchewan, noted a pattern of three differing joint systems in a central boulder core within several drumlins. From this pattern he theorised that the joints were created after the bedrock or boulders failed due to the overburden stresses built up by the overriding ice sheet and the subsequent thinning and retreat of the ice which was accompanied by stress relief in the rock material.



Similarly McGown et al. (1974) have noted fissure and joint patterns akin to Kupsch's findings but in contrast, within the till matrix itself in drumlins in Ayrshire. They tried to explain these fissures and joints as resulting from either weathering, released overburden pressure, syneresis (i.e. spontaneous loss of water from a gel during aging) or dessication or some combination of these mechanisms. Minell (1973) observed fissuring and jointings in drumlin till around Narvik, and completed small scale photo-elastic experiments to try to reveal the subglacial stresses a rock knob or obstacle might undergo and the subsequent stress patterns produced within the obstacle as the ice advances over it. The work of McGown et al. has revealed the multiple possible origins of these fissures and joints which thus tends to reduce the effectiveness of these patterns in aiding in an explanation. If the origin of the fissures and joints could be more precisely known they might indicate a great deal about ice overburden pressures, their size, extent and history of development. These patterns will be discussed later in context with till fabrics and their position within individual drumlins (Chap. 6).

THE EFFECT OF TEXTURE ON STRUCTURES

Structures are either present or absent not only as a factor in relation to varying ice pressures but also in relation to the nature and texture of the internal material (Russell, 1907, p.707). Structures in a clayey silt as compared with a sandy silt may not remain present or develop when subjected to similar ice pressures. Because clays have a greater surface area contact, particle to particle, there is subsequently a higher friction when stressed in comparison with a sand which is of larger particle sizes and much lower surface area contacts,

provided both materials have been similarly consolidated.

Several past theories have been deliberately altered or constructed in order to account for textural and structural peculiarities found within drumlin sections (e.g. Gravenor's "Modified Erosion Theory"). The effect of these peculiarities has been to cause a proliferation of theories none of which have been broad enough to cope with subsequent variations.

STRATIFIED AND LAMINATED DEPOSITS IN DRUMLINS

Most of these deposits have become incorporated into drumlins via the subglacial system. Material either deposited subglacially or proglacially, was advanced over, picked up by the ice and later incorporated into the basal-ice and, when deposited, made part of the internal material of a drumlin. The effect of the overriding ice on the deposited material has been to bend and contract the beds into wavy and asymmetric-like patterns and tectonic-like structures with pseudo faulting and overthrusting (Slater, 1929; Jewtuchowicz, 1956; Muller, 1974). Where vast spreads of older outwash have been readvanced over as in North Dakota (Lemke, 1958; Aronow, 1959) it appears the material has become incorporated into the subglacial system subsequently being moulded into sand cored drumlins (cf. Gravenor, 1953, p.678; Goldthwait, R. P., 1974). However it cannot always be assumed that such a direct relationship exists. Much of the material advanced over by ice is re-sorted, abraded and ground down and completely altered in texture, structure and appearance.

TILL IN DRUMLINS

The problem of till origin has in the past been too often ignored or overlooked (Goldthwait, R. P., 1971, p.20). Drumlin till

is usually identical with inter-drumlin till and the till in front of and behind the drumlin field. The tills are of similar colour, grain size distribution and stone content. The till is dominantly of local origin being largely derived from no more than three or four kilometres up-ice of any point (Shaler, 1893; Martin, 1903; Gravenor, 1953; Harrison, 1957; Flint, 1957, 1971; Embleton & King, 1968; Dreimanis & Vagners, 1969, 1971, 1972).

This localisation of till means that erosion and deposition must have occurred within a very short distance of each other. A model in which processes of erosion are separated from those of deposition by considerable distances will not suffice. Instead a more complex model to account for this localised derivation is demanded, a model in which erosion and deposition are both sporadic and random in time and space over a small local area. In some areas for example, bedrock will be eroded, the eroded material abraded and deposited as till fairly close to the point of erosion. In other areas till already deposited will be completely or partly eroded, re-abraded and re-deposited again close to the point of erosion and so on in complex variants of this localised erosion/deposition process. Till origin theories have been consistently derived with the implicit assumption that erosion and deposition are separated in time and space, both occurring only once in an enormous geomorphic reaction or in a kind of Davisian cyclical process.

From the above it therefore becomes clear that any theory of drumlin origin demands an explanation of till deposition.

Till Fabrics

As another approach to the understanding of the structure and

organisation of the drumlin constituent material, till fabric analysis provides some useful observations and explanations. Till fabrics, apart from revealing the general ice direction, may also reveal how the till was deposited. H. E. Wright (1957), basing his work on the Wadena drumlin field (Minnesota), found that the till fabrics were distinctly parallel to the drumlin trend, exhibiting an up-ice plunge. This led him to speculate: a) that the till was from the basal zone of an ice mass and b) that the up-ice plunge was a relict feature inherited from the glacier, similar to the upward curving dirt bands or shear planes observed near the front of present-day glaciers (e.g. Barnes Ice Cap) (Evenson, 1970).

Gravenor and Meneley (1958) in Alberta and Hoppe (1959) in Northern Sweden both reported evidence of strongly preferred fabric orientations within the top few metres of drumlins. Hoppe, however, when investigating fabrics deeper within the drumlin till, found transverse fabric orientations. Parallel or sub-parallel orientations of stones within a few metres of the surface have been observed by several recent workers (Evenson, 1970; Minell, 1973; Shaw & Freschauf, 1973; Walker, 1973). Andrews and King (1968) obtained evidence of till fabrics in a drumlin that were at an oblique angle to the general ice direction (a 33 degree variation, with a maximum deviation of 54 degrees and a minimum of 12 degrees)(cf. Hill, 1971, p.28). As in the Wadena field an up-ice plunge was noted, but a less well developed preferred orientation was found close to the drumlin surface.

Strengths of Preferred Orientations Hill (1971) investigated strengths of preferred till fabrics from the basal zone of a drumlin to its upper surface. He found a gradual increase in divergence between the drumlin trend and the mean orientation of fabrics from the base upwards. The

reason suggested for this divergence was that with increasing drumlin size so the ice flow was increasingly deflected around the obstruction. These above till fabric investigations tend to indicate a zone or core of till within a drumlin that is unaffected by the velocity and direction of the ice, and an outer shell of till that is greatly affected (cf. Hill, 1968). Harris (1968) has drawn a direct correlation of strength of fabric parallelism with ice velocity (ice direction) from work on the Arapahoe Glacier foreland. Ice moving at speed with little deviation from the general ice direction produced till fabrics that appeared to deviate less from the primary mode of the ice direction.

Various workers have shown that preferred till fabric orientations in stony tills are weaker than in less stony tills. Similarly variations in orientation strength can be correlated with local relief; the rougher, the weaker the orientation (Virkkala, 1960; Harris, 1967). Till fabrics remain a delicate tool by themselves to prove or disprove any hypothesis but when used along with other techniques, they can undoubtedly be of great assistance.

The Meaning of Variations in Fabric Orientation Evidence obtained by till fabric analysis, from top to bottom of a stratigraphic section, may point to one or more ice directions. The differing ice directions may suggest either different glacial phases and subsequent periods of till deposition onto a drumlin or two or more ice directions of the same glacial phase. They may also indicate the erosion of previous tills which were then incorporated into the one new till (Harris, 1967; Hill, 1968) or simply exhibit the finer details of ice moulding and till accretion (Svensson & Frisen, 1964).

Till fabrics in Wisconsin drumlins revealed through their lack

of variation that the drumlins were moulded by the same glacier that deposited the till within the drumlin, rather than the drumlins having been shaped by a later glaciation (Wright, H. E., 1962, p.89).

Comparison of Drumlin Till with Non-Drumlin Till Fabric Orientation

Variations Hill (1971, p.27) has noted from statistical tests on the comparison of drumlin tills with other tills that there is a significant statistical level of difference between them (Table 2). This tends to indicate some slight difference at the stage of drumlin till genesis when compared to other forms of till deposition.

TABLE 2

<u>Author</u>	<u>Deposit</u>	<u>Mean Plunge</u>	<u>% Plunging $\leq 10^\circ$</u>
Holmes (1941)	Till	11	74
West & Donner (1956)	Till	14	62
Young J.A.T. (1969)	Till	11	66
Hoppe (1952)	Dead Ice Moraine	10	77
Wright H.E. (1957)	Drumlins	23	34
Hill (1971)	Drumlins	14	51

Therefore although till deposition has to be explained when drumlin origin is resolved, a slight difference associated with drumlin till deposition must also be recognised as a possibility.

Analysis of the Value of Fabric Data In the analyses of fabric information there often appears to exist a disparity between what is derived and what is thought to have been derived, and therefore an unwarranted stress frequently seems to be placed upon fabric data.

This disparity can be seen for example in the divergence of opinion over the direction of ice movement in the Fraser Lowlands, British Columbia, where several totally different interpretations have been put on one pattern of fabric data (Roberts & Mark, 1970; Armstrong et al., 1971).

Several authors, for example Savage (1968) and Shaw and Freschauf (1973), have developed hypotheses solely on the rather delicate foundation of their analyses of till fabric data. This appears to be putting too much stress on the significance of till fabrics as a means of proving or disproving hypotheses. Evidence of the inadequacies and vagaries of till fabrics are well documented (Holmes, 1941; Harrison, 1957; Dreimanis, 1961, 1969; Drake, 1968; Young, J.A.T., 1969; Kruger, 1970, 1973; Lindsay, 1970; Andrews, 1971; Mark, 1974).

CORES

Many workers have theorised that some form of core or nucleus around which the drift material may adhere is a necessary prerequisite to drumlin formation. Several workers have shown from investigations in various drumlin fields that a rock core to the drumlin is not uncommon (Chamberlin, 1883; Shaler, 1889; Tarr, 1894; Högbom, 1905; Hollingworth, 1931; Crosby, 1934; Ebers, 1937; Armstrong, 1949; Deane, 1950; Flint, 1957, 1971; Aartolahti, 1966; Hill, 1968, 1971; Savage, 1968; Vernon, 1968; Lundqvist, 1970; Repo & Tynni, 1971; Minell, 1973).

Similarly cores of highly consolidated, cohesive till have been detected (Upham, 1892; Wright, 1912; Fairchild, 1929; Slater, 1929; Miller, 1963; Hill, 1968, 1971) as have blocks of "supposed" frozen till (Armstrong & Tipper, 1948; Lasca, 1970), cores of sand (Nechay,

1927; Glinicka , 1936) and boulder dykes (Kupsch, 1955).

Vernon (1966) has suggested that drumlins form when a pressure differential between the proximal and distal sides of an obstacle is induced by ice flow. Ice pressure melting at the proximal end of the obstacle causes the ice to have a greater mobility, enabling it to move towards the zone of low pressure behind the obstacle and deposit till in the distal end. Smalley and Unwin (1968, p.389) have criticised Vernon's theory on the basis that unless the critical obstacle is drumlin sized, the obstacle will tend to be insulated from the ice by the deposited till load thus preventing, after a critical thickness has been attained, any further pressure melting (cf. Hillefors, 1973). Although this mode of formation beginning with a core may be common, it by no means explains all drumlins. It is the explanation of drumlins with no apparent core that is sought and will be fully discussed later (Chap. 14).

CONCLUSION

Although sufficient detail of variations in texture of drumlin internal material exists there remain major gaps in knowledge regarding the mechanism of till deposition and the mechanisms by which structures develop. Both these areas of doubt must be re-investigated using new methodologies and deriving new evidence. When they are better understood, the explanation of the origin of drumlins will be much closer to being solved.

QUESTION 3 Why does the constituent material with its inherent structures develop into isolated mounds?

Within this question lies the key to solving the drumlin problem. If a mechanism can be found which will allow material, in certain areas of a glaciated landscape, to agglomerate into isolated mounds and be streamlined to produce a drumlin with concomitant sedimentary variations and structures then the other questions, interdependent as they are, can be answered. Aronow (1959) and Smalley and Unwin (1968) recognised the special significance of drumlin distribution and origin suggesting that a certain "something" (Aronow, 1959, p.202) was necessary, before a drumlin could develop. However Fairchild (1907, p.705) had previously outlined the factors he regarded as fundamental in the mechanics of drumlin construction: a) those pertaining to the ice itself; b) those relating to drumlin-forming drift and c) external influences of topography and climate.

Theories that tried to resolve the above question have been reviewed by various workers (Davis, 1884; Ebers, 1926, 1937; Gravenor, 1953; Embleton & King, 1968, pp.322-343). Gravenor divided past theories into four discrete groups, namely, erosional, depositional, modified erosional and accretional. To this must be added theories of till squeeze, dilatancy, frost heave and glacial kinematic fluting (Hoppe, 1959; Smalley, 1966; Smalley & Unwin, 1968; Baranowski, 1969; Shaw & Freschauf, 1973).

EROSIONAL THEORY

The erosional theory attempts to account for the following facts namely: a) the proximity to existing morainic belts, b) the depth of till, c) the juxtaposition of several tills and more especially of stratified and laminated sediments, d) the proximity to and

similar final shape of drumlins in comparison with rock drumlins which are obviously eroded landforms, and e) the unnecessary requirement of a core. The principal concept of the theory is that drumlins are fashioned by re-advancing ice eroding the pre-existing till and stratified deposits. Tarr (1894) in Alaska noted the similarity in shape between rock drumlins and till drumlins and concluded that the same erosive process must account for both types.

Objections to this theory are well documented (Thwaites, 1941, pp.43-5; Gravenor, 1953, p.677; Embleton & King, 1968, p.339). The major criticism is that the material within a drumlin often cannot be shown to have the glacial history the theory demands and is therefore not a deposit of a penultimate glaciation but of a final ice advance in any one locality. Criticism that a drumlin field may be the eroded remnants of a morainic belt is based on the fact that known widths and lengths of drumlin fields and morainic belts do not appear to coincide and are therefore not of identical origin. Normally morainic belts do not exceed more than 2 to 5km in width whereas in length they may extend for hundreds of kilometres (e.g. in the area south of the Great Lakes)(Flint, 1971, p.205).

Where an older till is seen overlain by a younger till and where a drumlin field, as at Guelph in Canada, is composed of two tills, an erosional theory would seem more consistent with the evidence (Harris, 1967, p.29). In Wisconsin Alden (1905, 1911) Russell (1907) and Evenson (1970) came to similar theories of erosional formation. Furthermore Prest (1968) has argued that in ice-scoured terrain, as in northern Canada, drumlins with distinct rock cores may exist amongst roches moutonnées and can only be explained as remnants due to the erosion of pre-existing drift or bedrock or both.

The inadequacies of the above theory are many but much of the theory has been incorporated into later theories. In the final process of large-scale streamlining or in the continuing process of streamlining during drumlin creation an erosional process would seem to dominate. However since the development of a drumlin is via a complex geomorphic system, as will be later discussed, no process whether erosional or depositional, other than in the broadest sense, can totally dominate at any one time.

DEPOSITIONAL THEORY

This theory along with the previous theory is chiefly criticised because it relies too heavily on one aspect of the whole geomorphic process of landform formation (Thwaites, 1941, p.39; Gravenor, 1953, p.676; Embleton & King, 1968, p.341).

The theory attempts to explain drumlin formation as isolated, unique occurrences where vast amounts of drift, especially till, are present in a few localised areas of any glaciated landscape. To achieve the emplacement of such large quantities of drift several possible processes were suggested: a) progressive (constructional) deposition around a core of rock, boulders, previously deposited till, frozen till or contemporaneous till deposited just prior to the build up of till from the oncoming basal ice or, b) high deposition rates of basally incorporated drift material as a result of ice stagnation. Three possible processes, it is argued, may help to account for such stagnation, either firstly the basal ice has become so highly charged with material that ice deformation creep and basal slip ceases because of the high friction developed due to this debris content (Russell, 1895; Synge, 1952); or secondly, because basal ice stress changes due to

variations in ice velocity, down or up-ice bedrock topography or ice direction have allowed areas of basal ice to stagnate (Weertman, 1957; Paterson, 1969) or thirdly, because of general ice stagnation due to local climatic changes, or fundamental climatic changes in the area above the glacier equilibrium line (Weertman, 1961).

One of the major objections to the theory, in the past, was its inability to explain the incorporation of sands and gravels in drumlins other than by a process of ice advance over proglacial stratified sediments (cf. Tarr, 1894). The concept of subglacially deposited sands and gravels as a possible source of material was not favoured until recently (Carruthers, 1953; Hoppe, 1963; Sissons, 1967; Johannson, 1968; Shaw, 1972). With the present knowledge of the subglacial system such an objection is no longer applicable. A primary objection to the use of a core within a depositional theory is that often drumlins occur with no obvious core and therefore cannot be explained by such a process.

Another refutation of the theory is the location of drumlinoid features in the floor of glacial grooves where scouring was the obvious dominant process as opposed to deposition (Alley, pers. comm. 1971).

With an increasing awareness of the intricacies of depositional mechanisms within the subglacial system, newer theories have evolved in order to incorporate new information in greater detail, but the basic depositional theory persists.

MODIFIED EROSIONAL THEORY

This theory, as postulated by Gravenor (1953, p.678), is based on the concept that if an active glacier temporarily halted during its advance, large masses of till and stratified material would be deposited

in its proglacial and submarginal areas. With a subsequent ice advance beyond this halt position the material deposited during the halt would be overridden, eroded and shaped into drumlins. The theory does not set out to suggest that on every temporary halt or minor glacier fluctuation followed by the glacier's advance, the deposited material would become "drumlinised". The theory only suggests that occasionally drumlins form when specific "conditions" are right.

However this theory, as in the case of the previous two theories, demands a unique or rare set of circumstances and the right "conditions" in order that sufficient material enters the subglacial system and can be then "drumlinised". The essential core of the problem that Gravenor attempted to solve was the question of highly localised agglomerations of material of differing textures and structures. He recognised this problem and set out to construct a theory to account for what was regarded as a rare and unique landform. What was needed, it was thought, was a theory embodying a unique set of circumstances. Once a theory requiring unique circumstances and conditions was derived, however, it was immediately noted that drumlins in other fields and other parts of the world did not fit into this unique set of demands. Drumlins were found in areas where no evidence of glacier advance, halt and re-advance could be traced. Others were found considerable distances from the last maximum glacier halt positions and yet were obviously of that geological age. The theory therefore failed within the broadest context and revealed the need to develop theories of drumlin formation based on more information than might be derived from one single drumlin field. However, like most of the other theories much that exists in this theory has had to be re-incorporated into the newer theories in order that the more exceptional constituents of drumlin material can

be incorporated (e.g. lacustrine clays).

ACCRETION THEORY

Concentric layering or banding led several workers to advocate that drumlins were built-up by successive additions or accretions of clayey till (Alden, 1918; Goldthwait, J.W., 1924; Fairchild, 1929; Flint, 1947; Hill, 1968). This accretional process, it has been argued, was dominantly depositional but the thicknesses of the accretion layers were dictated by erosion.

The major objection to the theory is that often banding is absent from till in drumlins, although often the drumlin material would be too coarse to reveal any subtle banding. Past workers when referring to banding normally mean that a marked till colour change or change in stone content provenance is observable. However banding of a more delicate and less distinct form that has not been recognised in the past may exist. Banding may occur as slight consistent changes of texture over a profile or as zones of much smaller or large stones. Band sizes may also be almost micro-scale in size, only millimetres thick and not easily detected. Since the till was once in close proximity to the base of the ice and a part of the subglacial environment, detailed studies of till may reveal a great deal about the conditions prevailing at the time of drumlin formation.

Probably some form of accretion layering occurs in drumlin genesis since any concept that suggests a drumlin (e.g. 60m high and 2km long) might be formed en masse at one instance in time verges on the absurd. Some building up or accretion of material from a small mass to the final feature seems therefore an essential part of any drumlin-forming mechanism.

Current bedding in fluvial sediments reveals many of the characteristics that accretion layers within a drumlin might be expected to have. Distinctly localised bands or patches of material within fluvial sediments occur; they are often truncated sharply, or grade imperceptibly into the next band and are thick or thin. Current bedding reveals the intricate relationships that exist between the processes of erosion and deposition.

Many of the characteristics of current bedding may equally be applied to the accretion layers found in drumlin material since again a delicate interplay of erosion and depositional processes exist. It seems most unlikely that accretion layers would occur as large complete shells or layers encompassing the whole drumlin in repeated layers, other than those with the most general of characteristics such as colour or stone content.

TILL SQUEEZE THEORY

The theory is based on the concept that when cavities are produced beneath an ice mass, the highly saturated till beneath the ice will be squeezed up into the glacial hollows and the till will then be shaped into drumlins by the subsequent advancing movement of the ice. Two mechanisms for developing these cavities exist: firstly, boulders or a rock knob may act as an obstruction to the path of the ice causing a linear cavity to develop in the lee of the obstruction and secondly, glacial ice when under radial extension as at valley mouths may develop, it is argued, longitudinal subglacial crevasses. When a cavity is formed a pressure differential develops between low pressure within the cavity itself and high pressure under the rest of the basal ice. To compensate for these pressure differences it is theorised that till

may be squeezed into the low pressure zone thereby equalising the subglacial pressures.

Alden (1918) in studying the drumlins of south-west Wisconsin suggested the second mechanism whereby a system of radial crevasses was created subglacially as the ice spread south from Canada in an ice tongue (Green Bay Lobe). Into these cracks till was squeezed and subsequently eroded to form the characteristic fan-like array of south-west Wisconsin drumlins (Alden, 1918, p.255).

The creation of till ridges in the lee of boulders or rock bosses led various workers to suggest similar cavity mechanisms for drumlin formation (Dyson, 1952; Hoppe & Schytt, 1953; Stalker, 1960; Vernon, 1966; Cowan, 1968; Flint, 1971).

Drumlins and Fluted Moraines

A major reason for linking fluted moraines with drumlins is the implicit belief that there exists a continuum between roches moutonnées, rock-cored drumlins, till drumlins and till-fluted moraines (Harris, 1967; Prest, 1968; Baranowski, 1969, p.206; McPherson & Gardner, 1969; Lundqvist, 1970; Flint, 1971, p.104; Muller, 1974). This continuum of landforms suggested to many workers not only a common origin (i.e. the subglacial system) but also a similar process of formation within this system.

A subglacial cavity no matter how it is formed creates, in theory, a longitudinal zone of low pressure within the high pressure basal ice zone. This low pressure cavity will normally be closed up by the ice, depending on how quickly the ice will re-deform to compensate for the low pressure zone and depending on how great a pressure differential is developed (Rothlisberger, 1972; Nye, 1973).

From what is known of the rheological behaviour of glacier ice, it would appear that an upper limit in cavity size must exist for any given thickness and velocity of ice beyond which deformation would be almost instantaneous (Nye, 1965, 1969; Paterson, 1969).

On this cavity mechanism rests the explanation of ice-pressed forms of till ridges (fluted moraine). Fluted moraines are common in many glaciated areas. Flutings are rarely more than a few metres high, although they may be of considerable length. The suggestion has been made that this mechanism may also be invoked in order to produce drumlins tens of metres high and several kilometres long (Stalker, 1960, p.27). There is little or no evidence for this, yet it would be unwise to dismiss the theory totally, since it incorporates many of the points raised that need explanation; in particular the need to find a mechanism that can account for large-scale localised agglomeration, the diversity of materials, the sub-marginal locations and the shape of drumlin. Either the mechanism can be invoked to produce a drumlin in its final form or to produce a small initial mass which may then "grow" by way of an accretion process. The latter mechanism seems the more likely of the two (Chap. 14).

Several examples exist that illustrate the ability of till to be extruded and squeezed. In America till that has been squeezed down into cracks and along joints in the bedrock has been observed (Deere & Shaffer, 1956; Savage, 1968, p.53). In Ayrshire, J. Smith (1893) observed till squeezed beneath soft shales. Also moraines formed by the extrusion of till at the glacier snout have been noted, for example in South Georgia and Iceland (Price, 1973). These observations do not verify or substantiate the Till Squeeze mechanism for drumlins but they do illustrate that the mechanics of the theory are sound;

only the scale of the process remains unknown.

DILATANCY THEORY

Dilatancy is the phenomenon observed when a mass of particles is put under pressure and instead of compacting (i.e. decreasing in volume) it dilates (i.e. increases in volume) (Reynolds, 1885; Mead, 1925; Terzaghi, 1943). The reason for this increase in volume and decrease in density is that the particles move in relation to one another as they adjust their packing arrangement from edge to edge particle contacts to point to point contacts under the applied pressure. Smalley (1966) and Smalley and Unwin (1968) argued that if the packing arrangement of subglacial material was such that dilatancy could occur, then when ice overrides this material, thereby applying pressure, the material will attempt to dilate but be prevented from doing so by the ice. This would then cause a protuberance or mound of subglacial material to form; the essence of a new drumlin (cf. Geikie, 1894; Russell 1895). In reality it would be a more delicate balance with specific ice pressures, particle packing arrangements, pore pressures and other factors to be taken into account, but the fundamental mechanism is substantially the same.

The critical ice pressures required for the dilatancy of subglacial material occur, as suggested by Smalley and Unwin (1968, pp.379-381, Fig. 2) in an intermediate zone (C) between an up-glacier zone (A) and a frontal glacier zone (B). In zone A the pressures due to the height of ice are too great causing the structural matrix of subglacial material to collapse and be pushed forward, extruded or smeared. In zone B where the pressure is much lower due to the ice thinning, the pressure is too low to allow dilatancy to occur. Only in zone C is there an "ideal" situation within which dilatancy may occur.

In the model that Smalley and Unwin set up, they visualised end moraines forming in zone B, being moraines rather than drumlins due to their different location with regard to the pressure zones (Smalley & Unwin, 1968, p.380). They therefore suggested that drumlins and moraines were largely contemporaneous and coexistent.

One criticism of the dilatancy theory can be made that of the inherent assumption that a direct relationship exists between end moraines and drumlins.

What Smalley and Unwin have highlighted with this theory is that the drumlin material was subjected to an immense variation in forces due to its subglacial position and that by examining this material from the geotechnical viewpoint, a new slant on the drumlin problem has been opened up. They have also overcome the two distinct problems of diversity of materials and differing types of drumlins in the same field. They have not produced a unique explanation but simply applied a geotechnical principle in a field where the application of geotechnical ideas and methods must soon dominate any explanation of how a process occurs (cf. Carson, 1971).

Only when more work has been done at present ice margins and beneath present ice sheets and glaciers, on the dilatancy of "new" till and sands and gravels can this theory be assessed. Already recent work by Boulton and Dent (1974, p.130) has shown that till in front of Breidamerkurjökull in Iceland exhibits dilatant properties.

FROST HEAVE THEORY

Baranowski (1969) suggested a theory which depended on the zero degree isotherm descending below the basal ice into the subglacial material thereby causing frost heave within the material at isolated

and random points over the glacier bed. These frozen heaved masses then act either like a boulder in the till squeeze theory or as a core in the accretional theory. The theory can therefore be subdivided into firstly, the process initiating the mound and secondly, its subsequent development. The process of development either as a creator of cavities or as an accretion core suffers from the same criticism as both the till squeeze and accretion theories. Once a mound has developed either it is in its final form which in terms of size seems unlikely (cf. Till Squeeze theory) or it must then be built upon by some accretion process which as a second stage process may very well occur.

The main criticism is that no detailed work exists to account for this initiating mechanism. It must be shown that a mass of frozen subglacial material when heaved up into the bed of a moving ice mass would remain at the ice/sediment interface and not be destroyed or incorporated into the basal ice. Only future research can finally ascertain the possible value of the theory.

GLACIAL KINEMATIC FLUTING THEORY

A relationship has often been suggested between drumlins and fluted moraines (Hoppe & Schytt, 1953; Harris, 1967; Prest, 1968; McPherson & Gardner, 1969; Lundqvist, 1970). Shaw and Freschauf (1973) argued that both landforms have undergone stresses and strains within the subglacial system. It was argued that since they are of the same constituent material a similar mechanism of formation might be invoked for both. It was suggested that at specific velocities ice may flow with a helicoidal motion as it passes over its irregular bed the resultant direction of flow being parallel to the main ice movement direction (Folk, 1971). Von Engeln (1938) and Demorest (1939) had

controversially discussed such possible ice motions in their remarks on wave motion in ice. Shaw and Freschauf suggested that this complex motion would create flutings within the subglacial material by a process of eroding the material where the ice flow was vertically directed downwards at the material and depositing the material in these fluted ridges where ice flow was upwards.

Till fabric analyses exhibited an anti-clockwise movement around the flutings (which were 2-3m high and several kilometres long) and it was argued that this revealed the postulated helicoidal motion. As already discussed, to base a hypothesis on till fabrics would appear to be highly dubious when operator variance, solifluction processes and other slope processes need to be taken into account (Rudberg, 1958; Hill, 1968; Young, J.A.T., 1969; Andrews, 1971; Kruger, 1973).

Whether helicoidal flow may or may not occur within an active ice mass is unknown. Once the fluting of subglacial material occurs, a situation somewhat akin to the frost heave theory and till squeeze theory develops in that either a mass of material is agglomerated with similar dimensions to observed drumlins or the fluting is the initiating mound or core from which an accretional buildup ensues.

SUMMARY OF THE THEORIES

In answer to the question "Why does the constituent material with its inherent structures develop into isolated mounds?" it can be seen that many of the present theories explain distinct sections of the drumlin origin problem but none appears to explain the whole problem. Each theory has attempted to overcome a specific problem or problems, but few theorists have realised or recognised the necessity

to explain the two distinct parts of this above question. Firstly, it is necessary to explain the process of localised agglomeration and secondly, some cognizance must be given to the future development of the agglomerated material. Because the second part of the question has rarely been discussed in these theories no clue as to the scale of the processes or the length of time required is ever given.

Muller (1963, p.26) has summed up the position with regard to drumlin origin theories in saying that: "Although it is generally agreed that drumlins are related, streamline features produced beneath actively flowing ice and that they possess forms which offer minimum resistance to ice movement, agreement appears to cease at this point".

GLACIOLOGICAL CONSIDERATIONS FOR A NEW THEORY

In reviewing these theories it becomes apparent that it is of fundamental importance that the glaciological conditions at the time of drumlin formation and at times before and after formation are known in more detail.

It can be assumed that a "dry-based", polar glacier, frozen to its bed, could not possibly produce drumlins since the availability of till would be too low and ice plastic deformation or "creep" movement over its bed would occur, rather than slip and slide. Drumlin formation and thick till accumulation would therefore seem to require, as a prerequisite, a "wet-based" temperate glacier (Ahlmann, 1935; Robin, 1955; Goldthwait, R.P., 1960; Embleton & King, 1968; Paterson, 1969).

Various questions do arise, however, concerning "wet-based" glaciers and their bed and bedform. It remains problematical whether water at the glacier's base runs either in distinct channels or in a sheet (Weertman, 1957, 1964, 1972; Lliboutry, 1968; Nye, 1973).

Many questions relating to till deposition, to the effect on the basal water on the till deposit covering the bedrock (Boulton, 1968, 1970, 1971; McKenzie, 1970; Goldthwait, R.P., 1971; Mickelson, 1971, 1973; Nobles & Weertman, 1971) and to the variations in hydrostatic pressure of the basal water over the glacier sole, remain unanswered and only lightly studied (Weertman, 1961, 1969, 1972; Mathews, 1964; Lliboutry, 1968; Rothlisberger, 1972; Shreve, 1972; Nye, 1973; Vivian & Bocquet, 1973). A further question that needs to be investigated is the effect that a drumlin or field of drumlins has on the basal ice and on water movements and pressures.

It is unlikely that observational data will ever be forthcoming to answer many of the above questions but theoretical explanations based on the observations of other factors may be of value.

QUESTION 4 What relationship exists between drumlins in terms of spacing, distribution, density, morphometry and terrain factors and the relationship of these factors to the flow of the ice?

Reed et al. (1962, p.209) have suggested that "the location of drumlin fields and spacing of drumlins within fields are controlled by characteristics of moving ice". Shape and other morphometric characteristics of drumlins have been observed, in the past, and quantitatively examined with the intention of elucidating the idea that relationships of size, density, height and orientation exist between drumlins and between drumlin fields (Jewtuchowicz, 1956; Charlesworth, 1957; Gravenor & Meneley, 1958; Reed et al. 1962; Heidenreich, 1964; Vernon, 1966; Hill, 1968; Baranowski, 1969; Barnett & Finke, 1971; Doornkamp & King, 1971; Trenhaile, 1971,

1975; Crozier, 1975).

DRUMLIN SPACING

According to Reed et al. (1962) drumlin spacing can be defined as the calculated perpendicular distances between individual drumlins. In studying the orientation of drumlins (Montezuma, New York) they suggested that they were characterised by a normal distribution and that the inter-drumlin spacing exhibited a multimodal distribution at 150 to 180m and 90 to 180m with some indication of periodicity in the spacing (cf. Drumlin Density). Trenhaile (1971) working on Canadian drumlins found a similar log-normal distribution.

Contrary to these findings Vernon (1966) in Northern Ireland found no such maximum frequency distribution in the spacing. Charlesworth (1967, p.960), however, has criticised Vernon's work on the basis that only 60% of all the drumlins in the Co. Down field were mapped and measured, resulting in an untrue picture of drumlin spacing. Newer work by Baranowski (1969) in Minnesotan and Polish drumlins has revealed in the former field an average spacing of 400 to 600m with no drumlins closer than 200m, but no multimodal distribution. In the Zbojna field in Poland drumlin spacing distances are less, with a maximum at 90 to 120m and, in this instance, with a multimodal distribution (cf. Reed et al., 1962).

It is difficult to attempt an assessment of these various findings due to the numerous variations, for example of location, till texture and ice conditions, and to the limited amount of work on drumlin spacing. An alternative reason for the largely contradictory evidence may be the fact that the areal and volumetric size of the individual drumlins are not considered. Since the spacing measurements were from

one drumlin centre to the next (not from edge to edge) they may be fallacious and confusing.

DRUMLIN DENSITY

Drumlin density is the number of drumlins per unit area in a drumlin field. Drumlin density varies from as high as 19.3km^2 (Appleby, England) to as low as 1.8km^2 (Nova Scotia) and many vary as in the Oswega drumlin field from 3.37km^2 to 8.39km^2 within the one field (Reed et al., 1962; Vernon, 1966; Hill, 1968; Miller, 1971, p.37; Doornkamp & King, 1971; Gravenor, 1974). Hill (1973) states that drumlin density frequently declines from the centre to the margins of a field but in contrast Smalley and Unwin (1968, p.381) have theorised that drumlin density might be expected to decrease the farther up-ice from the ice margins the drumlin field extends due to the increase in ice overburden pressure on the available till (Fairchild, 1929; Hollingworth, 1931; Charlesworth, 1957; Wright, H.E., 1957; Vernon, 1966). This contradiction between observation and theory must be further examined and will be discussed in greater detail later.

As Doornkamp and King (1971, p.298) have pointed out, density measurements have several inherent inadequacies. No account is taken of widely spaced large drumlins or widely spaced small drumlins. Drumlin density measures drumlins as single points, no account of drumlin areal extent or volume being taken into consideration. Doornkamp and King (1971, p.298) suggest "that the forces allowing very regular, but fewer, drumlins to form also allow them to grow larger". This conclusion must remain largely unjustified until more facts emerge.

Theories on drumlin density are intrinsically linked to the

spacing of drumlins. Reed et al. (1962) found a periodicity or multimodal characteristic in their studies of drumlin fields as did Baranowski (1969) in a Polish drumlin field. These findings tend to indicate that drumlins may be found in distinct groupings of varying densities. Hill (1968, 1973) has confirmed this conclusion finding bands of high and low density drumlins. Previously Vernon (1966) had suggested that zones of high drumlin density might represent areas of low ice pressure which were subsequently favourable to drumlin formation allowing greater deposition than normal (cf. Shaw & Freschauf, 1973). Whether this conclusion, later accepted by Hill to explain the density banding, is justified, still remains in doubt but it illustrates how work on drumlin density may give clues to the process of drumlin formation.

As with drumlin spacing, the density measurements at present tend to obscure any possible conclusions because of their widespread variability and contradictions. It may be that insufficient data have been collected or that direct comparisons (e.g. between, Appleby in England and Zbojna in Poland) are unscientific because of differing subglacial conditions or that a new method of measurement is required. One possible future approach is to take into consideration the size both areally and volumetrically of the individual drumlins (Miller, 1971; Trenhaile, 1975). Doornkamp and King's criticism of density measurements may be removed if such measures are adopted.

DRUMLIN DISTRIBUTION - RANDOM OR NON-RANDOM PATTERN?

Drumlin distribution is the statistical measure of whether or not a pattern of drumlins can be observed in a drumlin field and whether it is totally random or non-random. Using two techniques, one

a random placement model, the other nearest neighbour analysis, Smalley and Unwin (1968, p.387) have shown that a random distribution may be expected within any one drumlin field. On the basis of their dilatancy theory they argued that: "Within the boundary conditions for drumlin formation the most important variable is probably the variation of properties in the available glacial till and these can be expected to vary randomly" (Smalley & Unwin, 1968, p.383). Hill (1973, p.228) has pointed out, however, that statements of random drumlin distribution are open to great misinterpretation unless qualified by some reference to scale, since drumlin spacing is so variable within any one field (cf. Reed et al., 1962; Baranowski, 1969).

Vernon (1966) and Hill (1968, 1973) in contrast found a degree of non-randomness in the drumlin spacing especially in zones oblique and at right angles to the general ice flow direction. The only possible reason for this non-random distribution, it is argued, would be some controlling or constant factor within the system in which the drumlins were formed. What this factor or set of inter-related factors might be, is, as yet, unknown (cf. Aronow, 1959). Hill stated however that, "If drumlins were initiated solely by the presence of a variety of obstacles, including rock outcrops, frozen till hummocks and even minor features such as boulders, it is possible that the resultant distribution pattern of drumlins would be random", and not non-random as Hill found.

The argument of inadequacy of definition, used by Hill (1973, p. 228) as already mentioned, can be just as easily applied to statements of non-randomness. It could be asked whether randomness and non-randomness have any significance. In the present definition of the terms all drumlins in a selected area of a field are statistically

measured. Rock knobs with thin coverings of till may be counted, as may stramlined mounds of fluvioglacial sands and gravels. Whether these pseudo-drumlins should be used in such a statistical analysis must be re-examined. However since an obstacle whether a rock knob or a mound of sand and gravel will influence the formation factors within the subglacial system, it may be just as valid to enumerate these pseudo-drumlins with the other drumlins. This argument, however, would not take into account features of a later depositional period or the removal of a drumlin within a field. Drumlins are therefore only random or non-random in relation to themselves giving no clue as to other inter-relationships. Instead of any single pattern of distribution, there may be several differing patterns each related to differing formative factors whose significance may have varied according to the length of time it took for a drumlin field to develop into its final form. Even in relation to each other there may exist more than one distribution pattern (Trenhaile, 1971).

SLOPE GEOMETRY

One of the fundamental characteristics of the drumlin form is a stoss slope considerably steeper than the lee slope. Several workers have investigated and analysed these slopes in the hope of finding either a constant factor or some fact indicative of how drumlins are formed (Heidenreich, 1964; Barnett & Finke, 1971; Miller, 1971; Trenhaile, 1971; Everett, 1976). Trenhaile developed, from data on a southern Ontario drumlin field, several interesting conclusions and graphs (Trenhaile, 1971, pp.118-123). He found that no drumlin theory could, as yet, explain the occurrence of drumlins in which the lee slope in 19% of the cases studied was steeper than the stoss slope.

He also concluded that the much greater variation in lee slope values as compared with stoss slope values could also not be explained. Although no clear relationship of lee to stoss slope emerged from Trenhaile's work, he has suggested from consideration of the drumlin's streamlined shape that the gradient of the lee slope may be one of the most fundamental adjustments that can be made to the drumlin in order that an equilibrium state be attained (Trenhaile, 1971, p.121).

At present no information exists relating drumlin slope value to the particle size distribution of internal material. It can be theorised, however, that there must exist relationships between slope angles, texture and the degree of consolidation of the material (Gravenor, 1974).

Trenhaile (1971, p.125) has noted that with increasing quantification the information on slope geometry and on other drumlin characteristics forms "a firmer basis for the investigation of drumlin genesis".

TERRAIN FACTORS

Work in North Dakota led Aronow (1959, p.200) to postulate that a relationship must exist between drumlins, till plains, fluted moraines and unknown glaciological factors. In a search for a specific key factor or factors that could distinguish drumlin terrain from non-drumlin terrain and thus drumlin forming processes from others, he compared the following terrain factors: a) regional slope (cf. Flint, 1971, p.102; Trenhaile, 1975); b) topographic grain (Taylor, 1907; Ebers, 1926; Hoppe, 1963; Heidenreich, 1964); c) drift character (Gravenor, 1974); d) bedrock configuration (cf. Savage, 1968, pp. 50-3; Trenhaile, 1975); e) bedrock character (i.e. lithology, structure) (Heidenreich, 1964, p.106) and f) pre-glacial topography and top-

ography before final glaciation. However, as far as he could determine, "no clearly discernible critical differences", accounted for the drumlins in the study area. Reed et al. (1962, p.209) later concluded from the evidence presented by Gravenor and Meneley (1958) and Aronow (1959) that, "drumlins and other streamlined glacial features cannot be directly correlated with either bedrock lithology or topographic conditions" (cf. Dean, 1953, p.27). Hill (1968, 1973) has since corroborated this conclusion in Northern Ireland by finding no correlation between drumlin density variations, geology and surface topography. Muller (1963, pp.27-9) in Chautauqua County, New York State, argued that neither bedrock nor the fabric of the till was a fundamental factor in drumlin development (cf. Smalley & Unwin, 1968). Only the quantity and availability of drift, it was argued, were important factors in controlling the form and type of streamline feature produced (Heidenreich, 1964, p.105; cf. Lundqvist, 1970, p.325).

It can be argued that if bedrock or underlying topographic restraints were covered by increasing amounts of drift, their influence would decrease in proportion to the thickness of drift cover (Vernon, 1966; Hill, 1968; Smalley & Unwin, 1968). The influence of terrain factors is therefore difficult to assess in terms of how the terrain could have affected drumlin formation or whether its influence was already subdued long before drumlin initiation.

Aronow (1959, p.202) concluded his investigations by suggesting that "something" critical "in the now vanished ice" must thus have existed in the ice conditions in order that drumlins should form there.

CONCLUSION

King (1974, p.161) has stated that, "The aim of morphometry is

to establish relationships between the measured variables of the features under consideration and the processes that created them". In the case of drumlin shape this above intent has been of tremendous value but in other relationships conclusions tend to be contradictory. The reason for this failure to recognise useful relationships between the differing factors considered arises either from an attempt to draw far too simple relationships or a failure to measure the correct factor or the factors correctly. Many relationships that have been suggested remain untested and therefore exist only as hypothetical statements.

A further assumption that may have led to many unknown errors in analysis is the acceptance of the idea that a drumlin field is a single complete pattern developed almost totally at one time. Trenhaile (1971), as noted, has observed that any drumlin field is most probably composed of drumlins in differing patterns from differing development phases or of a pattern that has become, since initiation, more and more complex.

Interrelationships therefore between drumlins, other drumlins and other factors inherent in the subglacial system are highly complex and in some instances may be beyond measurement or isolation. This conclusion however does not mean that useful relationships cannot be derived. Often, in the past, measurements have been taken and relationships tested without any theoretical background. This procedure must be reversed with new hypothetical relationships considered first, and then the factors measured in order that the hypotheses be tested (cf. Trenhaile, 1975) (cf. Chap. 10).

QUESTION 5 Why is a drumlin so shaped?

Drumlins have been likened to almost every conceivable streamlined shape: tear drops, eggs, torpedoes, cigars, aircraft wings and even a racing car (Ebers, 1926; 1937; Chorley, 1959). Drumlin dimensions such as width length ratios vary from 2:1 to as great as 60:1 (Lemke, 1958; Doornkamp & King, 1971, pp. 298-304), the average ratio being between 2:1 and 3:1.

Drumlin heights are not often recorded but they may range from less than one metre (e.g. some drumlins in the Tweed basin) to over 60m. Trenhaile (1971, p.125) found in 5 drumlin fields in southern Ontario that average width, height ratios were 13.3:1 and average length height ratios 44.4:1.

It has been generally observed that drumlins of a similar size and form are invariably grouped together over all or part of a field (Charlesworth, 1957, p.390; Vernon, 1966; Hill, 1968, 1971; Heidenreich, 1971). Heidenreich (1971, p.105) in discussing shape postulated that during drumlin formation once a certain critical drumlin width was attained, only the drumlin length would thereafter increase (cf. Savage, 1968, p.54). Trenhaile (1971, p.119) disagreed with Heidenreich finding no evidence for this hypothesis. Previously Chorley (1959) had noted that drumlins that tend to be oval and symmetrical about two axes, at right angles, are commonly smaller drumlin forms. Several workers have noted this relationship (Trenhaile, 1971; Doornkamp & King, 1971) which Chorley suggested was related to conditions other than glaciological factors. He suggested that some factor or factors preventing the attainment of a true equilibrium form must be involved. For example drumlin shape might be expected to vary from the equilibrium form if the velocity of the ice was

particularly high, or if bedrock was exposed with a distinct pattern, or if the till was of a particular texture or shear strength (cf. Chap.14).

EQUATIONS OF SHAPE

Several workers have suggested various mathematical equations of best fit for the drumlin shape (Chorley, 1959; Reed et al., 1962; Church, 1964; Doornkamp & King, 1971, pp.298-304). The elongation ratio, that is the maximum length of a drumlin divided by the maximum width, is both the simplest and the crudest.

The lemniscate loop is calculated using the following equations:

$$r = \sqrt{a^2 \cos k \theta} \dots\dots\dots(1)$$

where r defines the form of the loop, a is the long axis length and k is a dimensionless constant defining the elongation of the loop (Chorley, 1959). The value k is calculated from the drumlin length and its area A:

$$k = a^2 \pi / 4A \dots\dots\dots(2)$$

The rose curve is calculated using the following equation:

$$R = a \cos k \theta \dots\dots\dots(3)$$

(Reed et al., 1962).

Lemniscate loops and rose curves have been compared graphically by Doornkamp & King (1971, p.299). The rose curves, which are much narrower than the lemniscate loops, provide a better fit to the observed drumlin shape. From Doornkamp and King's work a close correlation between the k factor and the elongation was noted (Doornkamp & King, 1971, p.301). Chorley (1959) argued that a large k value indicated a small resistance to flow and thus large k values should be associated with maximum ice pressures. Similarly larger k values

are associated with greater elongation; therefore more elongated drumlins would appear to have been created under greater ice pressures. Several workers have postulated that, where ice has been largely unidirectional, drumlins tend to be larger and more elongated (Wright, 1912; Hollingworth, 1931; Charlesworth, 1957, p.394; Vernon, 1966; Gravenor, 1974).

SHAPE AS AN EQUILIBRIUM FORM

The shape achieved by a drumlin is a dynamic balance between the ice pressures and the internal drumlin material (Reed et al., 1962; Church, 1964; Hill, 1968; Smalley & Unwin, 1968; Gravenor, 1974). As already noted, when considerable ice pressure is applied to the drumlin material, it will tend to be deformed into more elongated, narrow and smaller forms. Conversely low ice pressures will tend to produce larger, fatter, but fewer and less elongated drumlins (cf. Crozier, 1975). Drumlin material when closely packed (i.e. highly consolidated) has a high surface area per unit volume and is therefore of a high shear strength. Such material should be less deformable under pressure than material that is loosely packed (i.e. highly unconsolidated) having a low surface area per unit volume.

The strength of a soil is defined by Wilun and Starzewski (1972, p. 145) as, "the maximum available resistance that it can offer to shear stress (a tangentially applied force per unit area of soil) at a given point within itself". In engineering terms, when this resistance is reached, continuous shear displacement takes place (i.e. the soil fails under the applied stress).

Several workers have inadvertently noted the close relationship that appears to exist between drumlin size and shape and the texture of the drumlin material. Fairchild (1907, p.704) argued that the

predominance of shale in north-west New York State supplied vast amounts of clayey, adhesive, drift which in turn was a contributing factor in the development of "close-set" drumlins. Likewise Putnam & Chapman (1943) in Ontario observed that drumlins were more numerous in loamy till than in clayey till. Recently Gravenor (1974, p.51) has suggested that sandy drumlins are larger because of a lower shearing resistance than clayey or silty drumlins (cf. Chap. 14). He points out that, as yet, no work has been done on the possible relationship that might exist between the K value and the textural composition of drumlins. It should, however, be noted that terms such as clay or sand only indicate texture and not the degree of consolidation that can be attributed to these materials. It is only coincidence and not a direct relationship that clays in subglacial drifts are invariably more highly consolidated than sands.

STREAMLINED SHAPE

The drumlin streamlined shape is recognised as the best possible equilibrium profile round and over which the ice can flow; it is the shape of least expenditure of energy, a low-energy profile (Slater, 1929, p.19; Flint, 1957, 1971; Chorley, 1959; Church, 1964; Heidenreich, 1964). How the streamlining process occurs has never been precisely analysed. Fairchild (1929) noted that a greater resistance presumably exists between clay and clay than between clay and ice. Similarly Wilson (1938), studying drumlins in Nova Scotia, suggested that the more cohesive the till (high clay content) the more likely an "ideally" shaped drumlin could be moulded.

The theory implicit behind both Fairchild's and Wilson's ideas is that material of a high shearing resistance is less liable to be destroyed or continuously deformed but is more likely only to be

moulded and shaped (cf. Chap. 14). Just as clay as opposed to sand is the medium for the potter's wheel, so the drumlin of a high clay content till, rather than a sandy till, was thought the most likely to be ideally shaped. Although in engineering terms this is strictly correct, if the clay till is less consolidated than the sandy till, the other factors of the subglacial system when adding their combined effects may cause the clay drumlin in a specific location not to be the most streamlined shape. This again finally reiterates the concept that no single formative factor can be used as a broad generalising explanation for all drumlins in every drumlin field. Certain factors may have dominated in some areas and in some drumlins, but any theory that is derived must take all possible formative factors into consideration.

CONCLUSION TO DRUMLIN REVIEW CHAPTER

From the review of drumlin literature several important conclusions have emerged that must be acknowledged in future drumlin origin theories.

Drumlins can no longer be regarded as unique features of a glaciated landscape but must be understood as peculiarities or aberrations of the subglacial system. The fallacy of the "unique" type of explanation has already been shown to be totally inapplicable to the derivation of a theory of drumlin origin. Any new theory must meet all possible permutations of size, shape, internal structure material, and location.

If the drumlin is viewed only as a part of the much broader subglacial system, then the first step in understanding the "aberration" must be the understanding of the system. The subglacial system may be defined as that set of interrelated forces and materials that

interacts within and between the basal layers of an ice mass, the underlying bedrock and the layer between these two bodies. Energy in the form of changing temperatures, water and material, in various stages of destruction, is fed into and passed through this system which is in a state of dynamic equilibrium. This system cannot ever be totally investigated for in doing so the balance of equilibrium is upset (cf. Kamb & LaChappelle, 1964). However the products of this system can be investigated and by an understanding of these products a picture of the mechanics of this system can be built up. The products of this system not only include drumlins but roches moutonnées, till lowland, eskers, kame-terraces, and meltwater channels of all dimensions.

Two conclusions emerge from this acceptance of drumlins as part of a much bigger and fundamental system. Firstly, drumlin origin theories can no longer be based solely on one process, either erosion or deposition (cf. Gravenor, 1953). Drumlins are a by-product of the combined effects of these processes and it is the explanation of this interaction that is sought. Secondly, with increasing research, especially with regard to till (cf. Goldthwait, R.P., 1971) and the subglacial system (Boulton, 1967, 1968, 1970, 1971, 1974; Peterson, 1970), a greater understanding of the subglacial system within the Quaternary ice sheets is beginning to accrue. The effect of this development is to cause greater awareness of the other equally important by-products of the subglacial system, when discussing the drumlin problem. It can be anticipated that with a better understanding of how till is deposited at present (Boulton, 1967, 1968, 1970, 1971; McKenzie, 1970) a better understanding of how it was deposited in the past is possible (Mickelson, 1971, 1973). This knowledge can then be related to drumlin till and thus a more precise understanding of how a drumlin

is formed may emerge. It is therefore crucial that the knowledge that has accumulated concerning the other parts of the subglacial system and its by-products be focused directly on the drumlin origin problem.

The final major conclusion to emerge from this review has been the necessity to utilise knowledge from other fields of science that are tried and tested and that can be applied to the problem in question. Perhaps the best example in this field of inter-disciplinary links is the application of aero-dynamics to drumlin shape (Chorley, 1959). Chorley, by introducing concepts of pressure and dynamic equilibrium, changed the whole concept of drumlin morphometric analyses. Drumlins are part of a system within which there exist forces and pressures interacting on material that is later deposited and that may exhibit the effects of such interaction. It is therefore highly likely that a field such as soil mechanics, which investigates the forces and pressures brought to bear on unconsolidated materials and the resultant nature of these materials, will be a fruitful area of inter-disciplinary application. Already Smalley and Unwin (1968) and Boulton and Dent (1974) have illustrated the value of soil mechanics in the elucidation of the subglacial system.

To help substantiate the above conclusions it is interesting that Reed et al. (1962, p.209) concluded by stating that "Any theory for drumlin formation must take into account both the dynamic conditions within the ice, and variations in physical properties of till and bedrock".

The above conclusions are largely methodological considerations but there also exists in the formulation of a drumlin origin theory a set of parameters or boundary conditions that any theory must satisfy.

Gravenor (1953, p.678) was the first worker to categorise these possible boundary conditions. Later Smalley and Unwin (1968, p.389) added to these conditions without amendment. However although it may be useful to state the necessary boundary conditions, previous lists must be reviewed and amended, not augmented by every new worker. With increasing knowledge of drumlin origin, an increasing number of conditions will become known until finally a statement such as below will be in essence a tabulated explanation of drumlin origin.

The boundary or limiting conditions that any drumlin origin theory must be composed of, are as follows:

- 1) Drumlins consist of a variety of materials, in varying proportions, with till being the commonest.
- 2) The internal drumlin material may exist as layers, folds or appear faulted. Such structures may exist throughout the drumlin or only in a small area or areas. The structures may also be restricted to specific materials and/or specific locations within a drumlin.
- 3) The thickness of the drumlin material will also vary from drumlins that are totally composed of glacially incorporated and derived material to those that have only a very thin covering of material over bedrock (i.e. rock drumlins). In other words, drumlins may exist with and without bedrock cores.
- 4) Cores other than bedrock, such as till of a highly consolidated nature, boulders, sand and possibly other material combinations, may also be present.
- 5) Many formerly glaciated areas do not have drumlins.
- 6) Drumlins normally occur in large numbers in areas that in length

are wider than known moraine belt widths. Drumlins may however occur in very small numbers and have in the past been ignored when there are only one or two.

- 7) Drumlins are normally landforms of the lowland, piedmont regions but exceptions occur in highland areas.
- 8) Drumlins occur in areas of massive ice sheet deposition, but may occur in areas of erosion.
- 9) Drumlins appear to be landforms created from ice sheet glaciation and not valley glaciation.
- 10) Drumlins only originate beneath temperate ice masses that are actively flowing.
- 11) Drumlins ideally have an ovoid, elliptical shape, the pointed-end facing down-ice, but shapes vary from circular to shapes that are ovoid but facing up-ice.
- 12) Drumlins with or without cores, of any type appear to have a similar variety of shapes.
- 13) Drumlins are in the broadest terms aligned parallel to the general ice flow direction of a region. However in detail drumlin orientation reflects the deviations of ice flow over small localised areas.
- 14) Drumlins are normally positioned some distance from one another in a random or non-random pattern; the two patterns may vary over a field or only one may persist. However drumlins are often found "sitting" edge to edge, a smaller one on top of another or end to end with little or no space between them.
- 15) Drumlins are a more unusual product of the subglacial system. Similarities in form and composition however exist between drumlins and normal till, eskers, moraines and roches moutonnées.

PEBBLE LITHOLOGY OF GLASGOW'S TILLS

This study of the pebble lithology of Glasgow's tills examines the localised and regional areal variations of three lithological categories. The collected evidence allows the formulation of hypotheses as to the source areas and glacial mechanisms that contributed to the formation of Glasgow's tills. Facts relevant to the red/grey till controversy will be presented. Further, it will be suggested that with a greater knowledge of the origin of till some light can be shed on the mechanics of drumlin formation.

PREVIOUS WORK AND THE FACTORS INFLUENCING THE DISTRIBUTION
OF THE PEBBLE CATEGORIES

It was recognised in the late nineteenth century that a relationship existed between the stone content of a till and the bedrock sources of these stones. G. Lundqvist (1935) made a comprehensive study of the lithologies of drifts in Sweden and also provided a record of past workers who had used the technique. Since then many workers have used this technique often as a part of more general studies (Eskola, 1933; Wolstedt, 1935; Milthers, 1942; Holmes, 1952; Dreimanis & Reavely, 1953; Anderson, 1955; Flint, 1957, pp. 126-29, 1971, p.174; Dreimanis & Terasmae, 1958; Arneman & Wright, H. E., 1959; Dreimanis, 1961; Kaiser, 1962; Willman et al., 1963, 1966; Dreimanis & Vagners, 1965, 1969, 1971; Drake, 1968, 1971; Mutanen, 1971; Shilts, 1973).

In seeking to understand the distribution of the various pebble

categories, several factors must be taken into consideration:

- 1) Area of outcrop of the source rock up-ice,
- 2) Erodibility,
- 3) Durability in transport and,
- 4) Distance transported.

The area of outcrop may become an invaluable aid to pebble provenance if, as in the case of the Lennoxton essexite outcrop or the distinct Ailsa Craig micro-granite, an individual pebble can be accurately linked to a specific isolated outcrop. Harrison (1960) calculated for each specific rock type the percentage of outcrop area up-ice of the sampled pebbles. He found an approximate 1 to 1 relationship between the weight per cent of a given rock type and the outcrop area. Within the thesis area however no rocks of small source areas could be used as indicators of till formation and composition.

The erodibility of any rock is closely allied to the size of the individual crystals or grains, as well as to joint patterns as in the case of igneous rocks. Igneous and metamorphic rocks yield less readily to mechanical breakdown than do shales and sandstones. Tills derived from igneous and metamorphic rocks tend to be coarse-grained, sandy or gravelly; whereas tills derived from shales, siltstones and mudstones tend to be more silty and clayey with fewer rock fragments (cf. grey till in Glasgow). Sandstones tend to produce a sand-rich till with smaller sized rock fragments than in other tills (cf. red till in Glasgow) (Flint, 1957; Dreimanis, 1961).

Several important papers have been published on the durability during transport of differing rock types (Holmes, 1960, Dreimanis & Vagners, 1965, 1969, 1971; Drake, 1968, 1970, 1971, 1972). Dreimanis and Vagners (1969, 1971) have shown that there is a terminal grade size

for each lithology beyond which it will no longer be mechanically abraded. Fine sands are the final stage from granite and metamorphic rocks, silts from fine sandstones and siltstones, and clays from shales and mudstones. Drake tested freshly crushed bedrock put into a drum and trundled for 0.01, 0.11, 1.11, and 11.11 miles respectively along with till as the abrading agent. He concluded that stone roundness and durability did not coincide with any single factor either of hardness, grain size or degree of foliation but was a combination of all these factors.

A further conclusion of Drake's work, after testing 1852 pebbles, was that only 0.1% of any lithology remained beyond 21 miles of transport. The implication derived from this conclusion is that tills are largely composed of local rocks (Flint 1957). This local derivation concept has however been challenged. After a detailed pebble lithology study, Harrison (1960), argued that approximately 90% of a typical till may consist of bedrock from outcrops more than 100 miles up-ice from the site of till deposition (Anderson, 1957). The only criticism to this argument of non-local derivation is that too many assumptions could have been made as to the identity of the pebbles in both Harrison's and Anderson's studies (Goldthwait R.P., 1971, p.15).

However because a rock once eroded takes some time and distance to be crushed to its terminal grade, often, for example tills derived on shales are not immediately clayey but only have shale fragments in their basal layers, the clay till derived from the shale being found a few kilometres down-ice (Dreimanis, 1961).

SAMPLING PROCEDURE

Two methods of sampling pebbles from the till were used:

- a) exposures, and b) borehole cores.

When sampling from exposures the face was cleaned and all slumped material removed. Pebbles were then extracted from greater than 2m below surface level in order that human disturbance be minimal. No igneous, metamorphic or lava pebbles that were rounded or sub-rounded were sampled, nor were any quartz pebbles. Weathered stones, if their lithology was definitely identified, were sampled; but areas of weathered till were avoided wherever possible. The pebbles were extracted one by one as in the till fabric sampling process (Chap. 6) and were, as far as possible, randomly chosen. Only pebbles between 2 to 6cm in length were sampled.

The main reason for using borehole cores was to avoid human contamination of the till and also to obtain till samples in urban areas where no possible exposures would be likely to exist. To avoid contamination from above as the coring auger descended, no pebbles found crushed or fractured and adhering to the core sides were sampled. The core, normally never greater than 45cm in length, was air dried and then crushed gently with a hammer. The crushed till was then passed through a sieve (mesh size, 1cm^2) and 50 pebbles randomly picked.

In both the exposure and core methods all pebbles were then split and a fresh face used to identify the rock type.

PEBBLE LITHOLOGY CATEGORIES

Of the 27 pebble lithology counts taken 14 were in grey till, 11 in red till and 2 in reddish-brown till. The pebbles sampled were grouped into 4 main categories: Carboniferous rocks, Old Red Sandstone rocks, rocks derived from the Highlands and Other rocks. The reasons for having these groupings were as follows. Firstly, it was decided that only 50 pebbles be counted at each site. With only 50 pebbles at each site it was recognised that numerous categories

of differing lithologies would become statistically meaningless. Secondly, because of the location of the thesis area in relation to the enormous variety of rock types in the source areas to the north-west, west and south-west, it was felt that only broad categories could be acceptable and meaningful. The choice of categories was also influenced by the known and hypothesised ice flow directions (Fig. 3).

Carboniferous rocks included sandstones, shales, siltstones, marls, coal and the loose conglomerate of the Calciferous Sandstone series. Within the Carboniferous category a subdivision of the percentage of coal observed was included. These rock types were easily recognised whether unweathered or not. Only the quartz, igneous and metamorphic pebbles of the conglomerate could not be distinguished from other lithological categories. The Carboniferous rocks were areally the most common and dominant lithology of the thesis area.

Old Red Sandstone rocks included red sandstones, mudstones and marls as well as conglomerates. There were three areas in which difficulties in recognition occurred. Firstly, it was impossible to distinguish accurately whether whitish sandstones were of Carboniferous or Old Red Sandstone age. Secondly, no distinction could be made between the quartz, igneous and metamorphic pebbles of the Old Red Sandstone conglomerate and that of the Carboniferous. Finally, no distinction could be made between Lower and Upper Old Red Sandstone. These difficulties were overcome by firstly assuming that all white coarse sandstones were Carboniferous; any inaccuracies that did occur were felt to be too small in comparison to the technique's other inherent inaccuracies. All pebbles that were sub-rounded or rounded and were quartz, igneous or metamorphic rocks were ignored. As already mentioned

it was hoped this would at least reduce the effects of the various conglomerate source rocks and would remove inaccuracies in the Highland rock category. The third problem was not felt to be important but did cause the possible source area for Old Red Sandstone to be much larger. The Old Red Sandstone rocks are the second most important lithology, being the dominant rocks on the edge of the thesis area in the west and north-west.

The rocks grouped into the Highland category included all granites, schists, gneisses and micro-granites. These rocks north of the Highland Boundary Fault are varied and diverse in their source areas. This category is therefore a rather broad one into which all rocks found north of the Fault are grouped. As already noted, only sub-angular and angular pebbles of the types commonly found in the conglomerates were sampled. Within this category no account was taken of the possible interference of Southern Upland rocks existing to the south and south-west of the area. It was assumed from the known ice directions that the effect of such southern source rocks would be of very little or no significance.

All pebbles that failed to be recognised and the few pebbles whose origins were debatable were included in the Others category. Where possible pebbles pertaining to the scattered small dykes and sills were noted and categorised in this group. The reason for this was the widespread location of source areas for pebbles from dykes and sills which meant that their significance as indicators of ice flow and glacial mechanics was limited.

METHOD OF PRESENTATION OF RESULTS

It was considered that the results of this study would be best

presented in the form of isopleth maps illustrating the percentage areal distribution of each lithological category and as graphs comparing the three till types in relation to each lithological category (Anderson, 1957; Gross & Moran, 1971; Johnson et al., 1971). The isopleth maps were hand contoured and therefore must to some extent suffer from operator bias. However inherent errors in the data would seem to preclude the use of techniques such as polynomial trend surfaces (Gross & Moran, 1971) to achieve a greater objectivity of data representation. A contour interval of 10% was thought sufficient to represent the areal distribution of the Carboniferous and Highland pebbles. Because of the much narrower range in percentage distribution of Old Red Sandstone pebbles a contour interval of 5% was used.

In producing these maps two sites were not used in the calculations. Summerston (568 703), (Site No. 27), where the sampled grey till was surrounded by red till and at Carntyne (633 649), (Site No. 23), where a grey till was sampled with an unusually high Old Red Sandstone content and a slightly weathered appearance; both sites apparently indicating highly localised concentrations of bedrock material. It was therefore thought that in the production of a general isopleth map these peculiar sites would be given undue importance when compared to the other sites and would give a false impression of reality to the isopleth maps. As another means of reducing the complexities of the isopleth maps all samples taken at Braidfield (506 721) and Baljaffray (533 738) were averaged and the mean of each lithological constituent plotted.

In plotting the three graphs, all the data from the 27 sites were used. The average of each lithological category and the standard deviation was calculated for both the red and grey till. By plotting all the sites examined it was anticipated that peculiarities and anomalies

among the sites would be revealed.

FACTORS TO BE CONSIDERED IN THE ANALYSIS OF RESULTS

The interrelationships between the three pebble lithological categories can best be analysed in the light of three fundamental principles.

PRINCIPLE OF DISTANCE DECAY

Anderson (1955, p.236) illustrated what he termed the principle of percentage pebble decrease with distance travelled down-ice from a source bedrock or drift. If ice passes over a bedrock source, for example, the number of pebbles of that lithology increases to a maximum down-ice of the source. With this maximum reached the percentage of pebbles decreases with increasing distance from the source area. The rate of decrease, provided no external additions occur, is a measure of the durability of the lithological type (cf. Drake, 1968).

PRINCIPLE OF DILUTION

Gross and Moran (1971, p.264) constructed this principle after acknowledging that each individual lithological group percentage was only a relative percentage and not an absolute percentage. Where a certain rock type that was easily eroded had contributed to a till the relative percentage of all other rock types declined or were diluted. This dilution effect produces what at first appears a sharp decline in rock type (A) whereas it only indicates a sharp increase in another constituent rock type (B) relative to the rock type (A).

PROBLEMS OF EARLIER DRIFT

Harrison (1960, p.442) believed that "the most recent advancing ice (sheets), by picking up the previous till, would simply be carrying

on where the last ice (sheet) left off". The effect of earlier drift on the final till sheet is to include a number of rock types in the till which are inconsistent with final known ice movements.

Once the previous till has been removed by erosion the underlying bedrock is again exposed to subglacial processes, thus providing a new bedrock source of material for the final till sheets. In many instances, as in Indiana, the Wisconsin till and the earlier Illinoian till were of almost identical pebble lithologies, having been derived from ice flowing over an almost identical route. The only variations found were in the distances some rock types had travelled in relation to their original bedrock sources (Harrison, 1960, pp.441-2).

SAMPLING ERRORS

The final group of factors that affect the results of this study are sampling errors. Such errors as misidentification, preferential removal of certain lithological types by the investigator, differential weathering of pebble lithologies, and human interference with till, prior to sampling, cannot be dismissed but equally their effect cannot be assessed (Shilts, 1973). In analysing the isopleth maps it must be remembered that the sampling density may be too low in some areas. Some sites that as a result appear anomalous may be part of narrow ribbons of highly concentrated or diluted pebble percentages and therefore may not be as anomalous as they would seem. Because quartz and igneous, sub-rounded and rounded pebbles were not sampled the Highland category may be slightly under-represented.

POSSIBLE BEDROCK TOPOGRAPHY DURING THE GLACIAL PHASE

Although the re-erosion of earlier drifts may be important in contributing to the pebble content of the final till sheet, the single

most important contributory factor is the topography of the bedrock beneath the actively eroding ice sheet. Although factors such as erodibility and durability are important in the production of the end product, the roughness or smoothness of the bedrock is of primary importance.

The bedrock topography at the time of the glaciations can only be guessed at. Within the Glasgow area multiple escarpments, sills and dykes and volcanic vents occur; the whole area being greatly affected by faults. These features were the most important bedrock obstacles to the path of the ice sheets. It is not apparent from today's landscape exactly how much bedrock has been eroded or where it has suffered the least or greatest amounts of erosion. Pockets of what appears to be in situ Tertiary weathered rock are said to exist (Godard, 1965; Sissons, 1967; Fitzpatrick, 1972), as are areas of shattered rock. However from the known thicknesses especially of till, rich in Carboniferous rocks, it can be perhaps assumed that many parts of this area, because of the above speculated bedrock topography and bed roughness, have undergone vast amounts of glacial erosion.

ANALYSIS OF RESULTS

SHORT DISTANCE VERTICAL AND HORIZONTAL VARIATIONS IN PEBBLE LITHOLOGY CONTENT

In the investigation of till using till fabrics J.A.T. Young (1969) has shown that marked variations can be expected over very short distances both vertically and horizontally. Following on from this work the writer attempted to discover if such variations could be detected in pebble lithology samples taken over short distances. At two sites, both in red till, at Braidfield and Baljaffray horizontal

and vertical sampling was undertaken. At Braidfield four samples were taken at 100m intervals along the long axis of a drumlin. At Baljaffray two samples were taken one 10m above the other on the side of a drumlin.

The Braidfield samples (Table 3) reveal a marked variation between samples especially in the Carboniferous pebble category. At Baljaffray (Table 3) a similar marked variation occurs again mostly in the Carboniferous category.

T A B L E 3

BRAIDFIELD (Horizontal)			
	Old Red Sandstone	Carboniferous	Highland
	%	%	%
1	18	32	42
2	14	31	45
3	18	16	58
4	23	22	47
BALJAFFRAY (Vertical)			
1	29	16	44
2	20	34	36

Although these samples are too few in number for statistical analysis, the evidence would suggest that the variations observed in till fabrics are also detectable in the pebble lithology. To show that the pebble content is variable is not the object of this study; the question why the till is so variable in pebble content, must also be asked. A

major element in this heterogeneity must be chance occurrences in pebble content but some suggestion also exists of variations through time in the pebble content as the till is deposited. As well as there being no uniformity in till content, no uniformity would appear to exist in the rate, time and place of till deposition.

It must therefore be pointed out that in the interpretation of results derived from the isopleth maps the variability of the pebble content, as above noted, must always be taken into consideration. Therefore conclusions derived from the isopleth maps must remain cautious and speculative.

ISOPLETH MAPS

In presenting the 3 isopleth maps 21 individually plotted sites were used. The Carboniferous pebbles reveal a general increase from the north-western edge of the thesis area towards the south-east and east (Fig. 7). Initially the Carboniferous pebbles double in percentage in the first 3km. A more intricate distribution is perhaps revealed of 3 dispersal ribbons; a more northerly slow increase, a central rapid increase and a slow southern increase. Because of the sparsity and variability of the evidence at each site however caution must be used in interpreting these ribbons.

The Old Red Sandstone pebbles have a rapid then gradual decrease from the north-west to the south-east of the area (Fig. 8). Initially the pebble percentage is halved in the first 2km, thereafter the decrease is halved in 5 to 6km.

The Highland pebbles decrease gradually towards the east and south-east, on average the percentage is halved in approximately 8km (Fig. 9).

Since the local bedrock is Carboniferous the explanation of these

ribbons will be made in terms of the Carboniferous pebble dispersion. It appears that the central ribbon, located roughly over the present route of the River Clyde, is possibly the result of a large amount of locally eroded rock being incorporated in the till or to a marked reduction in the other two pebble categories. The 3 ribbons appear to fan out from around the Yoker area (510 690) prior to which only one ribbon appears to have existed. The most likely explanation for this fanning out process would appear to have been the effect the entry into the Glasgow basin had upon the ice flow previously constricted in the lower Clyde between the Kilpatrick and Renfrew Hills. To complicate this picture of ice movements ice appears to have crossed over the Kilpatrick Hills and down into the Milngavie area (Fig. 3).

Gross and Moran (1971) while working on mineralogical gradations within the till of the Allegheny Plateau in north-western Pennsylvania and north-eastern Ohio, discovered that a consistent relationship could be found to exist between the relationship of glacial striae to till mineral gradational isopleths, and areas of glacial erosion and deposition. The writer, instead of using glacial striae, utilised the long axis orientations of the drumlins within the thesis area as indicators of ice movement. By then superimposing the drumlin orientation lines on top of the Carboniferous isopleths a similar diagram as that shown by Gross and Moran was constructed (Fig. 10). Using this map it was possible to distinguish between areas where glacial erosion and deposition had predominated (cf. Gross & Moran, 1971, p.270). Areas of erosion are detectable where the drumlin orientation lines are normal to the isopleths (e.g. Drumry to Milngavie (545 741). The composition of the till in these areas changed rapidly with distance

down-ice, due to the increased additions of newly eroded material. Areas of deposition or areas of equal amounts of highly localised deposition and erosion as might be expected if previous till was the source material are observed where the drumlin orientation lines are parallel to the isopleths (e.g. at Wellfield Street). At these sites the composition of the till has remained constant.

As the thesis area is almost totally within a drumlin field, the map (Fig. 10) reveals an area of considerable deposition as would be expected. However the puzzle remains of how areas of erosion, as revealed by the isopleth maps and the localised nature of the grey till, can exist within an area that is dominantly depositional. The only explanation would appear to be that the processes of deposition and erosion operate on a much smaller scale than previously thought. This enigma has already been mentioned and is only substantiated by this study of pebble lithologies using Gross and Moran's technique of ice flow and pebble isopleth comparison.

PEBBLE LITHOLOGY GRAPHS

Of the 3 tills distinguishable on the basis of colour only the pebble lithological contents of the red and grey tills could be statistically analysed; there being only 2 sites of reddish-brown till. From the 3 graphs some overlap can be seen to exist between the red and grey till, the reddish-brown till found at Rough Mussell and Hamilton Hill being in the area of this overlap (Figs. 11,12,13). Three sets of standard deviations were calculated for both the red and grey tills. The Old Red Sandstone pebbles were found to have the smallest deviation ($\sigma_{RG} = 4.5\%$). These are standard deviations of sample populations taken at increasing distances down-ice from the

source rock. It therefore seems that the Old Red Sandstone pebbles were the least variable and were the least affected by distance (Carntyne is 15km down-ice from Braidfield). In achieving such a constancy of pebble percentages in an area beyond the Old Red Sandstone pebble source an equilibrium seems to have been attained either by the Old Red Sandstone pebbles reaching a terminal grade size or by the other pebble categories being constant through destruction and addition of eroded Carboniferous pebbles. However as will be noted below this second possibility can be discounted and the first hypothesis tentatively accepted. In contrast much higher standard deviations ($\sigma_R = 11.6\%$, $\sigma_G = 13.9\%$) were found for the Carboniferous pebbles. The explanation for this variability may have been the irregularity of Carboniferous bedrock erosion in the Glasgow area.

The graphs reveal that the pebble lithology between the two tills is markedly different. Since the red till is found up-ice of the grey till, the difference in pebble lithological contents can be possibly explained either by the tills being deposited during one glacial phase or by the red till being deposited at a later period from the grey till.

When the bedrock sources of the two tills are located in relation to the positions of the tills it can be seen that the red till, dominantly derived from the Old Red Sandstone bedrock west of the Kilpatrick Hills, is found covering Carboniferous bedrock east of the Old Red Sandstone/Carboniferous bedrock boundary. In changing from red to grey till a transitional phase has been observed of reddish-brown till. The grey till dominantly of Carboniferous rocks then follows eastwards across the remainder of the Carboniferous bedrock basin (Fig. 14). The geological sequence, as seen in Fig. 2, would

appear to be best explained as follows: the red till deriving its colour from the haematite particles in its clay content, persists into the Carboniferous basin and is only superceded in a lateral direction by the grey till. Once the Carboniferous rocks had travelled far enough the clay particles of the Carboniferous mudstones and shales changed the colour of the till from red to reddish-brown to grey and to almost black in the eastern edges of the thesis area. This above explanation of lateral progression from west to east in the down-ice direction would seem to be best explained if a single glacial phase for both tills in the Glasgow area is accepted.

The graphs, as well as revealing the down-ice percentage changes of one rock type to another, also reveal the sites that appear anomalous in terms of location and till pebble content.

SAMPLE ANOMALIES

As the subheading to this section implies many sites that were sampled and then compared and plotted with the other sites appear in context atypical and do not match the expected overall pattern.

At Milngavie (Site No. 10) in red till a particularly high content (54%) of Carboniferous pebbles was found. Before attempting to explain this apparent irregularity several observed facts must be stated. Firstly, as was previously mentioned when discussing the Carboniferous isopleth/drumlin orientation map (Fig. 10), the area surrounding the Milngavie site is one where glacial erosion has greatly affected the pebble lithology content. Secondly, it was noticed when sampling at this site that a high percentage of the pebbles found were rounded and sub-rounded, quartz and quartzite pebbles which were not included in the sample count. Finally this site at Milngavie revealed, by drumlin orientations and meltwater channel routes (Fig. 4), that it was down-

ice of the Carboniferous, quartz-rich, calciferous sandstone escarpment whose present remnants can be seen at Douglas Muir just over 2km west of Milngavie. The conclusion from the above evidence is that the Milngavie site was enriched by Carboniferous rocks due to the up-ice glacial erosion of the Carboniferous escarpments. This enrichment also led to an apparent reduction in the other pebble categories due to a dilution effect. The site nearby at Windyhill (524 735), (Site No. 9), reveals a similar but far less pronounced Carboniferous enrichment (30%).

A site in grey till at Elmvale Street (601 683), (Site No. 17) reveals a remarkably high Carboniferous pebble content (88%) in comparison to other nearby sites (e.g. Wellfield Street (61%)). Although because of this high Carboniferous pebble content the other two categories are anomalously low, the pebble category which would seem the most likely to change quickly in this part of the study area is the Carboniferous, the local bedrock source. The Carboniferous isopleth/drumlin orientation map (Fig. 10) revealed that this was an area affected by glacial erosion. From the Rockhead map (Fig. 49) which will be discussed in detail later, a rapid rise in bedrock elevation is noted beginning west of Elmvale Street and rising eventually to crop out in Springburn Park (608 684). The rising bedrock appears to have acted as a reverse slope and barrier to ice movement causing the ice to erode the bedrock.

A third abnormal site is at Rough Mussel (516 613), (Site No. 24) in reddish-brown till. A high percentage (14%) of Old Red Sandstone pebbles was found in comparison to surrounding sites. Three explanations are thought possible:

- 1) that the surrounding sites at Ibrox, Leverndale (516 627) and

Blackstone (458 664) have had their Old Red Sandstone pebble content diluted by excess Carboniferous pebbles due to highly localised erosion;

- 2) that a very restricted and local source of Old Red Sandstone has supplied the higher percentages or
- 3) that it is a chance occurrence due to the vagaries of glacial deposition.

As revealed by the Carboniferous isopleth/drumlin orientation map, this area is one of glacial erosion. It therefore seems possible that the first explanation may be correct in some degree. The Rockhead map reveals the buried channels of the lower Clyde and lower Cart to the west of this area which may have caused the ice to erode the side walls of these channels. This area around Rough Mussel is geologically complex with faulting and up-thrusting evident from the Geological map and Memoir (Clough et al., 1925) and as a result this also may have allowed glacial erosion.

With regard to the second possibility no evidence exists to suggest that a localised outcrop of Old Red Sandstone exists in this area.

The possibility that the percentage pebble content is a chance occurrence would appear to be the most likely explanation; although the effect of Carboniferous pebble dilution must also have played a part.

In discussing what appears to be atypical sites, some understanding was gained of the local variations of erosion and deposition, pebble dilution and of the overall distance decay of Highland and Old Red Sandstone pebbles. A complex pattern has therefore emerged of till deposition and glacial erosion over the study area.

CONCLUSIONS

Several conclusions have emerged from this study of till pebble lithology. Firstly, on the basis of colour and pebble lithology content, 3 tills, one of which is an intergrade, have been identified; secondly the complex nature of till deposition and the effects of localised erosion are noted and finally, from the overall pattern displayed by the Isopleth maps, the movements of the depositing ice sheet are revealed.

The Isopleth maps have revealed that ice depositing the tills in the Glasgow area moved from a fairly constricted zone around Dumbarton to fan-out into the sedimentary basin to the east. Ice movements were complex with possibly 3 different ice movement units covering the area. From west to east, a red till, then reddish-brown till and finally a grey till were recognised each with different average pebble lithology contents but with considerable intergrading. These tills would appear to be different only because of their locations in relation to their source rocks. No sudden changes in pebble content were found, only gradational changes. In some instances, for example the red till at Milngavie and the grey till at Wellfield Street had pebble lithology contents that were not dissimilar. This would seem to suggest that the tills were different only in terms of the changing emphasis and dominance of source rocks and not necessarily in chronology. The writer would not suggest that this evidence proves or disproves any particular theory as to the red and grey tills but it does tend to give support to the theory of contemporaneous deposition in one glaciation.

The large variation in till pebble lithology content has revealed the complexity and diversity of the mechanics of till

deposition. Erosion may be dominant in one location for some time then it may be superceded by deposition, yet the records of that previous domination are left in the composition of the till. The pebble content is the end-product of an intricate balance between deposition, erosion, the effects of transport and the effects of other pebble variations. This evidence suggests that till is not deposited rapidly in a short time period but over a long interval of time. If the changeability of till is so great over horizontal and vertical distances then the processes of till deposition and erosion must be confined to small localised areas and not to huge regional areas. The mechanics of till deposition must therefore not be investigated at the macroscale but at a much smaller scale.

TILL FISSURE FABRICS IN DRUMLINS

During the investigation of several exposures cut in drumlin till it was recognised that both the red and grey tills in Glasgow were highly fissured. The fissures were normally small in size, only a few centimetres long, and were observed with dips varying from 90 degrees (vertical) to 0 degrees (horizontal) (Plates 4-5). Subsequent discussions with engineers indicated that, as well as greatly affecting the geotechnical properties of the till, the fissures also appeared to have preferred orientations. As a result of this preferred orientation or fabric, McGown (pers. comm. 1972) while working on drumlins around Kilmarnock, hypothesised that a more general overall drumlin fissure pattern might be expected (Fig. 48). Since two of the causes of fissuring in superficial deposits are directly related to stress conditions at the time of and directly following deposition, it seemed possible that till fissures might give some clue as to the stress conditions and subglacial environment existing at the time of drumlin formation. With a greater understanding of the subglacial conditions at the time of drumlin formation a better idea might be obtained of how and why drumlins are formed.

HYPOTHESIS OF TILL FISSURES

From McGown's observations and measurements on a motorway section passing through a drumlin near Kilmarnock, Ayrshire, it was hypothesised that a fissure pattern had evolved in relation to the stress conditions immediately after drumlin formation. Comparing these till fissure patterns with those observed by Kupsch (1955) in a boulder dyke within

a drumlin in Saskatchewan, McGown suggested that the high angle fissures ($>70^\circ$) were either shear- or tensile-induced features of the till. The low angle fissures ($<40^\circ$) were thought to be produced by stress relief of overburden pressures after ice retreat. Although it was recognised that other causes could explain the fissures, McGown suggested that the dominant causation of the fissures and fissure pattern was glacial action. It was therefore the purpose of this study to investigate fissures in drumlin till and to note if a fissure pattern could be detected in drumlins.

BACKGROUND LITERATURE

Fissures or cleavages have been recognised in tills for some time but have been rarely measured until recently (Virkkala, 1952; Flint, 1957, 1971; Harrison, 1957; Elson, 1960; Penny & Catt, 1967; Dreimanis, 1969; Boulton, 1970; Johansson, 1972; Kazi & Knill, 1973; McGown et al., 1974).

Work in other overconsolidated and fissured clays such as the Cretaceous clays of South-East England indicated that there often exists a preferred system or systems of fissures in these clays related to past depositional and post-depositional processes (Fookes, 1965; Fookes & Wilson, 1966; Fookes & Denness, 1969; Lo, 1970; Marsland, 1971). Shear strength of till when calculated by testing the till normal to the fissure patterns is considerably greater than when the till is tested parallel to the fissure pattern (McGown et al., 1974, pp. 20-3).

As well as considering the geotechnical aspects of fissured till both McGown et al. and Kazi and Knill endeavoured to explain the significance of the fissures in terms of the mechanics of till deposition and post-depositional processes. Kazi and Knill concluded that

fissuring of till was most common in areas of multiple glaciation for example, East Anglia (cf. McGown et al., 1974, p.14).

Five major mechanisms have been suggested that would seem likely to influence and create fissuring in material: weathering, syneresis (a spontaneous loss of water from a gel during aging), desiccation, chemical action and stress relief (Kazi & Knill, 1973, p.46; McGown et al. 1974, p.5). Kazi and Knill concluded that the fissures in the East Anglian till could be attributed to two principal factors: firstly, glacial action causing stress relief and secondly, the active slope instability of the specific site causing stress relief.

McGown et al. arguing on the basis of a discontinuity between till fabric and drumlin orientations suggested that the drumlins in North Ayrshire were created in a two stage process. Firstly, till was deposited as a water-soaked, plastic material and was shaped later into a drumlin. They argued that the till fissures could not have developed either as shear or tensile fissures in the first ice movement because of the nature of the material since it would have absorbed most stresses. The fissures that were near-perpendicular and those near-parallel to the a-b planes of the stones, were therefore formed during the retreat of the first ice movement.

Such stress relief fissures would be normally tensile fissures formed as the material stretched elastically with the reduction in overburden pressure. However McGown et al. point out that the distinction between shear and tensile fissures remains an intractable problem. Little evidence is presented to suggest a two stage drumlin evolution other than the different orientations between one till fabric and the long axis of the drumlin on which the fabric was taken. No indication of where the till fabric was taken in relation to the overall

drumlin surface is given. It would therefore seem unsound to base such conclusions simply on the findings of one till fabric. This criticism is only directed at the conclusions given for drumlin evolution and not on the subsequent arguments applied to fissure formation.

McGown et al., (1974, p.19) investigated the intensity of fissuring in the till, finding the higher parts of the drumlin most intensely fissured. As might be expected the upper parts of the drumlin were subjected to the greatest stresses applied by the ice but only once the drumlin formed. Therefore these fissures would appear to be all post-depositional features of the till indicating the final stress history of both non-drumlin till and drumlin till.

TECHNIQUE OF MEASUREMENT OF TILL FISSURES

In the present study measurements were made using the Cavity technique (Fookes & Denness, 1969; McGown et al., 1974). This technique is very similar to that used in till fabric measurements (see below). A vertical till face was cleaned, at least 2m below ground surface level, and a 60cm square was marked on the till face. The bottom left-hand corner of the square was taken as the zero of a cartesian co-ordinate system of $x = \text{vertical}$; $y = \text{horizontal}$ and $z = \text{normal into the face}$. The compass orientation of the till face was taken with a Suunto compass to within ± 5 degrees. By using a pallet knife and carefully picking at the till face, fissures could readily be detected. Fissures were chosen randomly for measurement. Once a fissure was chosen, its length and width were ascertained by following the fissure to its end or to where it was intersected by another fissure. The face of the fissure was measured as is shown in Figure 15. It was noted whether the fissure face was stained or not and, if

so the colour of the stain. Surface roughness characteristics were observed either as slickensided, smooth or rough. The surface shape or geometry was noted as planar, semi-planar or curved. The strike and dip of each fissure was then measured using a Suunto compass to within ± 5 degrees. Finally the fissure was located exactly in space using the approximate centre point of the fissure face. The co-ordinate axes were measured to within ± 1 cm. This process of identifying, excavating and then measuring fissures was then continued until 50 fissures at each site had been measured.

PRESENTATION OF DATA

At each till fissure fabric site a table was compiled. The data for each site were then presented in the form of a stereographic plot. The method of plotting dip was the opposite from that used in the till fabric stereograms. In the case of the till fissure fabrics the centre of the circle had 0 degree dip and the outside circumference a 90 degree dip or vertical. The strike of each fissure was measured, it being easier to measure than the orientation. Before plotting on the stereogram, 90 degrees were added to each strike in the direction of the dip of the fissure. This then allowed comparison of till fissure fabrics with till fabrics. When a vertical fissure was plotted both possible orientations had to be plotted 180 degrees apart on the outer circumference.

Rose diagrams were constructed in a similar manner to those used in till fabric studies. As another aid to visual representation several contoured stereographic plots were constructed. Using a Kalsbeek counting net (Ragan, 1968, pp.80-2) contour lines were plotted with a 2% density per unit area of fissures measured.

Work using till fissure fabrics in conjunction with till fabrics was restricted to two drumlin sites for reasons of access.

This work was done in co-operation with members of the Department of Civil Engineering at Strathclyde University, who carried out a programme of geotechnical tests on the fissured till. The major findings of their work appear in recent papers (McGown et al., 1974, 1975).

PROBLEMS ENCOUNTERED IN PROCEDURES

Several problems arose in the measurement of the fissures.

Firstly, it was occasionally difficult to ascertain the exact co-ordinates of a particular fissure. When a fissure was found continuing some distance into the till face, assessment of the co-ordinates became difficult. This problem was solved to some extent by using a set square and metre stick.

A second problem, linked to the first, was the uncertainty that existed as to the exact dimensions of a fissure. When the till face was being picked out in order to trace the extent of a fissure it became necessary at times to stop excavating in order not to destroy many other fissures lying in front of the fissure under investigation. In most instances fissures that could be completely excavated were dealt with first. However when intersecting fissures were common at the till face, there was no method of avoiding partial excavation.

To avoid measuring fissures that could either have developed from stress release due to excavation of the trenches in which the investigations were made or from recent dessication, all till faces were cut back at least 1m into fresh till. How effective this was is difficult to assess but McGown et al. (1974) noted from similar investigations at Hurlford in Ayrshire that even after 5 weeks of exposure,

cut slopes showed little or no effects of recent stress relief.

MEASUREMENT OF TILL FABRICS

The field procedure adopted for taking both the orientation and dip of stones within the till was as follows. The face of an exposure in the drumlin till was first scraped clean, then a horizontal rectangular step was cut into the face. This horizontal face was cleaned and stones carefully excavated with a knife until the desired number was obtained. In order to avoid fabric variations, as noted by J. A. T. Young (1969), the step excavated was never increased beyond 60cm^2 and never decreased vertically by more than 10cm. The stones were measured along their longest axis with a compass to ± 1 degree of compass bearing. Only stones less than 6cm and more than 3cm long were measured. Normally only blade-like stones or stones with a distinct long axis were measured. Fifty stones were measured at each site, this number being thought statistically significant (Hill, 1968; Kruger, 1970, p.137). An accuracy of ± 5 degrees for the angle of orientation was accepted (Andrews & Shimizu, 1966; Harris, 1969, 1971). Stones dipping at angles greater than 40 degrees were thought to be too difficult to measure accurately (Kruger, 1970). A similar ± 5 degree error for the angle of dip was also assumed acceptable. The stones were measured either in situ or were removed and their casts measured.

TILL FABRIC REPRESENTATION

Rose diagrams illustrating orientation and dip combined were constructed (Hill, 1971, p.26). On these diagrams a dip of 90 degrees was represented by the centre of the circle on which the rose diagram was constructed. The lengths of the radiating lines indicate the

number of stones that have an orientation within each 10 degree sector.

In producing a stereographic diagram an equal area projection was used (i.e. each angle of degree represented on the diagram is the same size). In plotting the till fabric data both orientation and dip were combined as in the rose diagrams. Contoured fabric diagrams were then produced in an identical manner to that noted for till fissure contour fabric diagrams.

INITIAL OBSERVATIONS AT EACH TILL FISSURE SITE

Two drumlins were investigated, one at Rottenrow (598 654) in grey till and the other at Gilshochill (569 694) in red till (Fig. 16).

SITE 1

At Site 1 in an east-west trench along the drumlin crest line, it was observed that the fissures appeared, in the majority of instances to be steeply angled, parallel to and coming out of the till face. Several large fissures with a strike, north-west to south-east, were stained by yellow mottles (7.5 YR 5/5) possibly the result of soil eluviation as the colours were similar to the colours observed in the weathered soil horizons above. Smaller fissures, in particular, were near horizontal and commonly had fine greyish brown sand partings along the fissure faces. Where possible it was noted that stones of all sizes traverse fissures at right angles and were never observed at any angle parallel to the fissures.

SITE 2

At Site 2 in the east wall of a trench ~~transverse~~ to the drumlin elongation fissures were observed parallel to and coming out of the till face (Plate 4). However at a point between 2 and 3m below the

unweathered top soil the fissures were found to be dipping less steeply. The latter revealed fine sand partings along the fissure faces. The intensity of fissures seemed to be greatly reduced as work proceeded into the till face. Similar staining to that at Site 1 was observed on some near-vertical fissures.

SITE 3

On the opposite wall of the transverse trench at Site 3, the fissures were steeply inclined, dipping back into the till face. In all other details the till face bore an almost exact resemblance to that at Site 2.

SITE 4

On the side of a drumlin at Gilshochill steeply inclined fissures were observed dipping out of the face while others dipped into it. No gently dipping or horizontal fissures were observed at this site. Staining on near-vertical fissures was not observed but this may partly be due to the low contrast weathering colours of the red till.

COMPARISON OF TILL FISSURE FABRICS AND TILL FABRICS

At each site investigated a till fabric was taken. It was intended that each till fabric be compared with the till fissure fabric of the same location. From the work of Glen, Donner and West (1957), Harrison (1957), H. E. Wright (1957,1962), Gravenor and Meneley (1958), Hoppe (1963) and MacClintock and Dreimanis (1964) it seems reasonable to suppose that the primary modal orientation in a till fabric is indicative of the directions of the principal shear stresses undergone by the till. It has been argued that till with a very high water content will, when subjected to a shear stress, contain embedded elongated particles orientated parallel to that stress. Since many fissures would

appear to originate from a stress condition set up in the material, it was anticipated that the till fabrics would be indicative of the stress conditions to which the till had been subjected. Work by Evenson (1971, pp.359-360) lends support to the idea that till fabrics may very possibly be shear induced and that the time of development of the till fabrics is in response to till deposition mainly during glacial overriding (cf. Ramsden & Westgate, 1971). However, as will be discussed later, the processes involved in causing stones to orientate parallel to the shear stresses set up by the ice would not appear to be contemporaneous with the formation of till fissure fabrics. It can only be hypothesised that the forces causing till fabric formation may have been possibly of a similar magnitude and direction as those forming till fissure fabrics and may therefore be a guide and estimate of the conditions that prevailed during till fissure fabric development.

SITE 1

At this site, of the 50 fissures measured, 42% were dipping with angles greater than 70 degrees and 22% were dipping with angles less than 40 degrees (The angles of 70° and 40° dividing up the fissures into high angle (>70°) moderately dipping (41-69°) and low angle (<40°) were chosen in order to allow comparisons with previous work) (Fig. 17). The overall fissure pattern has a general north-north-east preferred orientation (Figs. 18-22). This contrasts with the drumlin long axis orientation and the dominant preferred orientation of the till fabric, both of which have an easterly orientation (Figs. 23-25).

If, however, only the fissures that have a dip greater than 70 degrees are plotted a slightly different pattern emerges (Fig. 19).

Two rather scattered zones emerge near the edges of the circle, one to the north and north-east, the other to the south and south-west . When the low angle fissures are plotted they group approximately close to the centre of the circle with a slight north-easterly orientation (Fig. 20).

Interpretation - Site 1

The interpretation of this site can be subdivided into two parts dealing with: 1) the high angle and 2) the low angle and moderately sloping fissures.

1) The pattern found by the writer is almost identical to that found by Kazi and Knill (1973, p.46)(Fig. 46). These fissures would appear to have been formed by both shear and tensile stresses. The first, caused by forward ice motion and positive stress; the second, caused by ice retreat effectively creating a negative stress.

It can be hypothesised that as the ice was moving over the till surface the already deposited till would be subjected to the tractive shear stresses set up by the moving ice. These stresses are transmitted directly to the till mass causing the till to be stressed. As is seen in a present-day shear box experiment when soil is sheared, zones of failure occur. The till would then tend to become dilatant (cf. Smalley & Unwin, 1968). This dilatancy or attempt to increase in volume by grain to grain rearrangement, would however be suppressed by the overburden ice pressures. A situation therefore is likely to develop in which a build-up of stress within the till mass cannot be released. The consequence is the production of cracks or fissures to dissipate this confined energy. These fissures occur at right angles or at a distinct angle to the principal stress orientation.

A practical example of this energy dissipation is the tensile stress relief observed when a sheet of paper pulled at two opposite ends will tend to tear down the middle at a sharp angle to the applied tensile stresses.

It seems reasonable to accept that the till fabric orientation in this instance is the equivalent of the principal ice-applied shear stress. Therefore the fissures at approximately right angles to this stress may be explained by this above mechanism. Tensile fissures would be produced in almost exactly the same manner, only the direction of principal stress is different, it being presumed in this instance to be 180 degrees different from the till fabric orientation.

Whether these high angle fissures are tensile or shear induced is, however, virtually impossible to ascertain. As McGown et al. (1974, p.15) have noted "what were initially tensile fissures may, due to subsequent stresses, move along their surfaces and obtain linear markings, while shear fissures may eventually lose any such features due to processes like weathering".

2) Both groups of fissures with a distinct orientation sub-parallel with the drumlin side would appear to be best explained as largely the result of stress relief. The results are again comparable with Kazi and Knill's findings in Cromer till. With the thinning of the overburden ice and its subsequent retreat, stress release parallel and sub-parallel to the upper ground surface is likely to have occurred. As the ice lay on top of the till a stress perpendicular downwards into the till was always present. When this stress was removed, the till was no longer confined and thus cracks and fissures at right angles to the direction of stress might have developed.

A further explanation for the low angle fissures may be suggested in relation to till layers (Chap. 9). Where these till layers were present within the till mass the fine sandy partings between the layers, because of their loose structure and matrix, may have provided zones of weakness that might well have been the first parts of the till mass to allow stress relief.

SITE 2

In contrast to the first site, of the 50 fissures measured, 22% were high angle ($> 70^{\circ}$) and 46% were low angle ($< 40^{\circ}$) (Fig. 17). The overall fissure pattern was found to have a distinct north-westerly preferred orientation (Figs. 26-30). The till fabric preferred orientation is almost the mirror image of the fissure fabric, having a broad south-east orientation (Figs. 31-33).

When the high angle fissures are plotted no distinct pattern emerges (Fig. 27). The low angle fissures cluster around the centre of the circle but in the north-western quadrant (Fig. 28).

Interpretation - Site 2

The site was situated on top of the drumlin with zero slope and it seemed surprising, after previous observations, that such a distinct north-westerly orientation should be found. Although the trench face had almost the same orientation as the fissure fabric, the fissure fabric at Site 3 that was taken on the opposite face of the same trench exhibits a similar north-west orientation. It therefore would seem that the trench face has little or no influence in terms of recent stress relief, for one would expect the fissure pattern exhibited by the effects of stress relief in a trench to be parallel or sub-parallel to the trench face.

An explanation that seems possible is that a stress relief gradient had once existed to the north-west of this site. The till fabric orientation is almost parallel to this orientation which therefore further emphasises the possible validity of this explanation. The present ground surface however is almost flat. This site is therefore anomalous in terms of the present drumlin surface.

SITE 3

The fissure fabric and till fabric patterns at this site are similar to those at Site 2 (Figs. 34-39). However at this site 75% of the fissures are greater than 70 degrees and only 4.5% are in the low angle category (Fig. 17).

Interpretation - Site 3

An almost identical hypothesis to explain the fissure pattern as suggested for Site 2 would seem to be demanded. The till fabric and drumlin orientation are, in this instance, almost at right angles to the fissure faces (Fig. 46). At both this site and Site 2 stress-induced fissures cannot be ruled out as a possibility but their influence on the fissure patterns observed seems minimal.

SITE 4

The fissure pattern at this site, on the steep (18°) slope of a drumlin, is slightly more complex with no distinct preferred orientation (Figs. 40-42). No fissures were found with angles less than 70 degrees which may be explained by the site location being on such a steep slope. Two areas of fissure concentrations do exist in the north-western and south-eastern quadrants.

Interpretation - Site 4

As is exhibited in Figure 43 the till fabric reveals a bi-modal

preferred orientation. This may possibly reflect the movements of ice passing along and at times slightly upwards across the side of the drumlin. These suggested ice movements, coupled with the location of the site, are perhaps the cause of the steeply dipping fissures. From the direction of ice movement, as reflected by the till fabric and drumlin long axis orientation, and the major grouping of fissure planes lying slightly to either side of that orientation it might be tentatively suggested that the fissure fabric is the result of shear-induced processes.

The other possible causes may also account for or be part of this fissure pattern. Stress relief due to ice removal from the drumlin side, with account taken of the steepness of the slope, may explain the north-westerly fissure pattern. Similarly the slope may have been, in the past, subjected to down slope material movements due to solifluction, slope wash or to an oversteepened slope being left after ice wastage resulting in both shear and tensile stress conditions being set up. These stresses, on such a slope, would tend to produce high angle fissures with a north-western orientation. In the writer's opinion, no definite single process can account for this fissure pattern but stress induced and stress relief processes seem the most probable.

DISCUSSION

In investigating these fissure fabrics it was hoped that some indication would emerge of an overall drumlin till fissure pattern. However from this small study it would appear that no overall pattern can be discovered.

The fissures are secondary features of the till unlike the till layers. Therefore a time lag would appear to exist between till

deposition under the stress conditions of an ice mass and the later changed stress conditions that would seem to dominantly influence fissure development. Accepting this hypothesis shear- and tensile-stress induced fissures would probably have formed during and immediately following glaciation, whereas stress relief fissures would tend to develop at some unknown time after glaciation or some time after a set of stress conditions had changed during glaciation.

As already noted the fissure fabrics at Sites 2 and 3 appear somewhat anomalous. To account for these fabrics the writer proposes that the following stages may have occurred during the drumlin and till fissure fabric development (Fig. 47 a,b,c,d,e). Instead of accepting the hypothesis proposed by McGown et al. that the fissure pattern is post-final drumlin formation, it is proposed that some fissures may form during drumlin formation. If the stress conditions imposed on an area or mass of till are changed then stress relief may occur. This situation is envisaged in Figure 47b where a stoss side, later buried by till has formed or been sculpted. The stress vectors at point A are therefore, as illustrated, dominantly tangential and slightly upward in direction. As an obstacle to ice movement this "early" drumlin must have been able to withstand the basal tangential stresses of the ice. In time new till would be deposited burying the once highly stressed stoss side (Fig. 47c). The stress conditions at point A would therefore become totally changed, with a downward stress dominant. The upper shear stress now would affect only the upper parts of the till having little influence on the buried till surface at point A. At some time either during further deposition or after a lull in deposition, the stress conditions at point A would become so altered that stress relief in the direction of the now buried stoss side would

probably occur. It would seem probably that stress relief would occur over a considerable length of time as the stress conditions gradually changed. Stress relief contours as illustrated in Figure 47d suggest that this particular drumlin may have developed by an accretive process growing in size in an up-ice direction (Fig. 47e). The consequences of such a possible hypothesised mode of formation on drumlin origin will be discussed later (Chap. 14).

These above tentative suggestions although based on only two sites do accord with observations on several drumlins in the Glasgow area. At all the sites visited in the palaeomagnetic study (Chap. 11) fissuring in the till was observed but often with fissure dips inconsistent with the overall pattern proposed by McGown (pers. comm.) (Fig. 48).

It can therefore be suggested that till fissures may reflect not simply the ice stress conditions after final drumlin formation but perhaps the varying stress conditions during drumlin formation. The major problem now to be solved, if at all possible, is to distinguish between fissure patterns formed by differing processes at one site and between sites.

CHAPTER 7

THE COLLECTION AND PLOTTING OF BORELOG DATA FROM CENTRAL GLASGOW

In reviewing the background literature on drumlins (Chap. 4) it was noted that very little information existed on their internal composition (cf. Slater, 1929) and little detailed information dealt with the bedrock topography beneath a drumlin field. Since borelog data not only reveal detailed stratigraphy but in most instances the depth at which bedrock was encountered, it was hoped that by using dense borelog information within a drumlin field the two above deficiencies in drumlin knowledge could be, to some degree, reduced.

It was therefore in an attempt to overcome these deficiencies that central Glasgow was chosen as an area of probable dense borelog information within a drumlin field. There were four basic objectives in collecting as much of this information as was available for central Glasgow: 1) To produce a Rockhead map in order to investigate the bedrock topography. It was hoped that possible relationships between the bedrock topography and the overlying drift and drumlins might be detectable using this map.

2) To produce a Drift Thickness map in order to note the variations in drift thickness and type throughout drumlins and the surrounding till sheet.

3) To collect information on the geotechnical properties of the till in drumlins and elsewhere.

4) To improve and help clarify the Quaternary stratigraphic succession in the Glasgow area.

SOURCES OF INFORMATION

As a source of borelog information Glasgow has several advantages over other cities in Britain. Since the mid-nineteenth century exploratory boreholes have been sunk throughout the city in order to locate coal, ironstone and fireclay deposits. Since the mid 1950's vast areas of new housing developments have covered the periphery of the city, high-rise buildings have been built in the city centre and in the late 1960's a ring-road motorway building programme was initiated.

Boreholes are used by mining, road and building engineers, as a means of identifying rock and drift strata. Boreholes in Glasgow have been sunk for two main purposes: 1) to locate mineral deposits (mineral boreholes) and 2) to give the civil engineer a sample from which can be calculated a precise value of the strength of the materials over which or through which a structure has to be built (site investigation borehole).

Within an area of approximately 180km^2 8000 borelogs were collected. This large number of borelogs is the result of several factors not all unique to Glasgow. Firstly, all engineers prefer to sink their own boreholes if only because responsibility for building errors will ultimately be borne by them. Secondly, boreholes sunk at the same site years beforehand may be of poor quality in terms of information given or because the boreholes were sunk for a different purpose. Thirdly, because of new foundation and building techniques, such as piling, new boreholes have to be sunk. Fourthly, many recent boreholes have been sunk to locate old abandoned and uncharted mine shafts and galleries. As building structures have increased in size and foundation weight the possibility has occurred that some of the old mine workings

may suddenly and disastrously collapse beneath these structures. Therefore the need to locate these workings precisely has become a necessity. For these reasons and because of a general lack of co-operation between engineering companies a vast number of boreholes have been sunk, often in concentrated areas, within the city over the last hundred and fifty years. A further but localised factor for the proliferation of boreholes is the complexities of the drift within the city.

The collected borelog information dates from the early nineteenth century to 1974. The following list illustrates the complete range of sources from which information was extracted:

- 1) Housing developments.
- 2) Office blocks, banks and department stores.
- 3) University and college buildings including libraries and museums.
- 4) Hospitals, police and fire stations and other public service buildings.
- 5) Electricity power and sub-stations.
- 6) Gasworks and gasometers.
- 7) Roads, motorways, railways and railway tunnels and all associated bridges.
- 8) Dockland buildings, warehouses, piers, slipways, causeways and crane sites.
- 9) Sewage works and main sewer tunnels.
- 10) Domestic/industrial water supply.
- 11) Mining: coal, fireclay and ironstone.
- 12) Published papers.

SURFACE LEVELS

In order to produce Rockhead and Drift Thickness maps the surface altitude of each borelog is required. The majority of borelogs had surface levels recorded to O.D. Newlyn. These borelogs were then checked where possible with 1:2500 O.S. maps and the ground surface topography. Where major errors in given surface levels appeared to exist the specific borelog was discarded. In a few old borelogs surface levels had been recorded to O.D. Liverpool. The correction factor however is so small for Glasgow that it was ignored since other errors are probably greater (O.D. Liverpool = 0.15m + O.D. Newlyn). Where borelogs had been collected with no date or approximate date of sinking recorded, surface level, if given, was assumed to be O.D. Newlyn. When borelogs had been taken in basements or on floating barges adjustments had to be made, in order to avoid inaccurate estimates of drift thickness and rockhead elevation. Boreholes sunk in basements were corrected to allow their surface level to correspond with the surrounding ground level. Where surface levels were not recorded these were determined from the 1:2500 O.S. maps or from large scale site plans. All other borelogs not included in these categories had to be discarded. This resulted in only 6,219 borelogs being used in plotting the Drift Thickness and Rockhead maps.

PLOTTING OF ROCKHEAD ELEVATION AND DRIFT THICKNESS DATAROCKHEAD MAP

Since most of the borelog information was derived from site investigation reports the accompanying site plans of borehole location were at various scales, 1:100, 1:200, 1:500 and 1:1250 being most common. These large scale plans were reduced to the 1:2500 scale by means of

a Grant projector and geometric reduction by hand. All borelogs collected from the Institute of Geological Sciences had their borehole locations already plotted at the 1:10560 scale. The accuracy of these plotted boreholes from visual inspection did not appear to be very high and locations were, wherever possible, checked against the boreloggers' site descriptions. These borelogs were plotted by hand or by scaling-up using the Grant projector to the 1:2500 scale.

All data were then plotted, using tracings, onto "Acetate" overlays over 1:2500 O.S. maps. At each site the rockhead elevation and the borelog number was plotted and an 8 figure grid reference was recorded (accurate to within $\pm 10m$). To avoid confusion in contouring in areas of dense borelog information, some boreholes had to be omitted. Diazo (dye-line) copies were then made of all overlays.

Using the diazo copies contouring was completed for each 1:2500 sheet by processes of interpolation and estimation of probable ground configuration. The choice of contour interval was based on two factors. Firstly, the contour interval had to be close enough to allow detailed variations to be illustrated and yet not too fine as to allow details to obscure more general areal trends. Secondly, the contour interval had to take account of the inherent inaccuracies of borelog information (see below). If the contour interval was too small and thus less than the inaccuracies of the data, the result would be a map of low accuracy. Yet to produce a map with a wide contour interval, to obviate these inaccuracies, would result in loss of detail and a map too generalised to be of any value. Taking these two factors into account for both the Rockhead and Drift Thickness maps a contour interval of 5m was used. Since it seems reasonable to accept that stratigraphy in borelogs is normally recorded to an accuracy of $\pm 1m$ (Sissons, 1971, p.186),

the accuracy of the contours in areas of extensive borehole coverage is assumed to be within the range of $\pm 1m$. Where borehole information is lacking or is scattered or where no information exists between areas of dense borelog information the accuracy of the contouring is very low. As a result a pecked line is used only as an illustration of the writer's considered estimate of the location of the contour line.

All contoured diazo copies were then photographically reduced to the 1:10560 scale. Subsequently these reduced copies were grouped in terms of the O.S. 6" sheets and a tracing was made of the maps. At this stage only boreholes either in isolated or critical sites were plotted with their rockhead elevation marked, all others being marked only with a dot (Fig. 49).

DRIFT THICKNESS MAP

When the borehole locations had been plotted, as noted above, another overlay was placed over the rockhead/borehole number overlay and the drift thickness of each borehole was recorded on the upper overlay. Drift thickness was calculated by subtracting the rockhead elevation of a borehole from its surface elevation. When plotting drift thickness, made ground was included within the calculations. It might be argued that made ground should be excluded but since, as the borelog records show, it so often has been used to replace in situ drift deposits it seemed a reasonable decision. Only in one area of central Glasgow does made ground seem to give greater thicknesses of drift than expected (601 669). A few surface hollows may be filled in by made ground but in using a 5m contour interval such inaccuracies were thought acceptable. All other plotting stages were identical to those noted for the Rockhead map, including the contour interval (Fig. 50).

OTHER ASSUMPTIONS AND APPROXIMATIONS IN PLOTTING DATA

In drawing the estimated (pecked) contours on both sets of maps a certain licence existed. In contouring rockhead topography the only variable is rockhead elevation. The geomorphologist must assume that a topographic pattern is to be anticipated and thus estimated contouring is carried out according to normal topographic shapes. However in contouring drift thickness, the isopachytes are a combination of two variables, namely, rockhead elevation and surface elevation. As a result no simple topographic relationship exists, and the drawing of the isopachytes is much more hazardous especially in a drumlin field where repeatedly, as a drumlin is encountered, sudden changes in drift thickness can be anticipated (although this does not always occur).

SOURCES OF INACCURACY INHERENT IN BORELOG DATA

The sources of inaccuracy can be grouped under four main headings:

LOCATION AND SURFACE LEVELS

In using the site plans included in site investigation reports inaccuracies inevitably occur in the draughtsmanship of the original plan. In some instances borehole locations were plotted on the site plans using very approximate estimates of location. Similarly, surface levels recorded by site levelling may be inaccurate due to faulty surveying. Both the above inaccuracies are largely beyond correction unless some obvious error can be detected.

Occasionally boreholes are sunk in very shallow foundations pits for piling purposes. It is not always noted in the site report that the recorded surface level is below true ground surface level. Such an inaccuracy, unless within an area of dense borehole coverage, may not be detectable.

STRATA

When the various strata are being recorded by the logger mis-identification of drift type is possible. This misidentification may also be due to the type of boring-rig used. At present two types of rig are most commonly used: 1) shell and auger and 2) hand rigs (Terzaghi & Peck, 1967, pp.299-301; Wilun & Starzewski, 1972, p.189).

Both methods of boring rely on continuous extraction of material. The auger is sunk into the soil, either hydraulically or by human force, without being turned for a depth corresponding to the size of the sampling chamber (U4). At this depth the chamber and attached rods are twisted through 180 degrees, the chamber is pulled up and the sample extruded either for inspection or removal for laboratory testing. The principal sources of inaccuracy with these two methods are in the compaction or destruction of very thin beds of strata, in the gravels, and in the misreading of depths at which samples were taken. With both methods of boring these inaccuracies tend to be minimised the greater the experience of the boring crew.

In the past many boreholes were sunk in Glasgow using the wash-boring technique whereby water was pumped down a steel casing to aid the chopping-bit or drill head (Terzaghi & Peck, 1967, pp.296-8). The resultant extruded material because of the washwater was invariably a muddy slurry and only an experienced logger could tell what drift type the bore was passing through. A paper by Legget (1974, pp.357-360) expands in detail the problems of inaccuracy encountered in the use of this technique.

A further inaccuracy in borelog data results from the miscalculation of strata thicknesses due to man's modification. Strata thickness

may be underestimated if in situ deposits are removed and replaced by greater or lesser thicknesses of made ground. As a consequence almost all strata thicknesses and depth, within an urban area, are subject to an in-built inaccuracy.

BORELOG TERMINOLOGY

Because of considerable uncertainty on the part of the logger, coupled with the necessity to describe the strata in terms understandable to engineers rather than geologists and geomorphologists, a till may be described, for example, as a coarse sandy clay with silt and gravel. This problem, of the logger's language, illustrates two major areas of inaccuracy on the part of the user of a borelog. Using the above example of a coarse sandy clay it may also be interpreted as made ground or gravelly raised beach deposits. In most instances however the actual location and surface level would tend to indicate if raised beach was a possibility or not but in other locations within known raised beach areas problems of actual borelog translation are considerable. Only experience and a knowledge of the drift variations likely to be expected allows for accurate interpretation and translation. However when the made ground is of a similar drift to the underlying sequence it is often undetectable and thus an unavoidable error is made. A problem concerning descriptive language is in determining the meaning of antique or local dialect words (cf. Clough et al., 1925, p.283). In the latter instance a constant meaning has been assumed; for example, fakes or plies denotes thin-bedded sedimentary rocks.

ROCKHEAD

A further source of inaccuracy is in deciding when a borehole has reached bedrock. Most borers try to sink at least 1.5m into fresh rock

when bedrock is suspected but this does not always indicate bedrock having been reached. It may be that a large boulder has been encountered instead of bedrock. However when several boreholes are sunk close to one another major discrepancies in bedrock level would be noted and the suspect borehole re-drilled. Such re-drilling programmes are common in Glasgow where boulders of considerable size ($> 2\text{m}$) are often encountered in till.

In contouring the bedrock topography distinction had to be made, where possible, between areas of naturally complex topography and areas of disturbed bedrock. Several quarries, long disused and forgotten, and filled in with made ground were located in localities close to the centre of Glasgow. A map, revealing all known areas of mineral exploitation in Glasgow (pers. comm. I. Stevens), was used to aid in the understanding of the bedrock topographic variations. In one instance over 15 boreholes were sunk into till in north Glasgow revealing bedrock close to the ground surface. A borehole was later resunk revealing till beneath the fresh rock. On later examination an enormous erratic slab of fresh rock was found lying within the till, in one place 15m above the true bedrock elevation. This example serves to indicate the caution that must be taken in interpreting bedrock elevation especially in areas of till. Anomalous bedrock elevations were discarded when no other evidence could be found to substantiate such a finding.

Borelogs that reveal either shattered or weathered rock above fresh bedrock present a problem in interpreting bedrock elevation. That shattered or weathered rock in a glaciated area may be in situ or may be transported material. If it is the latter then such material should not be regarded as bedrock; yet this distinction can rarely, if ever, be made. The rock may be so comminuted that in terms of the

borelog description it could be interpreted as a gravelly till. Therefore it was decided that whenever shattered or weathered rock was clearly indicated and was encountered above fresh bedrock it would be regarded as bedrock. Inaccuracies must therefore occur. In a few older boreholes rockhead elevation was given as an approximate figure between two values. In such instances rockhead elevation was given a value greater than the minimum rockhead elevation recorded. In the borelog appendix rockhead was indicated as being "near".

FINAL REMARKS

Before discussing in the next chapter the details of borelog records and the valuable information revealed by the Rockhead and Drift Thickness maps several general points must be made. Both types of map can, at best, be only as good as the amount and quality of data available at the time of compilation. These maps are therefore only "preliminary" in nature and will require continuous revision. As progress continues in site investigation procedures the ability to detect changes of strata and bedrock elevation accurately will improve such that some of the above sources of inaccuracy will be either greatly reduced or removed. As data increase the errors in drawing isolines will decrease, inaccurate borelogs will be filtered out and the areas of estimated interpolations will become fewer and smaller.

Although the problems and inadequacies of borelog records have been discussed at length, there is no intention to underestimate the value of borelogs and the maps compiled from the borelog data. The data, once collated and used along with the compiled maps, are of immense value not only to the geomorphologist and geologist but to the civil engineer and urban planner (Christiannsen, 1970; Sissons,

1971; Karrow, 1973; Legget, 1973). The maps are most suitable as a guide or indicator, for example, as to what bedrock elevations and types are to be expected or what variations in drift type and bearing capacity might occur over a length of motorway or office block site. By supplying data over a specific area site investigations can be slightly less detailed and costing of foundation programmes can be more closely estimated. The final use of these maps would be to reduce construction costs at the site investigation phase, to prevent such expensive mistakes as occurred in the past (Legget, 1974, p.356-7) and ultimately to benefit the urban population (Eden, W.J. 1973).

CHAPTER 8

B E D R O C K T O P O G R A P H Y

A N D

G L A C I A L D R I F T I N C E N T R A L G L A S G O W

I N T R O D U C T I O N

This chapter comprises the observations and interpretations made on 8,000 borelogs collected by the writer for central Glasgow. A summary of these borelogs has been made (Vol. 3) in which surface elevation, bedrock elevation and major drift strata thicknesses are recorded.

A map of "the rock surface round Glasgow" (Clough et al., 1925) was prepared for the Glasgow District Geological Memoir from boreholes largely sunk during the nineteenth century (Fig. 51). This map is speculative in many parts but served as a guide in the production of a Rockhead map. The earlier map and its report (Clough et al., 1925, pp.215-220) reveal several interesting suggestions. A link is shown as existing between the buried channel of the Kelvin and that of the Clyde, with a gradient in the buried Clyde channel to the west and then north where it joins the buried Kelvin channel at Drumry. Mention is also made of the deposits within the buried channels where till was occasionally found intercalated with sand and gravel lenses. It was further suggested that the infilling of the buried valleys occurred as the sea-level rose due to land submergence just prior to the onset of glaciation. These suggestions will be discussed using the evidence provided by the large number of borelogs now available. These records also provide a better knowledge and understanding of the stratigraphic

succession in the Glasgow area.

THE STRATIGRAPHIC SUCCESSION OF DRIFT DEPOSITS

AS REVEALED BY BORELOGS

(A General Outline)

In Chapter 3 the general stratigraphic succession of drift deposits known prior to this study was discussed and analysed. The stratigraphic succession as revealed in Figure 52 is not intended to be an accurately scaled diagram but only representative of the broad findings of the writer. Before discussing each deposit, in turn, the general stratigraphy will be outlined in order to clarify the relationship to each other of the various deposits.

The most extensive and variable deposit within the area is till. Till forms the major part of all drumlins in the area and extends over the wide interfluves between the buried channels of the Clyde and Kelvin and other smaller channels. In a wide area close to the present River Clyde and below 26m O.D. this till is buried beneath raised beach deposits. Below -15m O.D. till is found in scattered patches lying beneath deposits of fluvial origin that infill the deep bedrock channel of the Clyde. Above this altitude till is more extensive and appears to be continuous with the till that emerges from beneath the raised beach deposits. Whether the lower till (below -15m O.D.) is of a similar age to the till that underlies and emerges from the raised beach deposits is not clear but the possible relationships between these two tills will be discussed later.

Within the till, itself, sand lenses are quite common (2.4% of borelogs) and are occasionally of considerable vertical extent. Lenses of laminated clays are also found but are far less common (0.54%

of borelogs). Inclusions of bedrock normally occur near the bedrock/till interface but also occasionally throughout a till sequence. What appear to be inclusions of laminated clays and silts of raised beach sequences may be rather the reverse and be inclusions of till due to erosive wave action or slumping of the till into the raised beaches. Mass movement may also account for the inclusion of peat within till beneath steep drumlin slopes. Within the drumlin till no specific variations unique to these landforms were noted but in one instance a lense of sand and gravel at the lee, distal end of a drumlin was found (588 656). Shelly till has been recorded only at Blythwood Square (585 655). Occurrences of shelly till have been reported in the past (Chap. 3) in several localities within the study area. Although the shells in the till are few in number they do indicate either the passage of the ice that deposited this till over the bed of the upper reaches of the Firth of Clyde or the erosion of older shelly till deposits.

Above the unweathered lodgement till a sequence of deposits 1 to 2m in depth interpreted either as ablation till or weathered till or a combination of both is normally found in all areas. Deposits closely resembling fluvioglacial material are occasionally found but these may be the washed surfaces of ablation till or a thin layer of melt-out till.

A variety of deposits is found beneath the till. Often sand and gravel deposits exist, although they rarely exceed 2m in thickness. In a few locations distinct sequences of laminated silts and clays have been found. These deposits are scattered throughout the thesis area and rarely exceed 1m in thickness. These latter deposits, as will be discussed later, may be the remnants of the glacial lake deposits that may be inferred to have formed with the blocking of the

lower Clyde estuary as the ice advanced into the western part of the Central Lowlands (Bell, 1874; Geikie, J., 1874). They may also be the remnants of small lakes and ponds overwhelmed in the ice advance.

As already mentioned, on either side of the present River Clyde up to a level of 26m O.D. raised beach deposits are found overlying firstly, the infilling deposits of the buried channel of the Clyde and secondly, the till (including a few small drumlins). Within and beneath the raised beach deposits peat and other organic remains are occasionally encountered.

Fluvioglacial deposits overlie the till in only a few scattered areas. The scarcity of such deposits in the study area, where frequent impeding of meltwater drainage during ice downwasting might have been expected to occur, remains a major problem. To the east of the study area, around Shettleston and Garrowhill, large accumulations of fluvioglacial material have been noted. These deposits were interpreted in the past as Stau moränen (Clough *et al.*, 1925, p.227) and may be the only extensive evidence of ice stagnation in the Glasgow area. Several small meltwater channels have been mapped in which thin layers of fluvioglacial sands and gravels overlie the till.

Within the buried channel of the Clyde a complex sequence of deposits is found of lenses of sands, silts, clays, laminated clays and gravels. From the limited borelog evidence available these deposits of variable vertical and lateral extent cannot be accurately correlated one with another. The deposits occasionally have been found to contain lenses of till (3.4% of buried channel borelogs) that may have several possible origins, as will be discussed later. Also, as already mentioned, the channel deposits overlie scattered patches of till.

There are very few boreholes sunk in other buried channels in the

study area but one put down close to Drumchapel Shopping Centre (517 712) indicates a sequence of deposits similar to that found in the buried channel of the Clyde. Because of the similarity in texture of many of the overlying raised beach deposits with the buried channel deposits it is difficult to accurately distinguish between the two sequences.

Peat and lacustrine deposits, the former often overlying the latter, are found scattered throughout the area in hollows between drumlins and in enclosed basins on the surface of the till sheet. These deposits, as already noted, have occasionally been covered over by slumped till as a result of slope movements.

The true areal extent of these peat and lacustrine deposits cannot be ascertained in the study area because of man's influence. In removing the top few metres of the drift deposits and replacing them with made ground, large parts of the study area have been totally altered. In a few areas made ground has replaced complete or large parts of drumlins (593 661) and in other areas hollows in the till and between drumlins (584 658) have been covered over.

TILL

The Glasgow area is dominated by landforms and deposits indicative of large-scale glacial deposition. The effect of glacial erosion on the landscape consequently is muted.

DISTRIBUTION

Both the Geomorphological map (Fig. 4) and the borelogs have revealed that till extends over the wide interfluves between the bedrock buried channels of the Clyde and Kelvin (Fig. 51). The till is normally

found lying directly on bedrock (Bore 1).

BORE 1 Grid Reference: 6098 6606 Surface Elevation: 64.00m O.D.

	m	m
Made Ground	1.07	1.07
Stiff, firm at surface, brown and red brown Till	1.83	2.90
Stiff to very stiff, grey brown sandy Till with occasional boulders	9.30	12.20
Soft, brown silty Clay, laminated in places	0.90	13.10
Stiff, grey brown Till with occasional large boulders	10.06	23.26
Hard Bedrock		

The till however does not extend, except in a few instances, into the deeper parts of the Clyde buried channel (Figs. 85-86) (where borelog information on the buried channels exists). As shown in Figure 53, till is present on the gentler sides of the buried channel but beneath depths greater than approximately -15m O.D. a "lower" till is found that is discontinuous and exists only in isolated pockets and patches. This "lower" till is essentially identical in matrix colour and composition to the till lying above the infilling deposits on the broad interfluvies. In plotting the distribution of the "lower" till and "interfluvial" till in relation to the buried channel infilling deposits (Fig. 53) care was taken to include only those borelogs that registered thicknesses greater than 1m (cf. Woodland, 1970). Care was also taken to observe whether the underlying bedrock could, if shattered, be confused with a stony till (e.g. a stony mudstone).

Where any possible confusion between till and bedrock might have existed the specific borelog was discarded.

The "lower" till because of its relationship with the infilling buried channel deposits would appear to be the remnant of a phase of glacial deposition prior to the channel infilling. Firstly, the position of the "lower" till in the stratigraphic succession (Fig. 52) within the buried channels would indicate such an age. Secondly, this "lower" till (Fig. 53) is restricted to deep hollows that probably would have been areas within the channel sheltered from the erosive power of the water that, from the evidence of the infilling fluvial deposits, appears to have flowed along the channel. In areas of the channel less sheltered from the erosive action of the channel water the converse was noted and no till was found existing beneath the infilling deposits (e.g. at 609 638).

Within the present Kelvin valley, south of Dawsholm Park, no till is found except on the upper slopes of the valley. From the Geomorphological map (Fig. 4) it can be seen that no drumlins were found to exist within the valley and no eroded parts of drumlins were found on the edges of the valley.

TILL STRATIGRAPHY

Flint (1971, p.154) states that "Till is possibly more variable than any other sediment known". Within the Glasgow area the variability within the individual profiles in drumlin and non-drumlin till, as recorded by borelogs and field observation, is considerable. The till is highly variable in matrix colour ranging from bright red (Plate 8) to very black (Plate 9).

Within the till several types of intercalations are found.

The most common are fine sand and silt layers (cf. Chap. 9). Wider and much larger sand and gravel lenses are also common (Bore 2).

BORE 2 Grid Reference: 6385 6431 Surface Elevation: 31.60m O.D.

	m	m
Made Ground	0.76	0.76
Soft, brown silty, sandy Clay with medium/fine Gravel in places	0.95	1.71
Very stiff, brown sandy Till	10.34	12.05
Medium dense to dense, coarse/fine brown Sand with some Gravel	2.52	14.57
Very stiff, brown very sandy Till	4.40	18.97
White Sandstone Bedrock		

Of the 64 borelogs that record sand and gravel lenses (2.4% of borelogs recording till) 39 have only thin bands or lenses less than 1m in thickness and of limited lateral extent. The remaining borelogs record inclusions with an average thickness of 1.75m and a maximum of 5m at 5814 6903 . In a few areas these inclusions in the till could be traced laterally from borehole to borehole. Inclusions of sands and gravels greater than 1m were scattered throughout the till stratum.

Two possible explanations may account for these sand and gravel inclusions:

- 1) the lenses may have been included into the till by erosion of subglacial or overridden proglacial sands and gravels that were redeposited within the till matrix down-ice,
- 2) the lenses may have developed as the result of changes in the subglacial environment allowing cavities or channels to develop and fluvial deposition to occur within them (Carruthers, 1939;

Boulton, 1970, 1974; Shaw, 1972).

Other inclusions, far less commonly found within the till, are laminated clays and silty clays (Bore 3).

BORE 3 Grid Reference: 6264 6599 Surface Elevation: 53.30m O.D.

	m	m
Made Ground	0.67	0.67
Firm, grey Till containing pockets of brownish grey laminated clay	3.04	3.71
Firm, grey Till with occasional sharp boulders	1.52	5.23
Whin Bedrock		

Of the 14 boreholes that record these laminated deposits (0.54% of borelogs recording till) only 4 borelogs reveal inclusions greater than 1m in thickness. A maximum thickness of 3m was recorded at 5646 6817. In most instances these laminated inclusions are undistorted but in two borelogs faulting and warping was noted (5646 6817, 5644 6815). The distribution of these laminated deposits (Fig. 54) is scattered with no obvious pattern. The inclusions were found to exist at no specific level within the till.

These laminated, fine textured, inclusions may be of several possible origins. Firstly, they may be the eroded remnants of proglacial lacustrine deposits incorporated into the till and contorted by the overriding ice sheet. Secondly, they may possibly be remnants of marine clays transported from the Firth of Clyde and thirdly, they may be the result of subglacial melt-out processes similar to those mentioned in explaining the sand and gravel inclusions. No clear explanation will be forthcoming, however, until further examination

of these laminated deposits is carried out.

The upper surface of the till is complex having been affected by glacial, periglacial and post glacial subaerial processes. The till has commonly a weathered appearance, with bright yellow mottling (10 YR 5/6). Many of the included stones are strongly weathered or in various stages of decay. The clay content of this surface till is usually slightly lower than that of the underlying till. At several locations in the study area differences of 20% in clay content occur. These variations in particle size distribution will be discussed later (Chap. 12).

This surface till horizon has an average depth of 1.5m. The variation in the thickness of this deposit across the study area and between crest ridges and hollows cannot be ascertained because of the limited data available. Often this upper horizon is disregarded by boreloggers and is recorded within the general till thickness (pers. comm. W. Anderson, 1973). In addition the top few metres of the till, in much of the study area, has been disturbed or replaced with made ground.

Three possible explanations may account for this surface till:

- 1) The surface till on exposure to the atmosphere may have been subjected to permafrost causing the structure of the till, after thawing, to be loose with many of the fines being washed downwards (Hughes, 1973).
- 2) The till might be an ablation till, which commonly has a coarse texture and a high stone content (Drake, 1968).
- 3) It may be a melt-out till formed above the lodgement till due to subglacial melting during the final stages of glacier stagnation (Boulton, 1970).

These above explanations coupled with post-glacial weathering, which would be intensified in this area due to the heavy annual rainfall and the low permeability of the lower till, could account possibly for this surface till horizon. These explanations may have a combined effect or some may not be applicable or may apply in only a few localities.

Blocks of fresh bedrock are often found within till (60-70% of borelogs recording till). These boulders, some larger than 2m in height, have been presumably eroded from bedrock, transported and later incorporated within the till. In areas of highly shattered bedrock the number of boulders of a similar bedrock type was found to increase rapidly immediately down-ice of the bedrock, indicating the localised nature of till derivation (cf. Chap. 5).

Within drumlin till no boulder pavements or horizons were found and in the sections that were examined no patterns of boulders were observed (cf. Alden, 1905, 1918).

While describing the drift deposits many boreloggers tend to give qualitative assessments of the strength of differing deposits. Terms such as soft, firm, fibrous and strong, mean different things to different people but as an initial guide to material strength these terms may be of some value. In almost all borelogs where considerable thicknesses of till were recorded, a variation in till strength was noted. Strength of till was described as soft or loose in the top zone of the till and very firm or strong in the lower zones. The "top" zone often exceeded 10m in thickness and therefore was probably not an ablation till (cf. Goldthwait, L., 1948).

The above changes in strength were noted in drumlins more than in non-drumlin tills and may be related to variations in stress conditions

during and after till deposition. Till deposited or plastered around a core of till or rock would tend to act as an obstruction to the ice and therefore might be heavily overconsolidated; whereas till deposited at the final stages of glaciation might be less consolidated.

COLOUR VARIATIONS IN THE TILL

In analysing borelog data great care was required when using boreloggers' colour descriptions; for example, brownish till may range from reddish-brown to brownish-grey. Therefore only distinct colour contrasts were used. This information was supplemented with data gathered during field mapping and observations made on sections and temporary exposures. Within the study area two main till types have been distinguished and in the past regarded as chronologically separated (Chap. 3). A distribution map (Fig. 55) based on the above investigations reveals that the boundary line between the two tills, Yoker to Maryhill, as reported by Clough et al. (1925, p.225), is correct in general. In detail, as the map (Fig. 55) shows, the boundary line or zone between the two tills is far less precise.

A third minor till type, reddish-brown till, was noted in a few sections but was less distinguishable from the borelog records (Chap. 5). This third till would appear to be, from its location at Hamilton Hill and Leverndale, an intergrade between the other two tills.

Only two instances were recorded in which red till was found overlying grey/black till. In a section on the stoss end of a drumlin in Maryhill (567 689) red till was observed overlying grey till. The boundary between the two tills although not sharp was distinct. This red till approached the reddish-brown phase in colour but did not appear to be weathered grey till.

In a borelog record taken from the East Barns of Clyde (5050 6940) a red till, 14m in thickness, was noted overlying 2.74m of dark bluey-grey till (Bore 4).

BORE 4 Grid Reference: 5050 6940 Surface Elevation: 21.20m O.D.

	m	m
Made Ground	0.30	0.30
Sand	2.13	2.43
Soft muddy Sand	4.90	7.33
Soft yellow Clay	2.45	9.78
Gravel	0.91	10.69
Red Till	14.00	24.69
Dark blue Till	2.74	27.43
Whin Bedrock		

Previous workers have always interpreted this sequence of red till over grey as evidence either of a readvance of the ice depositing the red over the grey till or of two tills of distinctly different ages and glaciations (Chap. 3). A third, perhaps more likely explanation, especially when no clear-cut boundary between the red and grey till appears to exist, is that of till matrix colour change due to underlying bedrock change. If the bedrock lithology changes in the down-ice direction then a gradual alteration in till texture, matrix colour and stone content might be expected to ensue. In the study area, as noted in Chapter 5, such changes in till stone content were observed. It would therefore seem possible that the colour changes noted in the till may have resulted from this process.

A further explanation may also account for this two till sequence. If, at final stagnation of the ice, the basal dirt layers were dep-

osited in sequence from the bottom of the glacier upwards the lowest dirt layers would be deposited first. These layers, being the most recently derived, might be expected to contain material that was highly localised in origin whereas higher layers would contain material derived from farther up-ice. With the higher layers being deposited on top of the lower layers a similar sequence, to that noted above, might be developed (cf. Boulton, 1970^b, p.235).

In three instances, at 5620 6885, 6026 6259 and 5066 6822 borelogs record "blue clay with stones" overlying red till (Bore 5).

BORE 5 Grid Reference: 5066 6822 Surface Elevation: 4.00m O.D.

	m	m
Made Ground	0.45	0.45
Grey/blue Clay with stones	1.10	1.55
Red Till with occasional boulders	13.60	15.15
Dark sandy brown Till	7.01	22.16
Sandstone Bedrock		

It is possible that these blue clay deposits are not till but marine clays transported and deposited inland from the Firth of Clyde. Further examination of the blue clays is required before a satisfactory explanation can be proposed.

Several instances occur where either red or grey till was found in isolated locations (Fig. 55). At Summerston, during excavations by contractors, a "dyke" of grey/black till was found within red till. The "dyke" was approximately 5m wide at ground surface level becoming slightly wider with depth. Whether this grey till extended down to bedrock was not established. Bedrock in this area was heavily shattered and near the surface. A dolerite dyke is known to extend into this

area and there may be other dykes not mapped. It is possible that this grey till, which was dolerite rich, may have been derived from the erosion of these dykes.

In parts of Parkhead, Polmadie and Carntyne, red till has been encountered in several borelogs and was mentioned by Clough et al. (1925, p.224). This red till may be the result possibly of either glacial transport and redeposition or matrix colour changes in the till due to the glacial erosion of red sandstones, siltstones and marls of the Carboniferous Barren Red Measures (Clough et al., 1925, p.3).

TILL THICKNESS AND THE RELATION OF TILL TO BEDROCK

From the Drift Thickness map (Fig. 50) it can be seen that the till in central Glasgow is comparatively thin. The thickness of till beneath drumlins (Fig. 91), calculated by subtracting the drumlin crest height of a sample of drumlins (34) from the total till thickness under the drumlin crest, gave an average of 6m of till with a minimum value of 1.0m and a maximum of 20.0m (cf. Trenhaile, 1975). The average thickness of till between the drumlins was 4m, calculated from a random sample of 50 points in north-central Glasgow. Individual values of inter-drumlin till thickness ranged from under 0.5m to 10m (cf. Piskin & Bergstrom, 1967; Flint, 1971, p.150). These values of till thickness, in the inter-drumlin hollows, include layers of made ground that could not be easily distinguished from till. However since till has often been replaced by made ground, it was felt that these approximate figures were not unreasonable.

The thinness of till in the inter-drumlin hollows may be the result of several processes, namely:

- 1) Till may have been deposited in only limited thicknesses in these

inter-drumlin hollows due to unknown glaciological factors perhaps related to drumlin formation.

- b) Till may have been deposited (or absent) in these areas and may have been subsequently eroded (or deposited) as the drumlins developed and ice was deflected around them (Goldthwait, R.P., 1974, p.183).

How significant the difference is in till thickness between the inter-drumlin hollows and the till underlying the drumlins must be investigated in greater detail on a larger sample when more suitable borelog information becomes available.

Within the buried channel, beneath the infilling deposits, till is found lying directly on bedrock with an average thickness of 2.5m. A maximum thickness of 8.4m was recorded at 5759 6424 in Kinning Park.

The thickness of till within drumlins is discussed in the Drumlin section (see below).

Before discussing each cross-section in detail a broad indication of the till/bedrock relationship can be observed by comparing the Drift Thickness map (Fig. 50) with the Rockhead map (Fig. 49). In general the gross relief of the bedrock topography has been subdued due to the dominance of glacial deposition over erosion but, as will be discussed later, many of the drumlins reflect bedrock control. Where bedrock highs occur the till may be in some instances thinner (e.g. 5640 6940) and in other places thicker (e.g. 5820 6900) than the surrounding till. Similarly in areas of marked bedrock lows the till may not be as thick as might be expected. (e.g. 6260 6640) (cf. Nobles & Weertman, 1971). In examining the two maps no simple and general relationship can be found to exist between the overlying till and bedrock topography (Flint, 1971, p.154).

Investigations carried out on drumlin morphology (Chap. 10) in which the till thickness beneath a sample of drumlins (34) was correlated with bedrock slope, in both the up-ice and down-ice directions, revealed no significant correlation ($R=-0.197$) between these variables. This statistical relationship, which will be discussed in detail later, does help to substantiate the above conclusions.

CROSS-SECTIONS

All cross-sections discussed in this thesis were constructed, where possible, using bores located in straight lines. The location of all cross-sections in the thesis are shown in Figure 56. Appropriate vertical planes were selected and bores were projected into them from a zone approximately 200m wide. The borelog data was supplemented with information derived from seismic surveys (Monkland and Renfrew Motorways). Borelogs encountered with marked horizontal variations in strata, in a direction normal to the orientation of the cross-section plane, were discarded, in order to avoid producing a misleading representation of the strata (Sissons, 1969).

The cross-sections drawn for Bellahouston, Ibrox, Plantation and Scotland Street are all within or on the edges of the Clyde buried channel. Because of this location the additional problem of till erosion by water action must be considered. As with all forms of erosion, fluvial processes have been selective. Exactly how much till has been removed or washed away cannot be estimated but what till remains may possibly be regarded as the remnants of at least a thicker, if not more extensive cover of till.

Bellahouston Cross-section (Fig. 57)

This cross-section lies along the southern edge of the Clyde

buried channel. The till, although thin, lies thickest on the bedrock slopes facing down-ice and within a bedrock hollow, indicated at point A. The sea in this area, whose former presence is revealed by the raised beaches, may have had an erosive effect on the underlying till. There are indications from evidence of flat-topped drumlins (see below) that marine planation may have removed some of the upper horizons of the till in areas where conditions were suitable for such a process to operate (Jardine & Moislely, 1967).

Ibrox Cross-section (Fig. 58)

This continuation of the above cross-section shows further till thinning, at point B, as the bedrock slope rises facing in the up-ice direction. To the east of point B, in the lee of the bedrock high, the till continues to increase in thickness. Beyond point C and to the east the till thins on entering the southern section of a large deep bend of the buried channel (Fig. 49).

The above apparent relationship between bedrock topography and till thickness cover from point A to the east of point B exemplifies the theoretical ideal relationship between a thin till deposited across bedrock rises transverse to the general direction of ice movement (Nobles & Weertman, 1971).

Why the till should thin out in the section beyond point C where the bedrock aspect is down-ice, the slope gradual and where theoretically a considerable thickness of till might be expected to exist is problematical. If fluvial erosion has caused this thinning in the till, it would imply that water impinged on this channel side to a greater degree than on the opposite side of the channel, at point D, where the till is much thicker. Alternatively the thinning of the

till may be a further example of the breakdown of the theoretical relationship proposed by Nobles & Weertman (1971).

Plantation Cross-section (Fig. 59)

This cross-section is the continuation of the previous cross-section revealing the continued thinning of the till down the side of the buried channel.

Scotland Street Cross-section (Fig. 60)

On the opposite eastern channel side the till rapidly increases in thickness to over 15m. The Drift Thickness (Fig. 50) and Rockhead maps (Fig. 49) show that at this location, south of the Kingston Bridge (580 649), a bedrock spur protrudes to the north. The channel appears to meander towards the north in a tight bend before again curving southwards into the Laurieston district. This bedrock spur is therefore apparently narrow and steep sided. At point E the till appears to thin very rapidly from greater than 15m thick to less than 1m thick in 115m. Such a rapid change in till thickness is not characteristic of glacial deposition and tends to suggest the possible influence of an erosive process. The relationship of the till to this bedrock spur is complicated at this point by the unknown effects of fluvial and glacial erosion within the buried channel.

Royston/Milnbank Cross-section (Fig. 61)

This cross-section lies in a hollow between two large and elongate drumlins. It parallels the direction of ice movement and, in part, passes through the side edge of one of the drumlins. The section reveals two features of interest. Firstly, the drumlin (G) and the surrounding till appear to be unaffected by the almost horizontal

underlying bedrock surface; and secondly, the till thickness therefore must presumably vary in accordance only with changes in glaciological factors. It is the change in till thickness illustrated from point F to G to H that must be explained before a reasonable theory of drumlin origin can be developed.

Blackhill/Riddrie Cross-section (Fig. 62)

Situated in a similar location to the previous cross-sections this section cuts across the stoss end of a drumlin as is revealed by the considerable thicknesses of till. However as the bedrock rises its influence would appear to have exerted an increasing effect on ice velocity and till deposition, causing both to be reduced, resulting in the till beginning to thin in the down-ice direction.

Milncroft Cross-section (Fig. 63)

This cross-section lies in a wide inter-drumlin area and reveals marked variations in till thickness and bedrock topography. At point J a small plug of dolerite stands up above the general bedrock topography and is covered by a thin layer of till. Down-ice of point J a thick layer of surface peat overlies till. The variations in bedrock relief would appear to be closely related to the differential erosion of the less resistant sandstones and shales compared with the fine-grained, more resistant, dolerite. The dolerite plug appears to have acted as a *smallroche moutonnée*. Later, peat developed in the lee hollow left by the glacial plucking.

Smithycroft/Gartcraig Cross-section (Fig. 64)

This cross-section has been drawn sub-parallel to the direction of ice flow crossing the stoss end of a drumlin and then obliquely

crossing a wide inter-drumlin hollow. At point K a small groove or depression around the stoss end of the drumlin is revealed and at point M the much wider inter-drumlin hollow can be observed. Bedrock would appear to have little influence on the till thickness changes except at point N where a plug of dolerite rises above the general bedrock relief and is covered by a thin layer of till.

Lying within an area of large drumlins (Fig. 4) this thinly covered dolerite boss, an ideal nucleus around which till could have accumulated, appears anomalous. Either till accumulated around this boss and has been since removed or conditions in the inter-drumlin hollow, in which the boss is situated, were not suitable for such thick till accumulation.

DRUMLINS

One of the major objectives behind the collection and plotting of borelog data has been to examine the nature of the internal material composing the drumlins and the relationship between the drumlins and the bedrock topography.

DRUMLIN DRIFT THICKNESS

Since the Drift Thickness map (Fig. 50) has been drawn in relation to both the ground surface and bedrock surface topography most of the drumlins that are little affected by bedrock control (i.e. have no rock core) can be readily identified. Many of the drumlins in the study area, unfortunately, have scanty borelog coverage. Within central Glasgow, however 55 drumlins have sufficient borelog coverage to allow, at least, tentative conclusions to be drawn on drift thickness and its relationship to drumlin form, size and bedrock slope (Chap. 10).

The average drift thickness for drumlins, calculated directly

beneath the drumlin crests, is in the range of 13 to 16m (Fig. 91). At Port Dundas (590 668) a drift thickness of 42m was recorded beneath the drumlin crest which was 24m above the surrounding inter-drumlin hollow.

Although evidence of drumlin drift thickness is not available for a large part of the study area an indication of its variability may be gained from a comparison of drift thickness with variation of drumlin crest height (Crest height was measured as the difference in height between the drumlin crest and the surrounding inter-drumlin hollows). In an analysis of 159 drumlins, a standard deviation of ± 7.7 m was noted in drumlin crest height. From this evidence a similar variation in drumlin drift thickness can be presumably expected but no large areas of thin or thick drumlin drift would appear to exist.

Several cross-sections have been drawn that illustrate the changing drift thickness within drumlins and the relationship of these drumlins to the underlying bedrock topography (Figs. 61,62,64,65,66,67). In these cross-sections the variation in drift thickness within the drumlin appears to bear little general relationship to the changes in bedrock topography: for example, in Figure 61 the bedrock is horizontal, in Figure 62 the bedrock inclines in an up-ice direction and in Figure 64 a bedrock hollow was located beneath a drumlin. In all these examples the drift does not appear to thin over bedrock highs or increase in thickness over bedrock lows (cf. Nobles & Weertman, 1971). Rather, drift thickness appears to vary in relation to the form of the drumlin that in turn is related to a complex inter-relationship of glaciological and non-glaciological factors. However exceptions do occur as will be discussed below.

The relationship of some of these non-glaciological factors such

as ground surface slope, bedrock slope and bedrock control to drumlin drift thickness will be discussed later (Chap. 10). No statistical correlations of these factors with drumlin drift thickness were found except between drumlin drift thickness and density. A correlation of -0.229 was found which, being only at the 80% level of significance, is perhaps more indicative of a possible relationship than significant (Cole & King, 1968). This relationship would tend to indicate that as drumlin drift thickness increases drumlin density decreases and vice versa.

THE INTERNAL COMPOSITION OF DRUMLINS

Much of the evidence gathered from borelog data, already discussed in the section on inter-drumlin till, is directly applicable to the material found within the Glasgow drumlins. In only a few important exceptions, noted below, was material other than till found within drumlins. In all borelogs examined in which till was recorded (2,572) no distinguishable difference was noted between the texture, colour, stone content, intercalations and sub till deposits of the drumlin till on the one hand and the inter-drumlin till on the other.

Within any one drumlin no stone or boulder pavements could be recognised from the borelog evidence nor were large horizontal layers of sands or laminated clays detected.

Strength variations were noted between upper and lower zones within the drumlin till. In many instances the till strength was recorded as high, strong or firm in the lower zone and weak, soft and loose in the upper zone (cf. Goldthwait, L., 1948). This upper zone descended into the till 5 to 10m from the ground surface.

Depths greater than 1.5m tend to preclude weathering as an

explanation for this reduced till strength (Mitchell & Jarvis, 1956). This upper till may be either an ablation till (Drake, 1968, 1971) or till that has suffered consolidation by the ice overburden pressures to a lesser degree than the till at greater depths. This second explanation may have important implications regarding drumlin formation and development (Chap. 14).

At Garscadden House (Fig. 68), Cloberhill (Fig. 69) and Maryhill (Fig. 67) cross-sections within drumlins revealed considerable thicknesses of sands and gravels beneath the till (Bore 6). The possible origins of sub-till deposits will be discussed later but their existence beneath drumlins may be of considerable significance in relation to the actual siting of these specific drumlins (Chap. 14).

BORE 6 Grid Reference: 6031 6608 Surface Elevation: 48.80m O.D.

	m	m
Made Ground	0.58	0.58
Brown sandy silty Clay	0.82	1.40
Brown sandy Till	2.56	3.96
Dark grey Till	1.25	5.21
Sand	0.28	5.49
Gravel	2.02	7.51
Laminated Sandstone Bedrock		

THE RELATIONSHIP OF BEDROCK TOPOGRAPHY TO DRUMLIN

LOCATION AND FORM

A common feature of drumlin fields is the large number of drumlins that have rock cores (Chamberlin, 1894; Flint, 1957, 1971; Muller, 1963). Of 34 drumlins analysed in central Glasgow 16 had significant bedrock highs. "Significant" was defined as bedrock elevations rising

steeply within or very close to a drumlin to form a knob at least 5m above the surrounding bedrock elevation. An example of bedrock control, in the form of a bedrock high at the stoss end of a drumlin, can be seen at Lambhill (581 690).

Several drumlins, in contrast to those above, are found overlying bedrock hollows, for example at Jordanhill (537 683) and Maryhill (567 693) (Fig. 67). The two cross-sections at Maryhill illustrate a bedrock rise up-ice from the bedrock hollow and underlying the stoss-end of the drumlin. Other examples of this bedrock rise and hollow beneath a drumlin occur at Milton (598 694) and Dowanhill (562 674).

The influence exerted by bedrock topography may be so great as to cause some drumlins to be orientated parallel to the grain or strike of the bedrock. For example, at Knightswood (536 694) a drumlin is located above a rising bedrock slope that finally crops out in a large north-south ridge. This ridge lies in the lee of the drumlin. The ridge slope appears to have caused the drumlin, during formation, to have been orientated obliquely to the general ice movement probably due to the local influence of the bedrock ridge on localised ice movements.

Drumlins can be seen to deviate from the general down-ice orientation where large bedrock outcrops such as Springburn Park or Necropolis Hill have acted as deflectors of ice movement. Examples are the two drumlins at Springburn (602 690 and 602 683).

For Darnley (530 590) detailed maps based on a large number of borelogs were prepared to illustrate the relationship between surface (drumlin) topography (Fig. 70a) and bedrock topography (Fig. 70b). By placing the surface topography map on the bedrock map it can be seen that a relationship would appear to exist between the location

of the drumlin crests and bedrock highs. Where a drumlin crest occurs a bedrock high is often located either just up-ice or down-ice of the crest. It is difficult to determine which bedrock high any specific drumlin crest is related to. A similar example of the relationship between a drumlin crest and bedrock high is shown in a cross-section through a drumlin at Maryhill (Fig. 67).

Two drift-filled hollows in the bedrock were found lying oblique to the direction of ice movement but were not reflected in the ground surface topography. Other hollows, in both the bedrock and ground surface, were noted existing immediately up-ice of the stoss-end of several drumlins. An example of this type of feature is the hollow followed, in part, by the present Brock Burn. Similar hollows exist on the up-ice side of Necropolis Hill and Springburn Park. In many instances, observed during field mapping and in later examination of the Rockhead map, a hollow was found to exist only in the surface drift deposits.

In discussing the geomorphology of central Edinburgh, Sissons (1971, p.188) has noted similar features around the Castle Rock and Calton Hill crag and tails. Such hollows, up-ice of both crag and tails and drumlins, may have been produced by glacial erosion caused by deflection of ice around an obstruction, by subglacial meltwater flowing under pressure around an obstruction, or by a combination of both processes (cf. Nye, 1973, p.192).

CROSS PROFILE ASYMMETRY

Asymmetric cross profiles were noted in several drumlins during field mapping. Drumlins at Yorkhill (562 661), Rottenrow (598 656) (Fig. 66), Blythswood Square (584 658), Partick (557 670) and Wellfield Street (708 679) exhibit this asymmetry with drumlin crest height

differences of 21m measured between opposite sides of the drumlin. Examination of the Rockhead map revealed that all these drumlins are on steep bedrock slopes transverse to the direction of ice movement.

These asymmetric cross profiles (Figs. 65, 66) may be the result of either till movement down the steep bedrock slopes or drumlin formation at the top of the bedrock slope and deposition down the steep slope. Since no slope movement scars or slips were noted the former explanation seems unlikely to have been the main cause of asymmetry. If the latter explanation is accepted, it must be explained why the drumlin crest and long axis lies normal to the bedrock ridge top and not to the bedrock slope.

DRUMLIN DISTRIBUTION IN RELATION TO BEDROCK TOPOGRAPHY

Rather than discuss where drumlins are located over the whole study area it is perhaps more pertinent to mention the areas where no drumlins are found. As already mentioned when discussing the Kelvin valley, south of Dawsholm Park, no drumlins are present within this deep narrow bedrock hollow. Similarly no drumlins occur within the much deeper bedrock hollow of the Clyde (cf. Wright, H.E., 1973) nor in the large depression around Possil Loch (585 700). At Springburn Park where in the up-ice direction bedrock elevation falls approximately 60m within 200m from the crest of the rock drumlin, no drumlins exist in this up-ice area where ice diversion would have been perhaps greatest. Around Yoker, north of the Clyde, very few drumlins were observed although several buried drumlins are known to exist in the area. This scarcity of drumlins in the Yoker district may be explained by the possible existence of a westward continuation of the Clyde buried channel into this area, where it may also intersect the bedrock channel of the combined Black and White Cart rivers. From the evidence available and from

from work in Minnesota (Schneider, 1961; Cushing, 1967; Wright, H.E., 1973) and Illinois (Horberg, 1945; Fiskin & Bergstrom, 1967) it seems reasonable to hypothesise that where deep bedrock channels or linked hollows exist and had been probably utilised either as subglacial melt-water routes or passages for rapid ice movement during drumlin formation phases, no drumlins or thick till deposits are found in situ.

BURIED DRUMLINS

During deglaciation, as the sea flooded into the area, several drumlins, lying close to the present Clyde, were submerged in raised beach deposits. Examples of "drowned" drumlin fields, at the present time, can be seen in Strangford Lough, Ireland and in Boston harbour, U.S.A.

During a drilling programme at Danes Drive (532 679), in the Scotstounhill district, a number of boreholes were sunk in a roughly rectangular pattern (Fig. 71) revealing a small buried drumlin. The writer was present during the drilling of some of these boreholes and the exact nature of the deposits removed during drilling was confirmed. Several cross-sections were drawn (Fig. 72 a,b,c,d,e,) revealing the buried drumlin and the surrounding raised beach deposits.

At Campbellfield Street (611 645), in the Gallowgate district, another buried drumlin was discovered from examination of borehole evidence and foundation excavations. Using 43 small foundation pits (1-2m deep) that revealed both the upper drumlin surface and the overlying raised beach deposits, the junction between these two deposits was accurately levelled at the 4 corners of each pit (except in several instances where the junction was not located and therefore depths to till could not be recorded) (Plate 9 a,b,c,d,). The levelling was accurate to within 0.01m and was double checked. From these levelled

points a map (Fig. 73) was drawn of the surface contours of the till lying beneath the raised beach deposits. This map revealed a flat-topped drumlin.

Slightly to the west, between Campbellfield Street and Tylefield Street, several other boreholes were sunk revealing the stoss end of the same buried drumlin. A map of the depth to the surface of the drumlin till (Fig. 74) was drawn from the borelog data. Several cross-sections were drawn (Figs. 75 a,b,c,d,e) revealing the drumlin outline and overlying deposits.

Other buried drumlins or suspected buried drumlins have been detected from borelog information and examination of the Drift Thickness map, namely, at Scotstoun (521 662) and (525 681), Shiels (521 666), Golspie Street (551 654), Finnieston (573 653), Cranston Hill (576 656), Canmore Street (626 636) and Merklands (549 664).

It is difficult to assess the size of these buried drumlins from the borelog information available but in the main these drumlins appear to be small, less than 300m long, 100m wide and 5m high. In only one instance, at Campbellfield Street, was a drumlin noted with a distinct flat top. This flat top may indicate planation by the sea while a beach was being developed across the top of the drumlin.

The discovery of these buried drumlins reveals that within the bedrock depression of the Clyde, drumlins were formed closer to the deep buried Clyde channel than surface geomorphic evidence indicates (Fig. 4).

SUB TILL DEPOSITS

Within the Glasgow area the deposits underlying till are varied in both composition and probable origin. The deposits lie directly on bedrock and can be subdivided into coarse-textured and fine-textured

sequences. Since glacial processes have acted across the surface of these deposits, it would seem probable that the deposits have been modified by glacial erosion and perhaps previously by other agencies.

SANDS AND GRAVELS

Beneath the till and scattered throughout the study area occur deposits described as loose sand, sands and gravels, gravelly sand and sand with boulders (Bore 6). The distribution of these deposits reveals no significant pattern or lineation (Fig. 54). On comparison with the Rockhead map, however, it can be seen that of the 27 bores recording sands and gravels beneath the till, 14 were located in bedrock lows, 10 on bedrock slopes of varying steepness and 3 could not be described due to lack of surrounding borelog evidence.

Of the bores located in the bedrock hollows several were in wide hollows parallel to the direction of the ice movement (e.g. 5522 6901). Several were located on the margins and within bedrock channels that appear to steeply descend into the buried channels of the Kelvin (5671 6685) and Clyde (5812 6545). Others were located in deep, partly enclosed hollows (e.g. 6274 6694). Bores also located sands and gravels in a bedrock hollow lying beneath a large drumlin in Maryhill (5671 6835) (Fig. 67) These sub till deposits, as shown in Figure 67, lie within a bedrock hollow in the lee of a bedrock rise at the stoss end of the drumlin and on a bedrock rise close to the drumlin crest.

Sands and gravels were found on slopes transverse to (6231 6436) and parallel to the movement of the ice (5979 6888). Some of these bedrock slopes appear to be fairly gentle ($< 10^{\circ}$) but in a few cases very steep slopes ($> 20^{\circ}$) were encountered (5848 6643).

The thickness of the sands and gravels ranged from 0.1m (6079 6510) to 7m (5671 6935), with an average thickness of 1.84m (S.D. = 1.68m). In only three cases did the thickness exceed 3m. At Maryhill (5671 6935) two bores recorded thicknesses of 6m and 7m beneath a drumlin. At Dalness Avenue in Shettleston (6405 6364) a bore recorded over 5m of sands and gravels beneath till at the stoss end of a drumlin.

These coarse-textured sub till deposits reveal no form of distortion or faulting. In logging a borehole containing coarse material however it would be difficult perhaps to detect such sedimentary structures. Also, sedimentary structures may not develop so easily in this type of material because of its large grain size and low packing density. The absence of these structures therefore is not necessarily evidence that these sub till deposits were not contorted by the movement and pressure of the ice.

Since the above collated evidence is only part of a sample of the drift taken from the whole study area any hypotheses created to explain these deposits must remain tentative until further evidence is available.

From the areal distribution of these deposits (Fig. 54) no pattern can be isolated that would suggest any particular method of formation namely, a linear or arcuate pattern. However the relationship of the deposits to the bedrock topography would indicate that these deposits may be found in hollows as well as on bedrock slopes and ridge tops. The deposits may be the result of 1) proglacial or 2) subglacial deposition.

1) During a previous retreat of the ice front in this area it is possible that large spreads of outwash material may have been deposited within a proglacial zone. Proglacial meltwater channels may have cut

across this area and become entrenched into the outwash.

With readvance of the ice either these proglacial sands and gravels would have become buried beneath till or they would have been eroded and possibly redeposited. Although this explanation may account for some of these sub till deposits and for their location on bedrock highs, as well as in depressions, it is not totally satisfactory.

Firstly, although proglacial deposits may have existed prior to the final glaciation it would seem unlikely that such deposits would lie directly on bedrock and not on drift of an earlier glaciation. Secondly, it seems unlikely that during a preceding deglaciation, outwash spreads would cover parts of the study area when after the final deglaciation there is such a scarcity of these deposits.

Proglacial meltwater channels however, if they had a large discharge or high velocity, may have been capable of cutting down to bedrock through the drift deposits left by an earlier glaciation. The deposits left by these meltwater streams would be characteristically composed of sands and gravels. The channels, in many parts along their course, would probably have little relationship to the underlying bedrock (Price, 1960; Clapperton, 1969). During a glacial readvance these deposits would probably be eroded and only remnants left. At Barlanark (Fig. 76) a meltwater channel has been located by borelogs showing a relationship to the surrounding till and bedrock similar to that hypothesised above.

2) Subglacial deposition of sands and gravels may occur as the result of two processes namely, melt-out (Boulton, 1970, 1972) and meltwater deposition (Mannerfelt, 1945; Carruthers, 1953; Sissons, 1961, 1967; Shaw, 1972). Subglacial melt-out of basal debris occurs when the

basal ice reaches pressure melting point and material is released from the ice. Subglacial meltwater deposition is far less well understood but appears to occur within discrete channels in which the water, either under hydrostatic pressure or not, flows in general towards the margin of the ice. In this latter case deposition occurs within the stream channel in a manner similar to deposition within a subaerial stream (Embleton & King, 1968; Flint, 1971).

Both processes are controlled by glaciological and bedrock topographic factors, one factor taking precedence over the other at differing times and at different points across the bed of the glacier. Therefore, although in most instances meltwater streams will probably flow within bedrock hollows, these streams may flow across bedrock ridges due to the influence of glaciological factors. It is therefore possible that sands and gravels, the result of meltwater deposition, can be expected to occur in bedrock hollows and on bedrock slopes and ridge tops (e.g. Maryhill, Fig. 67).

The following processes could have occurred during the burial of these deposits firstly, the erosion of the sands and gravels and secondly, the squeezing and contorting of sub till deposits.

Since the original distribution and thickness of the sands and gravels cannot be ascertained any evidence of erosion must be speculative. Alternatively the scattered nature of the deposits and their variability in thickness might be used as an argument for evidence of erosion but no facts have emerged from the borelogs to substantiate this suggestion.

The evidence for distortion and squeezing of these sands and gravels is equally inconclusive and is only a possibility.

Both processes are likely to occur when sediments are overridden

by ice but until further evidence is available these processes must remain only possibilities.

CLAYS AND SILTS

Several borelogs record deposits of clays, silts and silty clays beneath till (Bore 7). These sub till deposits are distributed throughout the study area (Fig. 54) in small patches, none of which are linked.

BORE 7 Grid Reference: 6337 6660 Surface Elevation: 76.20m O.D.

	m	m
Made Ground	0.91	0.91
Soft, muddy Clay	1.07	1.98
Clayey Sand	0.34	2.32
Grey Till	3.21	5.53
Laminated Clay with traces of silt	2.44	7.97
Shattered Sandstone Bedrock		

From the Rockhead map (Fig. 49) it can be noted that of the 24 bores recording these fine-textured deposits, 17 were found within bedrock hollows (e.g. 6339 6658), 5 were located on the sides and on top of bedrock ridges (e.g. 6252 6654) and the remaining 2 could not be described due to the lack of surrounding borelog evidence. Several of these sub till deposits were located within bedrock "valleys" that descend into the Clyde buried channel (e.g. 5306 6541). In a long bedrock hollow between two large drumlins and parallel to the direction of ice movement a patch of laminated clays was located (e.g. 6338 6666). Another small patch was located at 5824 6628 on the slopes of a steep bedrock ridge.

These fine-textured deposits vary in thickness from 0.3m near Knightsbridge Street (5392 6894) to 3.3m at Fielden Street (6146 6434)

with an average thickness of 0.91m (S.D. = 0.74m). In only two cases were thicknesses greater than 2.0m recorded, at 6146 6434 and 6339 6658 (Smithcroft Bridge).

At 5814 6573 a bore recorded a laminated silty clay in which the laminae were reported as being "distorted". No other borelog contained such a description although when dealing with thin strata boreloggers might not record or observe such structures.

For reasons of sample size, already noted when discussing the sub till sands and gravels, any explanatory hypothesis must remain tentative until further evidence accrues.

The areal distribution of these fine-textured deposits (Fig. 54) is of no aid in understanding their origin namely, no linear or major areal spreads. The distribution of the deposits in relation to the bedrock surface would suggest several possibilities. Firstly, the deposits tend to be found in bedrock hollows where perhaps they have been sheltered from the erosive action of the ice. Secondly, the bedrock slope and crest sites may be explained either by a process of re-deposition or by a once much wider and thicker spread of the laminated sediments, completely covering at least the local bedrock topography.

Clays and silts are likely to have been deposited in still or almost still water where sources of coarse material were at some distance. It therefore seems unlikely that a subglacial environment where coarse material dominates would be a suitable location for this form of deposition. These deposits may have originated from three sources where fine sediments might be laminated suggesting differential sedimentation: 1) marine environment 2) proglacial ice-dammed lake 3) proglacial ponds and streams.

1) It is not unlikely that marine clays removed from the bed of the

Firth of Clyde were transported inland and redeposited (n.b. Clava beds, Sissons, 1967, p.196). Previous workers have observed marine shells within the till (Chap. 3) and suggested the same process of erosion and redeposition. Such redeposited material would be scattered over a wide area and have little relationship, in final location, to the underlying bedrock.

2) The proglacial sources of these clays may range from small ponds and lakes to temporary lakes created by ice damming. As already mentioned (Chap. 3) the hypothesis that a large proglacial lake formed in the Glasgow area has been suggested several times, but no evidence in the form of extensive deposits has ever been discovered to substantiate the existence of this lake. Two arguments against these fine sediments being the remnants of this ice-dammed lake are: 1) that a more widespread occurrence of such sediments would have been noted in the analysis of 6,219 boreholes (2,572 in till) and 2) that it seems unlikely that such lake deposits would have accumulated directly on bedrock, especially in an area where previous glacial deposits or weathered rock probably existed. However such an origin cannot be totally discounted on the basis of the evidence available.

3) The evidence presented reveals that these sediments are often confined to bedrock hollows and at Smithycroft were traceable within a hollow for 600m. It is possible that these sediments may have formed subaerially within the proglacial zone and were later covered by till as the ice advanced over these sites. This interpretation like all others for the sub till deposits does not explain 1) why these sediments are, in the main, un-distorted and occasionally laminate and 2) how such sediments can occur on bedrock slopes and ridge crests and not have been removed by glacial erosion.

Until further evidence and direct examination of both types of sub till deposits is possible these explanations must be combined as the most likely group of processes that can explain the origin of these deposits.

BURIED CHANNELS OF THE GLASGOW AREA AND IN PARTICULAR THE
BURIED CHANNEL OF THE CLYDE AND ITS INFILLING DEPOSITS

In and around Glasgow several deep bedrock trenches are known to exist. Most of these trenches are now buried beneath terrestrial drift but a few extend seaward beneath estuarine and marine deposits.

Within the city deep trenches are known to underlie the rivers Black and White Cart, the River Clyde between Shiels in the west and Dalmarnock in the east, and along a line from Drumry to Bearsden connecting eastwards to a trench beneath the River Kelvin in the Kirkintilloch area (Bennie, 1868; Croll, 1870; Clough et al., 1925). Other trenches have been located in the Wishaw/Chapelhall area (Dick, 1867) and in the Bonnington area south of Lanark (Stark, 1902), both with possible connections to the Clyde drainage system. Farther east deep trenches are known to exist in the Carron valley (Cadell, 1913; Sissons, 1969), in the lower Devon valley (Soons, 1960) and farther east in the Forth estuary.

Several of these trenches do not appear to be coincident with either bedrock trends or the present drainage system. In particular, if, as has been suggested (Chap. 3), a connection does exist between the Kelvin and Carron trenches then a major unconformable channel system lies across Central Scotland (Sissons, 1969, 1974).

The trenches that are known to exist in west central Scotland do not appear to have an overall pattern or network. This is in marked

contrast to the distinctive patterns found in other parts of the world where similar trenches are known (Woodland, 1970; Wright, H.E., 1973). In East Anglia and Minnesota buried channels with dendritic drainage patterns extending back from the former ice margins have been mapped.

In the past a pre-glacial origin was suggested for the buried channels of the Clyde, Kelvin and Cart rivers (Clough et al., 1925; George, 1958). It was suggested and illustrated in a rockhead map (Clough et al., 1925)(Fig. 51) that the Clyde and Cart flowed to the north of their present courses, in the Shiels/Yoker area, to join the Bearsden channel, the westward extension of the Kelvin channel, near Drumry. From Drumry it was proposed that a much deeper channel, the confluent of these other channels, flowed west to join the Clyde estuary around Bowling (Bennie, 1868; Clough et al., 1925). The evidence for this hypothesis is based on a few very deep bores reported by Bennie. However crucial areas such as the proposed junction of the Clyde buried channel with the Bearsden/Kelvin buried channel and the westward extension of this channel to Bowling lack borehole evidence.

In discussing deep trenches in the upper Forth valley, Sissons (1969, 1974) argued for a subglacial origin to explain the Carron buried channel. He referred to large thicknesses of sands extending along a considerable length of the channel and resting directly on bedrock and overlain by till. The bottom of the channel is well below sea-level and thus it is unlikely, from the evidence presented, that the channel is of subaerial origin (Sissons, 1969, p.26). Other trenches that are exceptionally deep and enclosed such as the lower Devon may have been produced by glacial erosion (Soons, 1960; Sissons, 1967; Eden et al., 1969).

Sissons (1969, p.26) has likened these buried channels to the

tunneldale of eastern Denmark and rinnentäler of northern Germany (Ussing, 1903; Madsen et al., 1928; Woldstedt, 1952; Hansen, 1971). These channels, formed by large subglacial streams flowing, probably at high speed, under hydrostatic pressure, have characteristically steep sides that are often precipitous, with a very slight sinuosity and a highly variable long profile. Similar channels have been described in East Anglia (Boswell, 1914; Woodland, 1970), and various other parts of England. In the U.S.A. channels of a probable similar origin have been recognised extending south from Lakes Superior and Michigan (Horberg, 1950; Cushing, 1964; Piskin & Bergstrom, 1967; Wright, H.E., 1973).

DESCRIPTION OF THE BURIED CHANNEL OF THE CLYDE

This description of the course of the buried channel is restricted to those areas best covered by borelog data. However to the west and north-west of Scotstoun West Station (522 679) a much wider and shallower channel may exist (Fig. 49). This channel may be the one described by Clough et al., (1925) that joins the Clyde to the Bearsden/Kelvin channel around Drumry. In drawing a rockhead map Clough et al. indicated that this "linking" channel extended to depths of -30m O.D. at its base but no evidence within the surrounding area has since substantiated such depths (Fig. 51).

Eastwards from Scotstoun West Station, where a borehole recorded bedrock at -18m O.D., the main buried channel stretches along the route of the present River Clyde to Shieldhall Timber Depot (532 668), where bedrock was reached at -28m O.D.

In the area of the King George V Dock a long, narrow, steep-sided bedrock ridge was located (530 665) to the south-west of the main buried channel. This ridge (the Renfrew Bank) is composed of sandstone

and is reported to be flanked on either side by considerable thicknesses of soft shale (Clough et al., 1925, p.216). As well as the main channel of the Clyde to the north-east, a possible bedrock channel is detectable to the south-west and south of the ridge where depths of -25m O.D. (528 662) have been recorded (Fig. 77). This more southerly buried channel, as revealed on the Rockhead map (Fig. 49), may swing eastwards into the Elder Park/Drumoyne area (542 652) where it rises to a bedrock col at around -5m O.D. (539 651) and then descends back to -21m O.D. within 200m at Mallaig Road (541 652). This channel may then join the main channel in the Govan area.

The main channel curves south from Shieldhall into Linthouse where rockhead was reached at -27m O.D. (Fig. 78). The channel continues beneath Govan towards the southern edge of Prince's Docks. This section of the channel is joined from the north by two bedrock gullies. A gully, located to the east of Meadowside Quay (554 662), descends to join the channel at a depth to bedrock of -20m O.D. (Fig. 49). However this depression does not extend back into the bedrock to the north-west and may have been cut partly in rock and partly in drift. The other gully appears to be related directly to the lower Kelvin river valley, joining the buried channel of the Clyde (557 660) at a depth to rockhead of -26m O.D. This gully extends farther back up the Kelvin valley to just beyond Partick Bridge (562 663) where bedrock crops out at 0m O.D.

The main Clyde buried channel passes beneath the South Basin of Prince's Dock (565 648) where bedrock is at least -21m O.D. (Fig. 79). The channel appears to widen at this point and curve very gently north-eastwards towards Lancefield and Anderston Quays (577 649) where rockhead was recorded at depths of -27m O.D. Just east of this area in the vicinity of the Broomielaw Quay (582 649) a borehole recorded a

depth of -23m O.D. in the central part of the channel. This, after careful checking, was found not to be an inaccuracy and may reflect branching in the channel (579 648). Several short but deep rock gullies enter from the north side of the channel, for example, at a point just east of Stobcross Quay (573 655) and at Anderston (580 654). Another much shallower gully enters the channel from a point west of Central Station (585 651).

To the east of the Kingston Docks (582 648) the main channel swings sharply south-eastwards into a more confined trench reaching a depth to rockhead of -36m O.D. in the area of Portugal and Norfolk Streets (589 643) (Fig. 80). Just east of this area the channel turns through a sharp meander, where bedrock was located at -35m O.D. in the Cumberland/Thistle Street area (591 639). The channel then passes north-east towards the present River Clyde where bedrock was recorded at -28m O.D. in the Rutherglen Road/Waddell Street area (596 641). Swinging back towards the east the channel crosses the present River Clyde in the King's Bridge area (600 638) at a bedrock depth of greater than -30m O.D. The channel continues into Bridgeton where in the bend of a very sharp meander a depth to rockhead of -42m O.D. was recorded (609 639). At this meander bend the channel appears to turn almost through 90 degrees and extend southwards, although this was not confirmed due to the lack of borelog data.

CHANNEL FORM AND LONG PROFILE

The buried channel is gently sinuous except in the few instances mentioned above and is rarely straight for any distance (Fig. 49). It may branch or bifurcate especially in the Prince's Dock area. The channel ranges in width, in its deeper sections below -20m O.D., from

250m just east of the King George V Docks (534 666) to more than 1500m between the Gorbals in the south and Ingram Street (594 653) to the north. The width of the channel measured from a height of 0m O.D. is far greater reaching more than 2km in the Shieldhall/Whiteinch area and maintaining a more constant width.

The sides of the channel vary from being precipitous ($>45^\circ$) to gentle ($5^\circ-15^\circ$). Several cross-sections of the channel illustrate the variations in channel side gradients (Figs. 77-82). In general the north side is steeper.

Depths of the buried channel range from over 40m in a few enclosed hollows to a few metres. A long profile, from Shieldhall to Dalmarnock, drawn along the approximate centre line of the channel, reveals an undulating thalweg (Fig. 83). This long profile is uncharacteristic of the smoother curving profiles exhibited by subaerial streams (Leopold *et al.*, 1964). Similar long profiles have been observed in various parts of the northern hemisphere, especially where subglacial meltwater may have been the agent of erosion (Woldstedt, 1961; Sissons, 1969; Woodland, 1970; Schumm & Shepherd, 1973; Wright, H.E., 1973).

Although Woodland (1970, p.559) found similar long profiles in buried channels in East Anglia, he also noted a progressive deepening of the channels in the up-ice direction away from the proposed ice margin. On present evidence the deepest parts of the Clyde buried channel are in the Gorbals and Bridgeton areas in eastern central Glasgow (Fig. 93). However this deep area may be localised and may not reflect the overall variation in depth of the buried channel.

THE INFILLING DEPOSITS OF THE BURIED CHANNELS

Knowledge of the infilling deposits of the buried channel is

dependent almost entirely upon borelog records. The infill sediments consist of stratified sequences of sands, gravels, silts, silty clays and clays, the last often being laminated. The sediments change very rapidly both laterally and vertically from very fine to very coarse textures as revealed in the cross-sections. Till has been recorded beneath the channel infilling deposits and its extent and depth from ground surface is shown in Figure 53. This underlying till, resting directly on bedrock, has an average thickness of 2.5m and was recorded in 29% of all borelogs with buried channel infill. Lenses of till are found intercalated with the other infilling deposits (Bore 8).

BORE 8 Grid Reference: 5484 6659 Surface Elevation: 6.58m O.D.

	m	m
Made Ground	0.90	0.90
Soft, brown silty Clay	0.15	1.05
Medium dense, fine brown Sand with traces of fine Gravel	1.98	3.03
Loose, medium to fine brown silty Sand with gravelly patches	1.98	5.01
Coarse to fine brown Sand with traces of Gravel	2.45	7.46
Dense, coarse Gravel with sandy patches	0.76	8.22
Stiff, dark grey Till	4.88	13.10
Medium dense, coarse to fine brown Sand with bands of grey silty Clay	0.90	14.00
Very dense, coarse to fine brown Sand and Gravel	1.26	15.26
Coarse to fine dark brown silty Sand	0.27	15.53
Black Shale Bedrock		

Of the 800 borelogs that record buried channel infill only 27 (3.4%)

have till lenses. These lenses could not be traced laterally in cross-sections and had an average thickness of 0.5m. Both these types of till deposits are similar in all respects to the till on the interfluvies between the buried channels.

Several detailed cross-sections and diagrammatic borelog columns have been drawn in order to illustrate the variability and character of the infilling sediments (Figs. 57-60, 77-80, Bores 9,10,11).

BORE 9 Grid Reference: 5713 6512 Surface Elevation: 15.30m O.D.

	m	m
Made Ground	0.71	0.71
Sand	1.80	2.51
Muddy Sand	1.98	4.49
Gravel with occasional sandy pockets	1.68	6.17
Running Sand	15.70	21.87
Sand and patches of coarse Gravel	1.58	23.45
Coarse Gravel	0.37	23.82
Sand with occasional boulders	4.24	28.06
Gravel	0.10	28.16
Grey Limestone Bedrock		

BORE 10 Grid Reference: 5891 6432 Surface Elevation: 6.70m O.D.

	m	m
Made Ground	1.53	1.53
Loose, grey clayey silty Sand	7.01	8.54
Medium dense, coarse to fine Gravel with traces of coarse Sand	4.58	13.12
Medium dense, coarse to fine Gravel and coarse to fine Sand	1.22	14.34
Medium dense, brown Sand with slight traces of silt partings	17.99	32.33

	m	m
Fine brown silty Sand with traces of Clay	7.02	39.35
Medium to fine brown Sand	1.83	41.18
Greyish black Sandstone Bedrock		

BORE 11 Grid Reference: 6109 6373 Surface Elevation: 10.67m O.D.

	m	m
Made Ground	0.15	0.15
Sandy Clay	0.91	1.06
Grey and brown silty Clay	1.10	2.16
Coarse Sand	1.40	3.56
Stiff, grey/brown silty Clay	17.68	21.24
Grey silty Sand	18.30	39.54
Coarse Gravel	3.35	42.89
Sand with traces of coal	1.83	44.72
Cobbles and large boulders	1.52	46.24
Gravel	3.35	49.59
Grey sandy Clay	0.90	50.49
Sandstone Bedrock		

These cross-sections and bores reveal the tendency for one type of deposit such as sand to be replaced horizontally and vertically not by a texturally gradational deposit such as sandy silt or sandy fine gravel but by a deposit such as laminated clay or coarse gravel. Occasionally gradational textural changes are found and may occur in one or two bores close together but rarely do such gradations continue over any horizontal distance (cf. Woodland, 1970, p.559). The nature and bedding of these infilling deposits would suggest that they are of fluvial origin deposited by a stream in which rapid changes in

stream load had occurred.

Considerable variations in the thickness of the infill deposits exist along the length of the buried channel that has been investigated. For example, at 5819 6401, in Camden Street, a thickness of 32.80m through sands and silts was recorded; at 5886 6434, in the area of Nicholson Street, a thickness of 39.00m in sands and gravels was found and at 6109 6373, in the area of Ruby Street, a maximum thickness of 50.00m in silty sand, laminated clays, and gravel was recorded (Bore 11).

At Garscadden House (522 711)(Fig. 68) and Cloberhill (534 704) (Fig. 69) two cross-sections reveal considerable thicknesses of sands and gravels beneath drumlin till. The drumlins appear to overlie buried channel deposits that have infilled the western extension of the buried channel of the Kelvin (the Bearsden channel). A borelog (Bore 12) at the Drumchapel Shopping Centre recorded the following sequence of deposits:

BORE 12 Grid Reference: 5167 7097 Surface Elevation: 23.00m O.D.

	m	m
Made Ground	1.37	1.37
Sand and Gravel	10.06	11.43
Till	1.35	12.78
Gravel	17.37	30.15
Sand and Gravel	15.54	45.69

In both cross-sections these underlying sands and gravels appear to be part of the lower sections of drumlins. This relationship between drumlins and the buried channel infill may be of significance in the understanding of Quaternary events in the study area and in the

formation of drumlins (Chap. 14).

THE ORIGIN OF THE BURIED CHANNEL OF THE CLYDE

The origin of the Clyde buried channel has been discussed in the past (Chap. 3) and a pre-glacial subaerial origin had been suggested by some workers (Clough et al., 1925; George, 1958). Sissons (1967, 1969, 1976) has suggested that subglacial meltwater and glacial erosion may explain the buried channel of the Carron and has argued that the Clyde buried channel may be, in part, similarly explained.

Subaerial Origin

In suggesting a pre-glacial subaerial origin Clough et al., (1925, p.218) argued that that the land surface must have been 100m higher than present in order that the channel could reach its apparent base level. There would appear to be no evidence to support such a degree of land emergence or sea-level fall in this area of Scotland (Sissons, 1967, 1974). The undulating nature of the channel's long profile, with the many deep hollows, as shown in Figure 83, appears to be unrepresentative of subaerial river erosion on such a large scale. Similarly at the entrance to the upper Firth of Clyde, rockhead altitudes of less than -40m O.D. have been recently recorded (Deegan et al., 1973, Fig. 9). This apparent bedrock ridge, at the mouth of the Clyde estuary, would seem to further negate a subaerial origin. It may therefore be concluded that on present evidence the buried channel of the Clyde has not been cut by a subaerial river.

Glacial Erosion Origin

In investigating buried channels beneath the lower Devon valley (Soons, 1960), the upper Forth valley west of Stirling (Eden et al.,

1969), the Carron valley (Sissons, 1969) and similar channels in central Scotland (Linton, 1963) it was advocated that glacial erosion might explain some of the much wider and deeper enclosed rock basins within these channels. In the buried Clyde channel, on present evidence, no areas could be found within the channel that were of a similar nature. In contrast the channel would appear to be narrow, steep-sided and sinuous (Fig. 49). It therefore seems unlikely that glacial erosion has been a major factor in cutting the channel.

Subglacial Origin

Various workers have argued that water may flow in large discharges within channels at the base of ice sheets (Rothlisberger, 1972; Nye, 1973; Weertman, 1973). This subglacial water may be under hydrostatic pressure, probably flows at relatively high velocities and has a large suspended load. Such streams, it has been argued, are capable of cutting bedrock channels and, due to the pressure and velocity of the stream, are capable of flowing up-hill and of cutting channels with undulating long profiles, deep hollows and incised meanders (Mannerfelt, 1945, 1949; Sissons, 1958, 1960; Price, 1963). Evidence of such subglacial erosion has been noted in Germany (rinnentäler) (Woldstedt, 1965); Denmark (tunneldale) (Ussing, 1903; Madsen et al., 1928; Hansen, 1971); U.S.A. (Bretz, 1969; Wright, 1973) and Switzerland (Woodland, 1970, Plate 26).

The buried channel of the Clyde would appear to have many of these above features, in particular an undulating long profile, to be narrow, steep sided and have a sinuous course. It therefore seems likely that subglacial meltwater erosion is the only mechanism, consistent with the evidence, that remains and is capable of such

bedrock erosion.

THE ORIGIN OF THE INFILLING DEPOSITS WITHIN THE
BURIED CHANNEL OF THE CLYDE

In suggesting a pre-glacial origin for the buried channel Clough et al. (1925) further argued that due to changing sea level, with the onset of glaciation, the channel became infilled due to river siltation caused by a rising base level. Recently Sissons (1967, 1976, p.86) has suggested that as ice advanced from the west into the Glasgow area an ice-dammed lake was formed. This lake which must have been gradually destroyed with further ice advance is recorded, it is suggested, by these infilling deposits that have been protected from later glacial erosion by being sheltered within the deep buried channel.

Non-glacial Subaerial Infilling

The arguments against the buried channel being cut by a subaerial river can also be applied to subaerial sedimentation. If a subaerial river did not cut the buried channel it would seem unlikely that the thicknesses of infill that have been noted could then be derived from subaerial river sedimentation.

Proglacial Infilling

If these infilling deposits are due to some form of proglacial sedimentation two possible origins seem applicable, namely 1) ice-dammed lake sediments, and 2) outwash train or deltaic sediments.

1) As has already been discussed, it seems possible that before ice advance and after ice retreat when ice still blocked the lower Clyde estuary, an ice-dammed lake may have existed in the Glasgow area. Although several possible outlets or overflows have been suggested

they would have been reached only once a considerable lake had formed. Outlets may have existed at Lochwinnoch (30m O.D.) and Kelvinhead (46m O.D.) (Bennie, 1868; Croll, 1870; Clough *et al.*, 1925; Price, 1975). Within these lakes, before and after glaciation, sedimentation might have occurred probably in horizontal sequences similar to normal lacustrine sediments. From the cross-sections drawn, however, no such horizontal sequences were noted, although considerable thicknesses of fine-grained silts and clays were located. The evidence from the Bearsden buried channel at Garscadden House and Cloberhill indicates till apparently overlying the infilling deposits. This sequence would indicate that these infilling deposits accumulated before till deposition but although an ice-dammed lake origin would be compatible with this evidence, so also would a subglacial origin. The evidence of borelogs and cross-sections would appear therefore to neither favour nor negate a proglacial ice-dammed lake origin.

2) In explaining the origin of infill in East Anglian buried channels, Woodland (1970, p.560) suggested that sedimentation occurred in a proglacial outwash spread that progressively infilled the channels as the ice front gradually retreated northwards. The main evidence used by Woodland (1970, p.559, Fig. 3), to substantiate this hypothesis, was the progressive textural change in the infilling deposits from coarse-grained near the ice margin to fine-grained progressively up-ice within the channels. Within the Clyde buried channel no large scale horizontal changes in texture were detected.

A similar form of sedimentation may have occurred if proglacial outwash deposition took place in the proposed ice-dammed lake. If outwash deposits had formed they might be expected to have developed

deltaic-like forms with steep foreset and large horizontal topset beds (cf. Koteff, 1974, p.126, Figs. 3-6). Such sequences and forms, however, were not observed in any cross-sections and therefore such a form of infilling seems unlikely.

Subglacial Infilling

The final possible explanation for these thick infilling deposits is subglacial deposition within a subglacial channel. Schumm and Shepherd (1973, p.8) have observed sedimentation occurring within flume channels designed to simulate subglacial stream channels. These deposits were described as large in comparison to the dimensions of the channel. These experimental observations tend to lend support to the hypotheses proposed by various workers (Carruthers, 1953; Sissons, 1958, 1961; Stokes, 1958) of subglacial sedimentation.

From analysis of cross-sections and borelog records subglacial sedimentation may best explain the sudden changes of texture that occur within the buried channel both vertically and laterally. The transverse cross-sections across the buried channel reveal sedimentary sequences akin to that observable in subaerial streams. No horizontal bedding is observed but instead "cut and fill" bedding is revealed characteristic of a stream channel bed wandering across its flood plain. Since subaerial stream infilling has been precluded, the most likely origin for the infilling deposits would appear to be subglacial stream sedimentation.

CONCLUSIONS

From the evidence available only the central section of the Clyde buried channel has been examined and the possible continuations of the channel to the east and west must be examined if and when sufficient

borelog data become available. The Rockhead map reveals that the buried channel of the Clyde does not appear to link up with the Bearsden channel in the manner suggested and illustrated by Clough et al. (1925).

If a subglacial origin is accepted for both the infilling deposits and the cutting of the Clyde buried channel several implications regarding the surrounding deposits follow and will be discussed later (Chap. 13). Although a subglacial origin for the infilling deposits seems the most likely explanation for the great thicknesses of deposits, a proglacial origin for some of the deposits cannot be dismissed.

PEAT AND LACUSTRINE DEPOSITS

In most drumlin fields peat is found within the inter-drumlin hollows. In Glasgow, however, much of the peat has either been removed or covered over with made ground. As a result only 46 borelogs record surface peat (0.80%) with thicknesses of peat ranging from 1m (5678 6962) to 7m (6491 6597) and an average thickness of 1.3m. No large expanses of surface peat exist within the study area except in the marshy ground around Possil Loch (585 698), Robroyston Loch (634 682) and Saint Germain's Loch (544 714), and in the major inter-drumlin hollow (in part followed by the new Monkland Motorway) between Ruchazie (651 660) and Queenslie Bridge (662 661).

Lenses of peat are recorded within the till close to the ground surface. These lenses are fairly uncommon (0.37% of borelogs) with an average thickness of 0.9m but often only lenses or traces of peat are mentioned in the bore records. A maximum thickness of 1.7m for buried peat within till was recorded at 5995 6973 near Vallay Street.

In several areas peat was discovered partly buried beneath deposits similar to till in appearance. At the Atlas Works (609 677), in Springburn, peat, partly buried beneath material described in the borelog as fill, was found at the base of a steep-sided drumlin. The maximum thickness of this partly buried peat was 3.4m. A map drawn of the areal extent of the surface peat, including the partly buried peat, reveals that the deposits overlying the partly buried peat have a distinct fan-like outline (Fig. 84). A cross-section, drawn at right-angles to the drumlin slope, shows that the partly buried peat and surface peat are one continuous deposit (Fig. 85).

Recently, at 609 678, two samples of peat were radiocarbon dated (pers. comm. R. J. Price, 1976):

Peat above Till - $5,994 \pm 50$ yrs. B.P.

Till - 4m in depth

Peat below Till - $11,140 \pm 110$ yrs. B.P.

Till

The buried peat at this site, located in an inter-drumlin hollow, may be explained either as overridden by the ice and buried beneath till or as peat over which till has slumped in part. Two main objections against the former explanation exist. Firstly, if the peat was overridden by the ice then the overlying till was apparently deposited after $11,140 \pm 110$ yrs. B.P., if the radiocarbon date is accepted as accurate. Since other radiocarbon dates within west central Scotland (Chap. 3) indicate that the Glasgow area was probably ice free by around 12,650 yrs. B.P. (Sissons, 1974, p.314; 1976, p.90) the suggestion that the till overlying the peat is of a much younger age must be discarded. Secondly, the fan-like outline of the overlying deposits beneath a steep drumlin slope and the partial covering of

the peat are both factors inconsistent with till deposition within an inter-drumlin hollow.

From the borelog records and observations in the field the overlying material, described by Price as in situ till, although similar in appearance to in situ till, may be instead reworked or soliflucted till that has moved down slope obscuring the surface peat that then occupied the inter-drumlin hollow. This latter explanation is consistent with the fan-like apron of the overlying till-like deposit, the continuous nature of the peat deposit and the relative ages of the radiocarbon dates. The lower radiocarbon date may be interpreted as only indicating the age after which the material slumped over the peat (details of depth of sampling for radiocarbon dates within the peat deposits were not given).

In several other areas peat was found partly buried under till-like material at the sides of steep drumlins, for example, at Westray Street (590 693) and south of Hillend Road (585 687).

Evidence of former lakes, in the Glasgow area, is provided by patches of laminated silts and clays often associated with peat and found lying in topographic depressions (Bore 13).

BORE 13 Grid Reference: 5658 6952 Surface Elevation: 40.50m O.D.

	m	m
Made Ground	2.74	2.74
Firm, brown laminated Clay with occasional sandy lenses and traces of peat	0.91	3.65
Peat	0.30	3.95
Firm, brown silty laminated Clay	1.83	5.78
Firm, brown sandy Till	1.37	7.15
Greyish brown Sandstone Bedrock		

Lake deposits with an average thickness of 1.5m were recorded in only 15 borelogs (0.26%). As lakes dried up or diminished in size it appears that peat grew over the sites of the former lakes. For example, at 5658 6952, 0.3m of peat overlies 1.8m of laminated silty clay which in turn, overlies brown sandy till. No large areas of lake deposits were found within the study area.

FLUVIOGLACIAL DEPOSITS

A major anomaly in the deglaciation history of this part of the Central Lowlands is the significant lack of fluvioglacial deposits and landforms associated with ice stagnation (Sissons, 1974; Price, 1975). Within the study area no landforms or spreads of fluvioglacial material were located. Only 24 borelogs record distinct layers of stratified sands and gravels above the till. Thicknesses ranged from 0.6m at 5764 6724 to 5.5m at 5710 6680 (average = 2.7m). Many of these borelogs were located in linear depressions that probably once carried meltwater streams that deposited these sands and gravels.

In Barlanark (651 649) a belt of stratified sands and gravels, over 2km long and 400m wide, was traced eastwards into the Shettleston/Baillieston area where extensive fluvioglacial deposits have been reported (Clough et al., 1925).

A cross-section (Fig. 76) at Barlanark cuts transversely across this belt of sands and gravels revealing a bedrock hollow in which these deposits lie. No till was found lying at the base of this hollow beneath the stratified deposits but to the north the sands and gravels were partly covered by till. The sands and gravels lie within an inter-drumlin hollow which appears to have been utilised as a meltwater channel that extended to the Shettleston/Baillieston area.

It seems likely that these stratified sediments were deposited from a meltwater stream either subglacially, proglacially or by a combination of both processes. The overlying till may be in situ or may have slumped across the deposits due to slope movement. The latter explanation would appear to be the more likely from the evidence of the adjacent steep slopes and only partial burial of the sands and gravels by the till.

RAISED BEACH DEPOSITS

Deposits of fine-grained laminated silts, clays and sands, occasionally containing material with an organic odour, have been traced on either side of the present course of the River Clyde up to an elevation of 26m O.D. These deposits have been described and examined for fossil content in the past (Chap. 3) and consist of a series of very gently sloping wide terraces or beach levels. These raised beaches were not levelled but, in mapping, three different levels were traced. Above the alluvial plain, extending on both sides of the present River Clyde above 3.0m O.D., a beach level extends back to a marked break of slope at 6.0 to 7.5m O.D., a further level extends back to 13.7 to 15.0m O.D., and finally a higher level extends to approximately 26.0m O.D.

In a few locations layers of buried organic material were recorded in the borelogs. For example, near Jordanhill Station the following sequence of deposits was recorded:

BORE 14 Grid Reference: 5470 6790 Surface Elevation: 19.20m O.D.

	m	m
Made Ground	0.45	0.45
Stiff, mottled, greyish-brown, laminated silty Clay, with rotten vegetation at base	1.99	2.44

	m	m
Soft, greyish-brown, laminated Clay with silt and sand bands with rotten vegetation, in upper portions only	3.96	6.40
Grey/black weathered Shale		

This sequence of raised beach deposits indicates an organic horizon lying at an approximate altitude of 16.8m O.D.

In several borelogs shells were recorded and in one instance varved clays (Bore 15).

BORE 15 Grid Reference: 5437 6452 Surface Elevation: 15.60m O.D.

	m	m
Made Ground	5.94	5.94
Grey/brown plastic Clay [with Varved clays at 7.24m depth]	1.86	7.80
Grey Silt	1.64	9.44
Firm, dark grey Till	2.61	12.05
Sandstone boulder	0.30	12.35
Firm, grey Till	4.40	16.75
Laminated grey silty plastic Clay	0.16	16.91
Firm, grey Till	2.29	19.20
Dark grey Shale Bedrock		

The relationship of the raised beaches to the other deposits is shown in the general stratigraphic cross-section (Fig. 52). As well as overlying the buried channel infill and till, in a few instances the raised beach deposits were recorded lying directly on bedrock (Bore 16). As already noted, buried beneath the raised beaches are several small drumlins, one of which (Campbellfield Street) appears, from its flat top, to have been planated by marine processes during

the invasion of the sea into the Glasgow area.

BORE 16 Grid Reference: 5402 6686 Surface Elevation: 6.67m O.D.

	m	m
Made Ground	0.23	0.23
Brown slightly sandy silty Clay	0.64	0.87
Brown, very fine, clayey Sand	1.89	2.76
Grey, very fine, silty Sand with fragments of wood and fine gravel	0.91	3.67
Brown/grey sandy, silty Clay	2.59	6.26
Brown clayey fine Sand with fine gravel	0.79	7.07
Brown silty Clay	1.52	8.59
Brown Silt with traces of wood at 13.7m depth	8.32	16.91
Sandstone Bedrock		

MADE GROUND

Material, variously described as fill, forced ground, waste forced material and rubble, deposited or disturbed by man and his actions covers almost the whole urban area in which borelogs were collected. Usually it is only a metre or two in depth but in one borelog near Cowlairs North 20m were recorded (601 685).

Within the city, in the past, many different forms of mining have taken place (Fig. 86). As a result of this work large bings and waste tips accumulated. Much of the made ground reflects the disposal and spreading of this mining waste in and around the main mining areas. Another source of made ground results from the demolition and filling in of basements with stone building material, especially along the line of the Inner Ring Road in Woodside and Cowcaddens and in the major housing clearance areas of the Gallowgate, Bridgeton, Gorbals

and Laurieston.

A large elongate area of made ground stretches from Broomhill House (598 665) north-eastwards along the railway line via the Sighthill Freight Terminal (608 668) towards Broomfield Road (620 671). Other large areas include Cowlairs Park (594 674), Cowlairs North, Garngad, (614 665), Carntyne (626 653) and Netherton (546 698).

In examining the borelogs four areas of enclosed bedrock depressions were discovered at North Woodside (585 667), Lansdowne Crescent (576 669), Queen Street/Buchanan Street (591 655) and Riddrie Knowes (635 659). All these depressions were buried beneath several metres of made ground and were invisible from the surface. On examination of old maps of quarry sites it was found that building stone quarries had existed at these four sites.

GLACIAL EROSION

The Glasgow area is dominated by features of glacial deposition such that landforms produced by glacial erosion are few and often totally obscured.

Necropolis Hill and Springburn Park, both large bosses of volcanic rock, have been moulded by the erosive action of the ice into features that might be termed rock drumlins. This term is applied since no large accumulations of drift have been found in the lee of these plugs (Fig. 49) and in the case of Necropolis Hill a shape akin to a drumlin has been produced. Several teschenite sills in the Riddrie Knowes area of eastern Glasgow have been eroded by the ice into elongate rock ridges (633 659).

As the ice advanced across these resistant rocks its normal flow was interrupted and deflected. Deflection around obstructions is

demonstrated at the base of Necropolis Hill and Springburn Park, where narrow, deep bedrock trenches curve around the stoss ends of these features. In the case of Necropolis Hill a trench, a kilometre long, can be traced on the north side of the feature.

Only a few enclosed natural bedrock hollows were encountered. A small hollow was located, 600m in length and 15m below the surrounding bedrock level, to the south of Garthamlock (660 660). This bedrock hollow is closely aligned with an inter-drumlin hollow. The hollow was infilled with deposits described in a borelog as "wet silts, sandy and silty clays". These infilling deposits may possibly be either lacustrine or meltwater sediments.

Several bedrock hollows were discovered in an area just north of the Royal Infirmary (602 659) where three distinct hollows were located (Fig. 87). The most southerly hollow forms part of the large bedrock trench curving around the Necropolis Hill. The other two hollows do not appear to bear any relationship to the surrounding drumlins. Other small hollows have been observed in several cross-sections, for example, at Maryhill, Yorkhill, and along the Monkland Canal (Figs. 67, 65, 64).

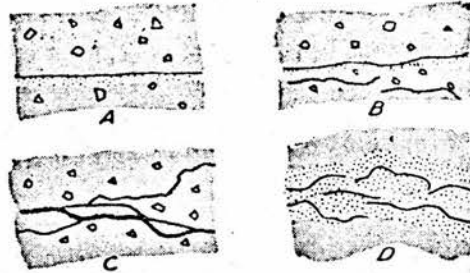
In general the bedrock topography of the study area, unlike central Edinburgh (Sissons, 1971), is subdued with no discernible topographic grain or evidence of structural control in the bedrock morphology. Since the till has been locally deposited and also locally derived it can be argued that both erosion and deposition occurred contemporaneously and extensively throughout the area.

TILL "LAYERS" WITHIN A DRUMLIN

During investigations of an exposure in a drumlin near North Hanover Street (595 657), distinct partings or bed limits in the till were noted and measured. The till in this particular drumlin is grey, being largely derived from Carboniferous source rocks. The till layers were observed between thin sand or silt partings 1 to 2cm thick and were nearly horizontal. The partings between the layers tend to be lighter in colour (10YR 4/2), than the surrounding till (10 YR 4/1)(Plate 10). Although these partings were easily detected they were wavy and often petered out or joined another till layer in a short horizontal distance. Till layers could be traced for over 5m in distance but normally they were only 30 or 40cm in length (Plate 11). From a study of these layers it was anticipated that more information could be obtained about the mechanics of till deposition within a drumlin.

Virkkala (1952, p.107) noted till layers in drumlins in eastern Finland terming them "bed structures". He recognised that the partings between these structures were not secondary features originating after till deposition but were primary structural features indicative of conditions in the basal parts of a glacier. No evidence could be found by Virkkala of post-depositional weathering or shearing along the till layer partings. The descriptions, figures and photographs of till layers given by Virkkala are identical to those found by the writer. Prior to this work several authors had noted what appeared to be fine sand partings in till (Richter, 1929; Bülow, 1939; Flint, 1947). Harrison (1957) suggested that these bed limits or S-planes,

as he termed them, were related to the basal, debris-charged layers of the glacier and may have been the relict slip planes of the "glacier tectonite" which had been deposited by a melt-out process. Much later



(After K. Virkkala (1952) - Bed Limits, Fig. 8 p. 104)

Boulton (1970b, p.239; 1971 pp.60-6) while investigating subglacial and melt-out tills in Svalbard noted similar bed limits. He suggested that these partings originated during differing periods of deposition. Firstly, following deposition of a layer of till, water at the base of the glacier may have washed over the surface of the till thus depositing the sands and silts and removing clay particles from the washed till thus giving the much looser structure of the ensuing parting. Secondly, more till would be melted-out and deposited on top of this washed parting thus leaving this parting sandwiched between unaltered till as a bed limit. The writer tentatively accepts this explanation of till layer formation and till deposition. When the thickness of the till layers is taken into account several important possibilities emerge regarding drumlin origin. These possibilities will be discussed later following the presentation of the results.

MEASUREMENT OF TILL LAYERS

Two sets of layers in a vertical profile, 10m in height, were measured. The exposed till face was cleaned up and a metre stick

embedded vertically into the face. As in all other till investigations the measurements were taken from till at least 3m beneath the ground surface level in order to avoid disturbed ground and the effects of post-depositional weathering. Starting with a till sand/silt parting at the base of the profile, the height between each parting was measured. Two sets of measurements, 105 in all, were taken, one metre apart. Readings were checked by starting at the last parting measured at the top of a section and re-measuring down the section. Errors in measuring the thickness of individual till layers were thought to be approximately ± 5 mm.

DISCUSSION OF RESULTS

From the two histograms (Fig.88) it can be seen that there exists a wide range of till layer thicknesses from 0 to 2cm to 56 to 58cm. In sample A 52 layers were measured and in sample B 53 layers. Since both sample distributions show strong negative skews difficulties occurred in statistical computation. Croxton and Cowden (1965, p.195) state that "Because of the effect of extreme values upon the arithmetic mean, it is sometimes a misleading figure to use to describe a distribution". In the case of the above sample population the averages are virtually meaningless because of the effect of the larger values. Neither the median nor the mode improve the ability to describe the distribution. As a result it was decided that a smaller in-sample population would be computed. Sample populations between 0 and 14cm were used since approximately 50% of all the layers lie within this limit (A = 49.6% 0-14cm; B = 49.1% from 0-16cm). Both sets of computations are illustrated in Table 4. The median values in this instance, are perhaps the best of the statistical measures of central

tendency.

T A B L E 4

Sample	n	Mean	Median	Mode	S.D.
		mm	mm	cm	mm
A	52	195.4	133.6	0.2	163.3
B	53	179.8	119.8	0.2	150.3

Sub-Sample	x	Mean	Median	Mode	S.D.
A	25	54.8	39.8	0.2	42.05
B	29	66.5	47.7	0.2	49.60

In order to test the significance of both samples a null hypothesis using the Kolmogorov-Smirnov test was set up. The null hypothesis tested was that no significant difference exists between the two samples. The value calculated for the largest difference between the two samples was 0.0800. Testing at the 5%, 1% and 0.1% levels of significance, which were 0.2654, 0.3182, 0.3806 respectively, the null hypothesis was proved. Therefore, between two independently taken samples no significant difference could be found even at the 5% level. It is therefore concluded that the distribution of layers shown by the histograms is a reasonable representation of the norm.

The medians of both samples are approximately in the range of 5 to 12cm. The reason for choosing the median is that it can be considered as the "mean expectation" of a sample population, giving equal importance to both small and large values (Gregory, S., 1971, p.14).

If till is deposited by the melting out of debris from an englacial position in an ice sheet some idea of the average rate of till deposition can be made (Nobles & Weertman, 1971). The release of debris from the base of the ice in response to basal melting may occur either under stagnant conditions or by pressure melting of the glacier sole as it moves over obstructions. In the case studied by the writer the till was part of a drumlin that must have been formed during active ice movement and is therefore composed of till probably deposited by some melt-out, plastering-on process similar to that described by Boulton (1970, p.235) and Peterson (1970, p.97).

An equation has been derived by Nobles and Weertman (1971, p.120) for the average annual rate of till deposition and is as follows:

$$\bar{D} = \left[\frac{C}{1-C} \right] \left[\frac{Q + JVO - K\nabla T}{L} \right] \dots\dots\dots(4)$$

where \bar{D} is the average thickness of till deposited in unit time, C is the volume fraction of debris within the ice, Q is the geothermal heat, J is the mechanical equivalent of heat, V is the sliding velocity, O is the shear strength acting at the bottom surface of the ice, K is the thermal conductivity of ice, ∇T is the vertical temperature gradient and L is the latent heat of fusion of ice.

Nobles and Weertman (1971, p.122) have calculated that an average annual rate of deposition with average ice velocities and thicknesses, would be between 0.5 and 3.0cm per year. This theoretically calculated figure is in accord with the recent calculations on Alaskan till where rates of 0.5 to 2.8cm year⁻¹ were found (Mickelson, 1971, 1973). In both calculations the assumption has been made that in the ice-till mixture at the base of the ice, the ice only represents 25% by volume (Harrison, 1957, p.296; Mickelson, 1971, p.47). A similar figure for rates of till deposition (approximately 3cm year⁻¹) has been

calculated by Gravenor et al. (1973, p.1076) using palaeomagnetic analysis of Port Stanley Till, Ontario. Boulton (1970, p.243) investigating tills in Svalbard assumed a 50% ice content by volume in the ice-till mixture and suggested a 0.5cm year^{-1} deposition rate.

The only known work on investigations of till layer thicknesses in drumlin till is that by Virkkala (1952). Although Virkkala does not state an actual figure for the thickness of till between the "bed limits" thicknesses of approximately 10 to 20cm can be estimated from his work. The present study revealed median thicknesses in the range of 5 to 12cm in drumlin till.

CONCLUSIONS

Before drawing any conclusions the possibility must be considered that the sandy bed limits discovered in the Glasgow drumlin till are annual deposition units. The theoretically calculated rates of till deposition would indicate that 3cm year^{-1} was an average maximum rate but this does not indicate the number of till layers possible within this theoretical thickness. It may be that one till layer represents one year's deposition but this seems unlikely. The pattern of winding and undulating forms of the bed limits, their short lateral extension before being cut-off by another layer and their tapered shape would seem to indicate that the till layers have been affected by erosion. The process of till erosion may be by basal water erosion or by the refreezing on of the till to the sole of the glacier. The remaining till is therefore a complex deposit not directly related to annual depositional units when examined in a vertical section. One till layer may represent not one but several annual deposition cycles or only part of a one year cycle. The latter possibility seems the more

probable when the sudden lateral changes and varying thicknesses are taken into account.

A further conclusion is that till that is formed by a melt-out process, is not deposited grain by grain but as complete layers of specific lengths, widths and thicknesses. Other till deposition processes such as smearing-on or plastering-on may well be by a grain by grain mode of deposition.

The thicknesses found for the Glasgow drumlin till layers are therefore either minimum values or are part of much larger, but as yet, incalculable values. If the layer thicknesses (5-12cm) are approximate minima for the rate of annual deposition; then they are greatly in excess of the estimated values. It should however be noted that the mode of the sample populations of both samples was in the 0 to 2cm range (i.e. within the estimated limits).

The conclusion reached by the writer, assuming annual deposition rates, is that the rate of till deposition on a drumlin would seem to be greater than on a till sheet. Virkkala has pointed out firstly, that in Finland till layers are seldom if ever observed other than in drumlins and secondly, that drumlins presuppose drift-rich ice. Several reasons can be put forward to account for such large rates of deposition; either the basal ice above a drumlin field is very much richer in debris than normal or the rate of deposition on to the drumlin is increased by greater melting for some reason or by a combination of both or by some other process. That the ice above a drumlin field is debris rich seems highly probably and in itself this localised concentration of debris may help to account for drumlin field locations.

However, to explain why till aggradational units appear to be greater on a drumlin than on a till sheet may lead to an explanation

of drumlin formation, itself. Nobles and Weertman (1971, p.123) have noted that rather than being higher, deposition rates over glacier base highs, as opposed to lows, should be very much lower, if a melt-out process is accepted as the dominant subglacial process. The problem of apparent high deposition rates over a drumlin contrasts with the theoretical argument for very much lower rates on the crest of an obstacle and is in essence the "enigma that is the drumlin" (Nobles & Weertman, 1971, p.125). To resolve this enigma with the known glaciological facts requires that the explanation for high depositional rates be a process other than "melt-out".

DRUMLIN MORPHOMETRY

Morphometry may be defined as the measurement of the parameters that delimit the shape of a landform and its relationship to similar landforms and other controlling factors. Drumlin morphometry can be subdivided into the analysis of either individual drumlin form or of the distribution of drumlins within a drumlin field, taking each drumlin as a point or area and analysing the resultant pattern.

The aim of this morphometric study has been to derive relationships between the measured parameters and the processes that created them. In pursuing this aim specific parameters were chosen that were thought might aid in understanding the factors that determine drumlin shape and size. As Trenhaile (1975, p.298) has pointed out, such factors " ... are extremely poorly understood ...".

It was hoped that in deriving possible relationships between morphometric parameters a better understanding might be gained of how drumlins are formed and of the relationship of drumlins to possible controlling factors such as bedrock topography and drift thickness. Finally, an attempt was made to substantiate some of the results obtained by other workers regarding drumlin morphometry.

FIELD MAPPING

Before the dimensions of individual drumlins could be measured a map of the landforms and deposits of the study area had to be made. A geomorphological map at the scale of 1:10560 was prepared, illustrating the distribution and pattern of glacial landforms and deposits, raised beaches, peat, lacustrine deposits and alluvium (Fig. 4).

The technique of field mapping differed between the agricultural and urban areas. In agricultural areas mapping was done by traversing the ground on foot in 100m strips with closer inspection of the ground where possible complexities of deposits or landforms were thought to exist. Aerial photographs, at a scale of 1:24000, were used to help detect areas of possible complexity. In urban areas mapping was done street by street, including all open spaces such as parks and golf courses. Within the city, aerial photographs were of little value except where large open spaces existed as at Ruchill Park (580 683) and Alexandra Park (621 658). Since landforms cannot be easily viewed in urban areas, breaks of slope were mapped first and the landforms drawn in later. Where landforms were known to have been either removed or partly destroyed as at Bell's Park (592 662) and Hamilton Hill (586 675) the landforms shape was drawn in, as accurately as possible, using old maps of the city.

Made ground may replace in situ deposits as at Gilshochill (567 691), infill hollows between drumlins for example, at Sauchiehall Street (585 659) or overlie glacial deposits as at Carntyne (627 653). Where the location and areal extent of made ground was known from borelog records or where it did not appear to reflect what was thought to be the original morphology of a landform, it was excluded from the map. In some areas, for example, Sighthill railway yards (601 665) the underlying undisturbed glacial deposits were not detectable by normal mapping procedures due to the masking effect of made ground and were only added to the map after examination of borelogs.

DRUMLIN MORPHOLOGY AND TERRAIN CHARACTERISTICS

Ten factors thought most likely to control drumlin form and location were selected for measurement or estimation. Within the

thesis area 160 drumlins were measured for orientation and dimensional characteristics and within this sample 34 drumlins were also measured for non-dimensional characteristics. Because the non-dimensional parameters measured are related to drumlin location and spacing and to terrain factors a specific area within the drumlin field was chosen within which no major topographic or geological secondary controlling factors were thought to exist. These secondary factors avoided were major valleys and large bedrock outcrops at the surface. The area chosen covered approximately 28km² of central Glasgow and stretched from Kelvinside in the west, to Barmulloch in the east, and from Lambhill in the north, to Necropolis Hill in the south.

The parameters chosen were as follows:-

Drumlin Orientation	Drumlin Nearest Neighbour
" Height	" Density
" Length	Bedrock Slope
" Width	Drift Thickness
" Volume	Surface Slope
	Rock Control

DRUMLIN ORIENTATION

The orientation of drumlin long axes provides an indication of the direction of ice flow. Measurements, accurate to ± 2.5 degrees, were taken off the completed Geomorphological map using a 360 degree protractor. The major problem in measuring drumlin orientation is in deciding the line of the long axes on some unusually shaped drumlins. Where two possible long axes occurred, as at Cloberhill, an average orientation was used.

DRUMLIN HEIGHT, LENGTH AND WIDTH

One of the major problems in calculating drumlin dimensions is in estimating or delimiting the areal extent of a drumlin. Often the lower slopes of a drumlin gradually merge with the surrounding undrumlinised till and show no clearly discernible break of slope. Although the stoss end is usually distinct, the lee ends of many drumlins stretch for considerable distances and grade imperceptibly into interdrumlin till; for example, at Alexandra Park (620 659) a drumlin stretches for 2 to 3km. These problems allied with the inability to distinguish drumlin till from non-drumlin till (Heidenreich, 1964, p.101-2) lead to errors in dimensional measurements. These errors cannot be easily overcome especially in an urban setting.

The dimensions of height, length and width were calculated as illustrated in Figure 89. In calculating drumlin height an estimate had to be made as to the highest part of the drumlin in some instances because of human interference. The highest point was normally restricted to a small crest area but in some instances for example, at Hamilton Hill, a flat plateau-like top occurred. Similarly, in a few cases as for example, at Riddrie (636 675), two distinct crests were observable. In these latter cases an average maximum height was used. Where a drumlin had an asymmetric cross profile, as at Yorkhill, two heights from base to crest were noted but in morphometric calculations an average figure was used. Drumlins located "sitting" on the side or top of other drumlins had heights measured relative to their elevation above the underlying drumlins (e.g. Lambhill).

DRUMLIN VOLUME

As no previous equation was known, it was necessary to derive

empirically an equation that would approximate the volume of a drumlin. A drumlin has many of the shape characteristics of a half-ellipsoid (Fig. 90). However slight, but significant, differences in shape and volume occur because of the position of the crest in the "ideal" drumlin (Fig. 90).

The final equation was derived by the following method. The drumlin shape was drawn on millimetre graph paper with horizontal segments five millimetres in height marked-off. (Fig. 90). Using the equation for the area of an ellipse and assuming each segment height to be unity, the volume of each segment was calculated.

$$\text{Area of an ellipse} = \left(\frac{\pi l \cdot w}{4} \right) \dots \dots \dots (5)$$

where l and w are length and width; width being calculated on the basis of a L/W ratio of 3.00.

$$\text{Volume of each ellipse segment} = \left(\frac{\pi \cdot l \cdot w \cdot h}{4} \right) \dots \dots \dots (6)$$

where l, w and k are length, width and height of each individual

$$\text{segment. Therefore } \sum \text{ Segments} \approx \text{Drumlin Volume} \dots \dots \dots (7)$$

Using the maximum values for all three parameters, width, length and height, the total volume of the "ideal" drumlin was again calculated. Since the maximum dimensions were the only figures available for each drumlin in the study area a correction factor (K) had to be included in the equation of maximum values in order to equal the former "segment" calculated volume.

$$\left(\frac{\pi \cdot l \cdot w \cdot h}{4} \right) = \left(\frac{\pi \cdot L \cdot W \cdot H}{4} \right) K \dots \dots \dots (8)$$

A mean correction factor (K) of 0.54 was calculated after different sizes of "ideal" drumlins had been empirically analysed. The final

equation for drumlin volume which is only an approximation was:

$$\text{Volume} = 0.43 (L W H) \dots\dots\dots(9)$$

Since this equation has been derived, Trenhaile (1975, p.308) has used a similar volume equation:

$$E = 2/3 (\pi a b c) \dots\dots\dots(10)$$

which resolves to $E = 2.09 (a b c) \dots\dots\dots(11)$

where a, b and c are maximum length, width and height. This equation (11) gives a larger volume than that derived from equation (9) because Trenhaile used the equation of a half-ellipsoid without any correction factor being taken into account.

DRUMLIN NEAREST NEIGHBOUR

In order to analyse the distribution and spacing of drumlins a measure of the proximity of drumlins one to another was adopted. This parameter could be correlated with measurements of drumlin density.

As Smalley and Unwin (1968, p.383) have pointed out past methods of drumlin spacing measurements have been "difficult to define and make" (cf. Reed et al., 1962; Vernon, 1966; Hill, 1968). As a result a method was adopted using a circular template placed directly on each drumlin crest, in turn, and measuring, to an accuracy of $\pm 10m$, the distance to the nearest part of the nearest neighbouring drumlin crest. Drumlins that were very small and "sitting" completely upon another, much larger drumlin were ignored in these measurements.

DRUMLIN DENSITY

Density was measured using two methods: 1) overall point density and 2) individual drumlin point density. The former method is based on a calculation of the number of drumlins per square area (Doornkamp & King, 1971, p.295). The latter method uses a circular template with

an area of 10.36km^2 (4 miles^2)(cf. Trenhaile, 1975, p.306). By placing the template on each drumlin crest in turn the number of drumlin crests within the template provided a measure of the drumlin density around each drumlin. The choice of 10.36km^2 , as the area of the template, was made in order to allow density comparisons with Trenhaile's work and also because it was found to be large enough to encompass marked density variations but small enough to be of significance to each drumlin.

BEDROCK SLOPE

In order to relate the drumlin to its immediate location, several non-drumlin parameters were measured or assessed. Bedrock slope was assessed from the Rockhead map by assigning a value to the slope of the bedrock immediately beneath each drumlin under scrutiny. Bedrock slopes were divided into orientation classes in relation to the direction of movement of ice over the area as follows:

Bedrock dipping Up-Ice	=	1
" " Down-Ice	=	2
Bedrock with no slope	=	3
Bedrock dipping obliquely to the direction of Ice movement	=	4

DRIFT THICKNESS

This parameter was assessed by taking the average depth of drift underlying the drumlin (cf. Trenhaile, 1975, p.309)(Fig. 91). Using the Drift Thickness map, depths were measured to $\pm 1\text{m}$.

SURFACE SLOPE

This parameter was assessed in an identical manner to bedrock slope with the same values assigned. Surface slope was taken to be representative of the surrounding ground surface slope on which each drumlin

was lying (Fig. 4).

Surface dipping Up-Ice	=	1
" " Down-Ice	=	2
Surface with no slope	=	3
Surface dipping obliquely to the direction of Ice movement	=	4

ROCK CONTROL

As mentioned in Chapter 4 many drumlins are apparently cored by bedrock knobs. It is commonly assumed that such bedrock cores acted as obstructions to ice movement and controlled the location and shape of these drumlins. Bedrock was arbitrarily defined as exhibiting control when a bedrock rise of more than 5m, above the surrounding bedrock topography, was detected beneath a drumlin. By superimposing the Rockhead map on the Drift Thickness map such rock-controlled drumlins could be picked out. Of the 34 drumlins analysed only two could not be assessed for rock control because of insufficient information.

The following values were given to the drumlins with or without rock control:

No Rock Control	=	1
Rock Control	=	2

THE "IDEAL" DRUMLIN

TWO HYPOTHESES AND THEIR MORPHOLOGICAL IMPLICATIONS

The execution of this work on drumlin morphometry was prompted by a number of questions. These questions were raised by consideration of what form, location and distribution drumlins might be expected to have, from an analysis of drumlin origin theories.

At present drumlin theorists can be probably divided into those

who completely concur with the dilatancy theory of Smalley and Unwin (1968), for example, Muller (1974), Crozier (1975), Trenhaile (1975), and those who do not reject the above theory but who have alternative hypotheses for example, Hill (1968), Miller (1970), Lundqvist (1970), Evenson (1971), Shaw & Freschauf (1973), Gravenor (1974)(cf. Chap. 4).

In both cases there appears to be general agreement that the shaping and final form of a drumlin is determined by ice velocity and pressure. However in the dilatancy theory, ice pressure is also assumed to determine drumlin location within the drumlin field.

Drumlin fields are commonly found relatively close to the maximum extent of ice masses indicating that drumlins were probably formed in the last stages of ice advance or the first stages of retreat or a combination of both (Chap. 4). If drumlins were to form over an idealised uniform plain where no external secondary factors were likely to operate certain assumptions relating to the above theories can be made.

In using a theoretical approach ice conditions are given precedence over all other possible controlling factors, thus carrying the implication that ice conditions are always singularly central to any theory of drumlin origin, which may not always be the case.

DRIFT THICKNESS

Depending on how drumlin till is derived before its deposition, whether from the basal layers of the ice mass or from till already deposited up-ice, it would seem likely from non-dilatancy theories that in areas of thick drift large numbers of drumlins might be expected to be found and vice versa. Drumlin point density would therefore be reduced in areas of thicker drift but nearest neighbour might be expected to remain constant (Trenhaile, 1971, 1975, p.306). In the dilatancy theory thick drift would tend to be found in areas where

non-drumlinising ice pressures (Zone B) existed and thus fewer drumlins would be formed but, due to these lower ice pressures, the drumlins would possibly be larger in size. This situation would cause drumlin density to decrease but nearest neighbour to increase.

DRUMLIN DIMENSIONS

Drumlin dimensions of height, length and width may be expected to retain approximately constant ratios if the dilatancy theory is accepted. In the dilatancy theory it is argued that drumlins are affected by pressures that totally encompass the drumlin during and after formation. These pressures from the ice therefore control and dictate the dimensions and dimensional increase or decrease of the drumlin. Alternatively, other theories would suggest that tangential pressures directed at the drumlin stoss end are more important causing drumlin dimensions to be distorted.

DRUMLIN DISTRIBUTION

Drumlin distribution over this "idealised" plain can be expected to vary due to changing ice thickness which in turn causes changes in ice velocity and pressure provided all other controlling factors remain constant. Trenhaile (1975, p.297) has argued that "a centre or zone within the ice at which conditions for drumlin formation become optimum must have occurred". The hypothesis is then extended to argue that conditions become less favourable farther from the optimum zone. The idea of an optimum zone with radially less favourable zones might indicate that drumlins are formed only when ice conditions are optimal (i.e. the dilatancy theory); whereas, although ice conditions favourable to drumlin formation may deteriorate, other combinations of factors equally fundamental may be favourable.

If an idealised uniform plain existed then, under the dilatancy theory, drumlin density would vary both towards the ice margins and up-ice from the central zone of drumlin formation. In the central zone Smalley and Unwin (1968, p.388, Zone C) argued that drumlins should be least dense. Farther up-ice where ice pressures increase, drumlins would be similarly spaced but much more elongated due to increased ice pressure. Towards the glacier margins, where ice pressure and velocity would decrease, drumlin density would increase but drumlin size should decrease (cf. Charlesworth, 1957, p.394).

Drumlin distribution following the non-dilatancy theories is less precise, having fewer constraints. If, as Chorley (1959) suggests, drumlin elongation is related to ice velocity, it can be argued that, on approaching ice margins, elongation and overall drumlin size should be reduced. However, if as Harrison (1958, p.86) has shown, drift thickness increases away from ice margins it can also be anticipated that drumlin density and elongation might increase farther away from the ice margin.

BEDROCK SLOPES

Where a bedrock slope faces up-ice and is a sufficient obstacle to the movement of the ice, changes in ice velocity and pressure can be expected due to ice retardation. Ice velocity will reduce but ice pressure will increase commensurately. These changes could cause the following reactions. Firstly, with increased pressure a situation might be created, accepting the dilatancy theory, in which drumlin formation might be precipitated. Such drumlins because of reduced velocity might be expected to be smaller than surrounding drumlins lying on flat uniform surfaces. Secondly, with both these above changes,

pressure melting (which is largely unrelated to ice velocity) might be increased causing till deposition to be increased. However once the bedrock slope becomes masked with increasing drift the effect of the bedrock will be gradually diminished. Thirdly, the ice pressure changes although initially causing greater till deposition may cause subsequent erosion of the till: thus the till on the bedrock slope may be thin and in equilibrium with erosional and depositional processes. Finally, it is possible that with both ice velocity and pressure changing in direct relation to one another, the effect of the changes might cancel themselves out resulting in the bedrock slope being a passive factor exerting no influence on either till deposition or drumlin formation (Aronow, 1959).

Up-ice surface slopes may have a similar effect on drumlin formation but, unlike bedrock slopes, if surface slopes do influence ice movement, this influence will not be so easily removed unless the ice changes cancel themselves out.

Down-ice bedrock slopes would initially cause ice extension, velocity increase and pressure decrease. From the arguments used in the dilatancy theory it might be expected that drumlins would be larger and more elongate. However since the bedrock slope would be in the lee of a bedrock high it would tend to be rapidly masked by deposited drift and its influence quickly removed. Similarly these glaciological changes might cancel themselves out such that the bedrock had no influence.

Down-ice surface slopes although unlikely to be masked by drift might otherwise be expected to react in a similar manner to down-ice bedrock slopes.

BEDROCK OBSTRUCTIONS

Although a small bedrock obstruction may act as a nucleus for till deposition and later drumlin formation the influence of the bedrock itself will presumably be rapidly lost beneath the thickening drift (Smalley & Unwin, 1968, p.389). Such a rock cored drumlin may, however, cause a change in the overall basal ice pressures and velocities radiating over a wide area, resulting in drumlin formation around the initial mode. This idea raises the question of whether within a large drumlin field several drumlins may have acted as nodes from which drumlinisation began over the whole field. If such primary nodes existed and could be identified it might be possible to note if they were "special" in any way or if they were chance occurrences.

INFLUENCE OF ALREADY FORMED DRUMLINS

Once drumlins have begun to form over an area, the effect of bedrock and all other forms of control may be greatly reduced due to the effect already-formed drumlins have on ice movement, velocity and pressure. With the establishment of the beginnings of a drumlin distribution pattern this pattern will presumably influence all other future depositional processes, at least in part. It is therefore likely that during the creation of a drumlin field, drumlins have formed due to diverse influences, some depending on bedrock control and terrain factors, others on changing basal ice conditions, and others on the effect of already-formed drumlins.

ANALYSIS OF RESULTS

In deriving information to test the above hypotheses much of the statistical work was of an experimental nature. Before discussing the statistical analysis and field observations made on the selected par-

ameters within the context of questions relating to the above hypothesis, two important considerations must be borne in mind. Firstly, the data, being derived from a sample population of the drumlin field, are not representative of the population but are only indicative of what might be expected in a larger sample population. Secondly, in deriving correlations between different parameters it must be noted that any significant relationships that are found are statistical and may not be causal.

In order to analyse the results of this morphometric study several fundamental questions relating to drumlin morphometry were posed. The questions are as follows:

- 1) How are the different drumlin dimensions related to one another and how much variation in these relations occurs within a drumlin field?
- 2) Does drumlin spacing vary in relation to drumlin dimensions?
- 3) Does drift thickness variation cause marked changes in drumlin dimensions and spacing?
- 4) Do drumlin dimensions, drumlin spacing and drift thickness reveal any relationship to surface and/or bedrock slopes?
- 5) Does bedrock influence drumlin dimensions?
- 6) Does drumlin size influence the L/W ratio and orientation of individual drumlins in relation to ice moulding and ice movement?
- 7) Do the drumlins have a random or non-random distribution?

QUESTION 1 How are the different drumlin dimensions related to one another and how much variation in these relations occurs within a drumlin field?

As already mentioned while discussing drumlin shape (Chap. 4),

under ideal conditions drumlins might be expected to attain an equilibrium profile. This equilibrium form will be dimensionally directly related to the velocity and pressure of the ice and to the availability and rheological properties of the material needed to compose a drumlin. In this particular study of 160 drumlins, height, length and width were directly measured and volume computed from these measurements (Table 5). No attempt was made to correlate these measurements with those from other drumlin fields (cf. Baranowski, 1969; Barnett & Finke, 1971) but the L/W elongation ratio of 2.23 compares with similar areas in southern Ontario (Heidenreich, 1964; Trenhaile, 1971).

In order to discover what relationships did exist between the different dimensional parameters each variate was regressed against all others (Figs. 92-97) and a correlation matrices were drawn up (Fig. 98). Since the methods of measurement and volume calculation were similar to those carried out by Trenhaile (1975) it was possible to compare the correlation matrix for a sample of Glasgow drumlins with that for southern Ontario (Trenhaile, 1975, p.305).

The correlation matrices reveal that, of the three primary dimensions, the best correlation lies between width and height, a similar conclusion to that found by Trenhaile (1971) in southern Ontario. This fact is borne out on sample sizes of 160 and 34 drumlins. Although all these parameters correlate positively with one another, as is revealed in the regression line graphs (Figs. 92-94), height and width appear to be consistently more closely correlated.

In discussing drumlin shape Chorley (1959) noted the similarity between drumlins and other streamlined objects. In extending Chorley's ideas it might be suggested that the width/height ratio once established will be less likely to vary compared to length during further drumlin

TABLE 5

A Summary of Data (160 Observations)

	Mean	Minimum Value	Maximum Value	S.D.
Height	13.3	3.0	37.0	7.8
Length	639.2	237.1	1391.9	201.0
Width	287.0	83.0	681.0	114.7
Volume	139.0	3.0	824.0	155.1

B Summary of Data (34 Observations)

	Mean	Minimum Value	Maximum Value	S.D.
Height	14.8	3.0	30.0	9.1
Length	726.2	319.6	1391.9	235.6
Width	343.9	164.9	628.9	107.0
Volume	209.0	16.0	790.0	212.2
Nearest Neighbour	4.3	2.5	6.6	1.2
Density	18.0	12.0	25.0	3.5
Bedrock Slope	1.7	1.0	4.0	1.0
Drift Thickness	6.0	1.0	20.0	4.4
Surface Slope	2.1	1.0	4.0	1.1
Rock Control	1.5	1.0	2.0	0.5

(All measurements in metres)

$$\text{Volume} = x \cdot 10^4 \text{ m}^3$$

development. It has been shown that with increasing speed past an obstruction the vortices in the lee of the obstruction move farther down-stream from the lee of the obstruction and vice versa (Leopold et al., 1964). Therefore once a drumlin is established with a specific width/height ratio, the length of the drumlin can vary to a greater extent due to changing ice velocities causing drumlin elongation or diminution. Heidenreich (1964, p.105) considered that once a specific width was obtained length would continue to vary. It might be suggested that it is the ratio of width/height once established for a specific drumlin that would be less easily altered. This above hypothesis of constancy in one drumlin between width and height would appear to be further borne out by the fact that of the six correlations made on these dimensional parameters the poorest correlation was that found between drumlin height and length (Figs. 92,98).

Within the thesis area considerable morphological variations can be observed (Fig. 4). In relation to the total drumlin field, the thesis area lies at the up-ice end of the field. Beyond Drumchapel and Duntocher few drumlins were mapped before the lower slopes of the Kilpatrick Hills were encountered. In this extreme up-ice area of the field (NS 57 SW) the drumlins were found to be more elongate, narrower and smaller in volume, as can be seen from Table 6 below:

T A B L E 6

	n.	L/W.	W.	L.	H.	Vol.
NS 57 SW	44	3.29	182.47m	600.32m	12.98	93.09 x 10 ⁴ m ³
Mean Values	159	2.23	286.99m	639.15m	13.33m	138.50 x 10 ⁴ m ³
NS 66 NW	30	2.32	311.62m	723.00m	13.77m	220.70 x 10 ⁴ m ³

In the Springburn district (NS 66 NW), approximately 6.5km down-ice from this area, the drumlins were found to have much larger overall dimensions. In both these areas (NS 57 SW, NS 66 NW) the drumlins were elongated although to a much greater degree in the former area. Drumlin height would appear to increase very gradually in a down-ice direction probably in relation to increasing width. Trenhaile (1975) working recently in southern Ontario, using trend surface analysis up to the 6th order, found similar trends in drumlin height, length, volume and L/W ratio in the down-ice direction.

Two possible causes that may have acted together or separately in producing these spatial variations are changing drift availability with changing bedrock type and changing ice velocity and pressure. Firstly, the area investigated to the south-west of Milngavie (NS 57 SW) was found to be dominantly covered by red till derived from the Old Red Sandstone series and to have a low Carboniferous bedrock content (Chap. 5). Although few borelogs were available in this largely agricultural area the drift in the inter-drumlin hollows was thin, often less than a metre in depth. Many exposures of bedrock were observed indicating the thinness of the drift in this area (Fig. 4). In contrast, in the Springburn area (NS 66 NW), drift was almost totally derived from the much softer and more easily eroded Carboniferous bedrock. The drift was thicker and only in the rock drumlins at Necropolis Hill and Springburn Park was bedrock exposed (Fig. 4). These contrasts in type and depth of drift may be indicative of the changing availability of drift as the ice entered the Glasgow basin and began eroding the local Carboniferous sediments. Such a contrast in drift availability for drumlin formation may account for the differing drumlin dimensions. However added to these dimensional

variations, drumlin density in the up-ice is markedly greater than in the other area which tends to disprove, at least in part, such a theory (Table 7).

T A B L E 7

	n.	NN.	Density
NS 56 SW	12	2.93	30.00
NS 66 NW	9	3.88	16.88

Secondly, if the drumlins, from both areas, were formed within a very short time span, relative to the period of glaciation during which they were formed, then it can perhaps be argued that those drumlins in the up-ice area (NS 57 SW) were subjected to higher ice pressures relative to those in the down-ice area (NS 66 NW) since they were farther from the ice margin. With higher ice pressures causing the drift to be more easily sheared and consolidated, Smalley and Unwin have suggested that drumlins in such a zone will be more elongated. However although this theory may help explain the variation in drumlin elongation it is not a totally satisfactory explanation. Following the dilatancy theory, in areas of high ice pressures, drumlins are less liable to form and those that do might be expected to be sparsely distributed and of large volume in order that they withstand the higher ice pressures (Smalley & Unwin, 1968, p.379; Trenhaile, 1975, p.298). These implications of the dilatancy theory do not bear out the findings in the up-ice area where although elongation is above the norm, drumlin spacing is closer, density is greater and volume is much smaller. It is perhaps probable that a combination of both mechanisms

has occurred in order to create such marked spatial differences.

QUESTION 2 Does drumlin spacing vary in relation to drumlin dimensions?

Both nearest neighbour and density measurements for each drumlin were calculated in order to assess spacing. It has been stated that drumlin volumes are inversely proportional to their number and distance apart (Charlesworth, 1957, p.389). This would suggest that drumlin spacing is controlled by the prior location of other drumlins and that external factors can be ignored.

The average nearest neighbour distance between drumlin crests was found to be 428m with a standard deviation of 116m. When this parameter was correlated with dimensional parameters two significant statistical relationships were found (Fig. 98). The correlation matrix reveals that both width (at the 97.5% significance level) and volume (at the 95% significance level) are positively correlated with nearest neighbour. As drumlin width and volume increase in size so the spacing between drumlin crests appears to increase. To a much lesser extent similar relationships are indicated for height and length. This conclusion is contrary to that found by Trenhaile (1975, p.306) who states that "no reduction in the distance between summits" was noted.

Density measurements revealed an average density of 18.2 drumlins per 10.36km^2 with a standard deviation of 3.5 drumlins per 10.36km^2 . Correlations of density with dimensional parameters reveal negative relationships that are not statistically significant, except for height which is significant only at the 80% level. These correlations, unlike the nearest neighbour correlations, are similar to that found by Trenhaile (1975, p.305) using the same technique of measurement.

There would therefore appear to be little relationship between density and drumlin dimensions. This tentative conclusion, however, is contrary to that suggested in the dilatancy theory.

It may be inferred therefore that drumlins, during formation, are less affected by the number of drumlins in the immediate area but are influenced by adjacent drumlins.

QUESTION 3 Does drift thickness variation cause marked changes in drumlin dimensions and spacing?

It has been recently argued that thin drift deposits, unlike thick drift deposits, would be more easily and more rapidly saturated and thus more easily deformed (Crozier, 1975, p.187). This relationship would, it was theorised, possibly result in a negative correlation between drumlin elongation and till thickness. In the present study an average drift thickness of 5.9m was noted with a standard deviation of 0.97m. Drift thickness values ranged from 1.0m to 20.0m and therefore a considerable spread of thicknesses was available for statistical analysis. No statistical relationship however was found between drift thickness and drumlin dimensions (Fig. 98). This result confirms both Crozier's (1975, p.187) and Trenhaile's conclusions (1975, p.312).

On comparison of drift thickness and drumlin spacing parameters a correlation was found only between nearest neighbour and drift thickness (at 80% significance level). This relationship may indicate very loosely that with increases in drift thickness, nearest neighbour spacing increases. However, since width, which is closely correlated with nearest neighbour, has only a 0.36% explanation in relation to drift thickness, the above correlation between nearest neighbour and drift thickness may be more statistical than causal.

Since there is no close relationship between drift thickness and drumlin dimensions and spacing it seems likely that the thickness of any pre-existing drift is not an important factor of drumlin formation in this area.

QUESTION 4 Do drumlin dimensions, drumlin spacing and drift thickness reveal any relationships to surface and/or bedrock slopes?

As already mentioned, both the dilatancy and non-dilatancy theorists have contended that drumlin dimensions should change in accordance with the surface and/or bedrock slope due to changes in ice velocity and pressure (Smalley & Unwin, 1968; Miller, 1970; Muller, 1974; Crozier, 1975; Trenhaile, 1975).

Since it has been hypothesised that drumlin dimensions should probably show a relationship with spacing parameters (Smalley & Unwin, 1968; Hill, 1968; Trenhaile, 1971, 1975) it might be argued that drumlin spacing should also show a relationship with surface and bedrock slope changes. In discussing the relationship of drift to changes in bedrock topography several authors (Embleton & King, 1968; Flint, 1971; Nobles & Weertman, 1971; Andrews, 1975) have argued that, where bedrock slopes are orientated in the up-ice direction, drift deposition should be less than on slopes orientated down-ice. This hypothesis may be also applied to surface slopes since the final surface slope of the drift may represent a previous ground surface slope over which the ice has moved and deposited drift. To test these hypotheses graphs were drawn of length against volume (Fig. 99), length against width (Fig. 100), height against drift thickness (Fig. 101), nearest neighbour against density (Fig. 102) and volume against nearest neighbour (Fig. 103). On each of these graphs the individual points were marked with a dot if the drumlin, in question, lay over

a surface slope orientated in the up-ice direction (Figs. 99a-103a) or over a bedrock slope in the up-ice direction (Figs. 99b-103b otherwise an asterisk indicated the point). By this method of graphical representation both up-ice slopes and all other slope orientations can be indicated. If a relationship, for example, were to exist between drumlin volume and up-ice bedrock slopes (Figs. 99b, 103b) then a clustering of either the asterisk or dot symbol might be expected to exist somewhere in the scatter of differing drumlin volumes; if no relationship existed a random scattering of symbols for bedrock and surface slopes would be noted. In interpreting these graphs it must be remembered that, because of the nature of the data, clustering may occur, as is shown in the graph of length against volume (Fig. 99). This tendency of the data to cluster was not a major problem but is difficult to overcome. A further interpretative problem is the factor of chance due to choice of samples or choice of sample area which can only be overcome with further research in Glasgow and on other drumlin fields.

All parameters tested against both bedrock and surface slope either up-ice or in any other direction revealed no clear relationships. Perhaps volume may show a slight relationship with ground surface slope in the up-ice direction. Of the 16 drumlins with volumes less than $110 \times 10^4 \text{ m}^3$ 8 are on up-ice ground surface slopes whereas of the remaining 18 drumlins, above $110 \times 10^4 \text{ m}^3$ in volume, only 4 were found on a similar slope.

From the evidence presented by these graphs it would appear that drumlin dimensions and spacing exhibit little relationship to bedrock or surface slopes of any particular inclination or aspect. The lack of any relationship between drift thickness and these slopes further

substantiates the conclusion tentatively derived from examination of cross-sections and comparison of Rockhead and Drift Thickness maps (Chap. 8). This lack of any clear relationships between slope and drumlin parameters is supported also by work done in several drumlin fields (Reade, 1882, p.267; Hill, 1968; Aronow, 1959; Crozier, 1975; Trenhaile, 1975).

QUESTION 5 Does rock control influence drumlin dimensions or spacing?

Using the same graphical methods, those drumlins that exhibited a degree of rock control were plotted using a triangular symbol as compared with the non-rock controlled drumlins denoted by an asterisk (Figs. 99c-103c). In no case was rock control seen to influence either drumlin individual dimensions or drumlin spacing. For example, drumlins with rock control did not appear to be larger or smaller in volume than other drumlins. This may be due, firstly, to the small population analysed or secondly, to the probable rapid masking effect of drift on rock obstructions. This effect would very quickly remove any influence the rock obstruction may have initially had on drumlin initiation and dimensions (Smalley & Unwin, 1968, p.389). The final drumlin form and spacing appear to show little influence attributable to rock control, as points of initial drift accumulation and drumlin development. However rock control presumably must, in part, have dictated the initial pattern of drumlins within the drumlin field (Vernon, 1966; Hill, 1968).

QUESTION 6 Does drumlin size influence L/W ratio and orientation in relation to ice moulding and ice movement?

Within a sample area of a drumlin field, it might theoretically be expected that, under the conditions of the dilatancy theory, provided

factors such as drift availability, ice velocity and pressure are constant, any drumlin formed would be of approximately similar dimensions (pers. comm. I. J. Smalley, 1974). Any drumlins of much smaller or larger sizes might therefore be regarded as anomalies perhaps due to changing factors of formation that have only affected specific drumlins. If these anomalous drumlins are the result of a differing combination of factors of origin it is possible that they would exhibit a poorer relationship to the influence of ice moulding (L/W ratio) and ice movement (orientation).

In order to test this hypothesis three groups of drumlins (small, medium and large) were selected on the basis of length and volume. The influence of ice moulding is perhaps best reflected in terms of individual drumlin L/W ratios. By testing which of the three groups best approaches an ideal L/W ratio, some indication might be gained of the efficiency of ice moulding. The ideal drumlin, it was supposed, has a L/W ratio of between 2.50 to 3.00 (Chorley, 1959; Doornkamp & King, 1971; Flint, 1971). In this study a ratio of 2.50 was selected since the average L/W ratio for this part of the whole drumlin field was 2.40. Using a Chi-square test, with the expected value as 2.50, the L/W ratios of 11 randomly selected drumlins from each group were statistically analysed. The groups were arbitrarily selected on the basis of drumlin length: the small group with lengths less than 400m, the medium group with lengths between 500m and 700m and the large group with lengths greater than 800m (Table 8). The sample group with the largest deviation from the expected value $\left[\frac{(O-E)^2}{E} \right]$ may be regarded as the least ideally moulded. Both the small (4.01) and large (2.45) groups had the largest deviations with the medium group (2.09) the

TABLE 8

SMALL LENGTH		MEDIUM LENGTH		LARGE LENGTH	
Length (m)	L/W	Length (m)	L/W	Length (m)	L/W
288.7	2.55	618.6	2.00	1000.1	3.23
422.7	1.64	577.4	2.00	835.1	4.05
237.1	2.09	628.9	3.59	1010.4	2.23
329.9	4.00	608.3	2.46	958.8	3.00
309.3	3.75	639.2	2.38	958.8	3.00
391.7	3.80	567.0	1.22	938.2	1.38
298.9	3.22	618.6	1.62	1165.0	2.13
329.9	1.68	649.5	2.63	896.9	2.17
340.2	1.94	628.9	1.97	1391.9	3.55
319.8	1.41	628.9	2.90	1154.7	2.43
319.6	1.55	628.9	1.69	1072.2	2.74

TABLE 9

SMALL VOLUME		MEDIUM VOLUME		LARGE VOLUME	
Vol. ($\times 10^3 \text{ m}^3$)	Orientation	Vol. ($\times 10^4 \text{ m}^3$)	Orientation	Vol. ($\times 10^4 \text{ m}^3$)	Orientation
18	87	128	95	453	90
7	82	149	80	422	85
7	110	134	90	636	65
3	95	139	85	434	100
11	90	149	90	409	70
5	95	150	115	516	95
21	90	144	100	790	55
17	120	135	110	824	90
5	110	127	105	433	92
11	120	152	100	591	75
4	95	158	110	821	95

least. It may therefore be tentatively concluded that, in this part of the drumlin field, the drumlins of medium length have been more ideally ice moulded than the other two groups.

To test the hypothesis that drumlins of different size groupings may be better orientated in relation to the mean direction of ice movement in this area (97°) the following analysis was made. The orientation of each drumlin within three groups, selected on the basis of volume, was tested using a Chi-square test (Table 9). The volume groups were subdivided into small volume ($< 30 \times 10^4 \text{ m}^3$), medium volume ($125 \text{ to } 160 \times 10^4 \text{ m}^3$) and large volume ($> 400 \times 10^4 \text{ m}^3$). As in the Chi-square test of L/W ratio, it was assumed that the larger deviations from the expected value $\left[\frac{(O-E)^2}{E} \right]$ were least related to the mean direction of ice movement. The least deviation was found in the medium group (15.66) whereas in the small (18.85) and large (44.12) groups deviations were much greater. Similar results have been found in the past (Chorley, 1959, p.343; Trenhaile, 1975, p.304). It may be therefore tentatively concluded that drumlins of medium volume were most closely affected by the direction of movement of the ice.

Although both these tests are more indicative than significant, due to the small sample populations, they do suggest that drumlins of either larger and smaller lengths or larger and smaller volumes than the norm have also been less efficiently ice moulded and affected by the flow of the ice in this small area. Although information does not exist for all of these drumlins, sufficient data exists from borelog records to be able to examine the small and larger groups used in the above tests. Many of the larger volume drumlins are rock controlled; several as at Necropolis Hill and Riddrie, appear to be

controlled by bedrock intrusions. Almost all of the very small drumlins were found lying on the sides or flat crest areas of much larger drumlins, as at Lambhill and Necropolis Hill. It is difficult to ascertain why these two groups of drumlins are apparently so poorly related to the processes and movements of the ice. It seems likely that a combination of factors such as drift availability, the stage in the period of glaciation when these drumlins were formed and the influence of final ice movement over the area may be influential in explaining the anomalous characteristics of these two groups of drumlins.

QUESTION 7 Do the drumlins have a random or non-random distribution?

In the past in several drumlin fields the spacing and distribution of individual drumlins has been analysed (Reed *et al.*, 1962; Vernon, 1966; Hill, 1968, 1971; Smalley & Unwin, 1968; Miller, 1970; Trenhaile, 1971, 1975). The findings of this work is varied but both randomness and non-randomness have been detected in different drumlin fields and in different parts of the same field (Vernon, 1966; Hill, 1968). Nearest neighbour analysis was used to test whether the drumlins in a small sample area within Glasgow, are randomly or non-randomly distributed. Nearest neighbour analysis "tests the manner and degree to which the distribution of individuals in a population in a given area departs from that of a random distribution" (Smalley & Unwin, 1968, p.385). The statistical equation (Clark & Evans, 1954) is as follows:

$$R = D_{\text{obs}} / 0.5 (A/N)^{-1/2} \dots\dots\dots(12)$$

where D_{obs} is the mean linear distance between the drumlin crests in a specified area A and the nearest neighbouring drumlin crests, and N

is the number of drumlins within the area. Values of R range from zero for maximum aggregation to 2.1491 for maximum (hexagonal) spacing. Random distribution give values of unity. Clark and Evans (1954) have pointed out that a random distribution is one in which any point has the same chance of occurring on any sub-area as any other point and any sub-area of specified size has the same chance of receiving a point as any other sub-area of that size.

Within an area of 27.65km^2 in central Glasgow, 34 drumlins were taken as a sample and their nearest neighbour distances measured. The average linear distance (D_{obs}) was 0.428km resulting, after calculation, in an R value of 0.949. This derived value indicates that the drumlins within this small sample area appear to approach a random distribution (cf. Smalley & Unwin, 1968, p.387; Trenhaile, 1971, p.117). It may be suggested that this apparently random distribution is the result of controlling formative factors having had little influence on drumlin distribution either because their influence has been limited or their distribution has been random.

In analysing drumlin orientations near Boston, U.S.A., Reed *et al.* (1962) suggested that the large standard deviation (17.4°) found implied "greater bedrock control". Similarly, Trenhaile (1971) found large standard deviations in the Owen Sound and Guelph drumlin fields which he attributed to bedrock control and to a lesser extent other factors such as ice velocity and direction changes. Such bedrock control has, in the past, been used as an argument to explain non-random drumlin distribution. In the Glasgow area, an examination of 160 drumlins, a standard deviation of 16.7 degrees was found. From the nearest neighbour analysis of a small area of the field no non-random influences could be detected; therefore this large standard

deviation may be the result of random controlling factors such as changes in ice velocity, pressure and direction of movement.

FINAL REMARKS

The recent morphometric analyses completed by Crozier (1975) and Trenhaile (1975) have both tended to substantiate the dilatancy theory, at least in principle. Since this study only examined the up-ice part of a much larger drumlin field such broad conclusions cannot be made. However although many aspects of the dilatancy theory seem applicable perhaps a more comprehensive theory must be devised to encompass the variations found contrary to the dilatancy theory. The conclusions relating to drumlin dimensions tentatively made in this chapter substantiate the results of most past workers. The use of the Rockhead and Drift Thickness maps allowed more accurate analysis of the relationships between drumlin dimensional characteristics and those of bedrock slope, ground surface slope, drift thickness and rock control. The result of this work would suggest that little or no relationship appears to exist between drumlin dimensional and non-dimensional characteristics (cf. Aronow, 1959, p.202). However since the form and location of drumlins presumably cannot be totally controlled by glaciological factors, relationships must exist with external factors although they may be indirect, complex and difficult to measure or estimate. This latter problem will be perhaps overcome only if other methods of measurement are used or devised.

PALAEOMAGNETISM AND THE MAGNETIC
FABRIC OF GLASGOW'S TILLS

Investigations into the palaeomagnetism and magnetic fabrics of the red and grey tills in Glasgow were motivated by recent work on the palaeomagnetism of till in Canada. Little work has been done in Britain on the palaeomagnetism of terrestrial unconsolidated deposits. As a result sampling methods had to be devised and the sampling errors qualitatively assessed.

Doell and Cox (1961, p.233) have shown from work with artificial sediments that it is possible for very small magnetic particles while passing through water or a slurry medium, to rotate and align themselves in the direction of the earth's magnetic field. The thickness of the water or slurry medium is not known but only a small quantity of water is necessary for magnetic particles to align themselves during deposition. Once the particles are buried under subsequent material no further rotation of the particles is likely to occur.

The aim of this investigation was four-fold, namely:

- 1) to attempt to locate the magnetic pole positions of the red and grey tills separately, in order to discover the relative age of the two tills;
- 2) by analysing the magnetic parameters to discover the nature of the material in which the magnetite particles lie and to estimate the percentage of water in the till at the time of deposition;
- 3) to utilise the anisotropic magnetic fabrics to indicate ice

- movements around and over drumlins; and
- 4) to discover what future research possibilities might exist in studying unconsolidated deposits associated with glaciation using this new technique.

PREVIOUS WORK

Several workers have very recently introduced this technique into glacial geology (Fuller, 1962; Jones, Beavers & Alexander, 1966; Vonder Haar & Johnson, 1973; Gravenor, Stupavsky & Symons, 1974). Although some disagreement does exist on the method by which particles are released from the base of a glacier (Goldthwait, 1971), two concepts divide most workers. There are those who accept a "plastering on" process (Holmes, C.D., 1941, p.1312; Flint, 1971, p.171) and those who accept a "melt-out" process (Harrison, 1957, p.301; Boulton, 1970, p.235; Shaw, 1971, p.370). However in both concepts it is normally assumed that the particles were released from the ice by basal melting, utilising geothermal and frictional heat which may be supplemented by heat from percolating meltwater or a combination of these.

It was therefore conceived that at the time of release of material from the base of the ice, rock and mineral fragments would be able to rotate in a slurry of water and suspended rock and mineral fragments. Any magnetic particle passing through such a medium would therefore tend to align itself with the earth's magnetic field at the time of deposition.

A. Holmes (1966, p.1206) has pointed out that the fundamental hypothesis on which palaeomagnetic investigations are based is that the geomagnetic field, averaged over an appropriate time, varies

according to the earth's spin and the relationship of continental land masses to one another. This has resulted in the concept of "polar wandering". This concept hinges on the idea that, at differing times in the past, the magnetic poles of the earth have occupied differing locations with regard to the present longitudinally defined geomagnetic poles. In many instances the earth's polarity has "reversed" but although many of these reverses have now been dated it appears there may be more reversals than are currently known resulting in an apparently chaotic calendar of magnetic events (Olavsson & Svenonius, 1975). Gravenor et al. (1973, p.1073) have demonstrated that palaeomagnetic data obtained from the Port Stanley Till, southern Ontario, which is dated in the interval 14,700 to 13,500 years B.P., revealed a virtual palaeogeomagnetic pole centred somewhere in north, central Russia.

The mineral that carries this magnetic remanence is a black opaque ferric oxide (Fe_3O_4) known as magnetite. This mineral, often occurring as titaniferous magnetite, is present in many igneous, metamorphic, and derived sedimentary rocks. Within the thesis area (Table 10) magnetite is commonly found in teschenite, essexite, quartz-dolerites, basaltic lavas and in the metamorphics north of the Highland Boundary fault (Clough et al., 1925; Bluck, 1973).

T A B L E 10

Rock	Essexite	Dolerite	Mugearite	Olivine basalt	Trachyte
Location	Lennoxton	Paisley	Bute	Kilpatrick Hills	Gourock
Percentage Magnetite by weight	8.81	7.37	6.46	8.30	3.32

(after Clough et al., 1925; Richey et al., 1930)

It should be noted that the above table gives only an approximate percentage of magnetite and this percentage may vary greatly from one locality to another over a short distance. For example, another olivine basalt sampled at Duncolm Hill (471 774) as compared with Auchinedon Hill (494 804) had only 4.62% weight of magnetite.

Strangway (1970) has noted that magnetic particles of less than 10 μ are "most likely" to carry a stable magnetic orientation. However Gravenor et al. (1973) found the best results from particles less than 37 μ in size. This stable magnetic orientation is termed, because of its history, a "Depositional Remanent Magnetism (DRM)" (Strangway, 1970, p.44). However for the purposes of this study the term used by Gravenor et al. (1973, p.1069) that is the "Natural Remanent Magnetism (NRM)" was adopted. The Natural Remanent Magnetisation of a material consists of any remaining primary magnetisation together with all secondary magnetisation. The primary factor is what is of interest, the secondary factor develops as the magnetic particles lie in situ within the deposited material and is a product of the changing earth's magnetic field which changes with time. The older a deposit the greater the tendency for secondary magnetism to be a major factor of error in measurements (Tarling, 1971).

SAMPLING PROCEDURES

In this preliminary study in Glasgow, 23 samples were collected: 6 were taken with plastic samplers, 16 with a brass corer and one was taken as a block sample. Initially a plastic cylinder 2.5cm in diameter, and 2.5cm long, was used as a sampling tool. The cylinder was pushed by hand as nearly horizontal as possible, into a freshly cleaned till face, sampling at least 3m below the ground surface. When it was inserted into the till, the orientation and dip of the cylinder was

measured using a Suunto compass. Problems however arose because the plastic cylinder was too easily warped when pushed into the till and was difficult to keep at a constant angle during insertion. Because it warped and deformed when small stones were close to the cylinder walls, and because of the consolidation of the till, several samples had to be abandoned. The time taken at the till face to get a good sample, undeformed, with no stones, was also too long. After six samples therefore, a new sampling tool was devised.

A brass cylinder corer, 20cm long and 2.5cm in diameter with a piston attachment to allow extrusion of the sample, was found to be much more satisfactory. The corer was of brass rather than steel to avoid steel parings from stone abrasion giving false magnetic readings. Like the plastic cylinder, the brass corer was inserted by hand, as nearly horizontal as possible, with the piston removed. Orientation and dip measurements were taken and as with the plastic cylinder, the corer was then dug out of the till face. The core inside the brass corer was then extruded using the piston. The core sample was placed in a plastic bag, numbered and sealed. When a stone or other obstruction prevented the corer from being inserted, the corer was removed and a new sample taken. If stones were detected on the sides of the sample core, after it was extruded by the piston, the core was discarded in order to avoid magnetic anomalies due to distortion and deformation of the till by the stone. Any major distortion of the core would have affected the orientation of the magnetite particles in the till core and was avoided at all times. A certain disturbance of the till occurs when using the sampler but this could not be avoided.

The other sampling procedure involved removing a large block,

approximately 75cm by 50cm, from the till face using a spade. Firstly a rectangle was marked on the till face, then the rest of the face was excavated back 50cm to leave the block protruding. The orientation of the block was then taken with a compass and a line normal to the till face painted on the top of the block. The block was subsequently cut from the till face. However this procedure had to be abandoned due to the high frequency of block breakages.

LABORATORY PROCEDURES

The samples were taken back to the laboratory where all contaminated or distorted samples were discarded. The samples taken in the plastic cylinder were measured in them. The brass core samples were removed from their plastic bags and cut into two or three smaller cylinders, 2.5cm long by 2.5cm in diameter. This allowed several small cores to be measured from the one sample. Samples were taken from the interior of the block sample and were cut by hand to squares 2.5cm by 2.5cm. All samples were marked with a fiducial mark along the line of orientation and the vertical axis. The plastic cylinders had a small plastic vertical indicator on top of the cylinder which substituted for a fiducial mark.

The natural remanent magnetisation (NRM) of each small specimen sample was measured using a spinner magnetometer. The specimen is spun in a slow speed fluxgate (Molyneaux, 1971, p.430) inducing an alternating voltage, whose amplitude depends on the intensity of the component of magnetisation along the axis of spin an perpendicular to the axes of the coils (Fig. 104). Each sample was spun on its vertical and then on its horizontal axis (Tarling, 1971).

The measured directions of magnetization were reduced to their

"declination" and "inclination". Declination is the angle (turning clockwise) between the specimen magnetisation direction and geographical north (0°). Inclination is the angle between the horizontal and the dip of the magnetization, positive downwards, negative upwards (Fig. 107).

Although the natural remanent magnetism (NRM) suggests that the magnetic particles were aligned in the earth's field during deposition of the till, there exists the possibility that this alignment was partly developed due to the action of glacier flow. As has been noted in discussing till fabrics, particles within the till may be aligned parallel to the direction of ice movement. It is therefore possible that the long axes of magnetic particles may also be aligned parallel to the direction of ice flow. This externally induced alignment is termed anisotropy (Fuller, 1964; Tarling, 1971; Gravenor *et al.*, 1973).

The magnetic anisotropy was determined by measuring the maximum and minimum magnetic susceptibilities of the specimens. These susceptibilities or small areas of magnetic concentrations, were measured by spinning the specimen between a pair of perpendicular induction coils and measuring the torque exerted by the specimen on the suspension fibre. If there is a preferred direction of magnetisation, the specimen attempts to turn to it, thus exerting a torque.

The maximum and minimum magnetic susceptibilities and the natural remanent magnetism of each sample were plotted on stereographic plots. Each plot is marked clockwise on its circumference 0 to 360 degrees, (i.e. "declination"). From the outside circumference to the centre of the plot, from 0 degrees on the edge to 90 degrees in the centre, is "inclination".

Other factors were derived and calculated from these above results and will be discussed and their methods of derivation shown later.

PROBLEMS ENCOUNTERED DURING PROCEDURES

The major problems of sampling tools, stone content and constant angle of insertion have already been mentioned. Whenever possible stony parts of the till face were avoided and the tool was impressed into the till at as slow a rate as possible, taking care not to move the tool from side to side. As already noted, finding good exposures in an urban area is difficult especially when representative samples of both red and grey till were required. Of the 23 samples taken, 13 were of red till, the remainder of grey till.

Samples were taken of fine-grained till with as few gravel size particles (>2mm) as possible in the specimen. This was to avoid the problem of having small rock fragments causing exaggerated and false magnetic susceptibility measurements. This distortion would be caused by the entrapped magnetic particles in the igneous and metamorphic rocks present having differing geomagnetic alignments in comparison to magnetic particles in the till. This problem, as will be discussed later, cannot be totally overcome and is partly the reason for the large scatter of measurements (pers. comm. R. Thompson, 1975).

All samples have, as well as a primary component of remanence, a secondary component which is 1) the result of the age of the material and the changing geomagnetic field since initial deposition and 2) the result of ice flow alignment akin to stone fabric alignment. Because this secondary component has the effect of causing seemingly greater variation in the natural remanent magnetisation (NRM) of the sample than is actually the case, this secondary component is normally

either reduced considerably or removed.

Gravenor et al. (1973, p.1071) have shown this process may alter the final reading of the remanent magnetization. In this study total removal of the secondary magnetic component was not carried out and therefore a far greater scatter of results has had to be handled than would otherwise occur after demagnetisation. Due to this factor no great stress was placed on individual scattered measurements and only a broad picture can be drawn. No major laboratory problems occurred in measuring anisotropy.

PERCENTAGE OF MAGNETITE IN SAMPLES

In order to determine the percentage of magnetite particles in each individual sample, 1500g of air-dried till from sample sites at Milngavie, Baljaffray, Blackhill, Ibrox and Hamilton Hill were sieved through a 1mm sieve. The material that passed through this sieve was then screened through a series of sieves down to a 75 μ mesh size. Fractions left on each sieve were collected, weighed and stored. From the fine sand fraction (250 - 75 μ) a 25g fraction was collected for each sample. These 25g samples were then treated with hydrogen peroxide, first by adding 50ml to a beaker and allowing the samples to stand for 24 hours, thereafter a further 50ml was added and the sample warmed in a water-bath until any effervescence subsided. Only in the case of the Baljaffray sample was any reaction visually noticed.

The samples were then diluted with water and filtered. The treated filtrate was weighed and then placed in a fractionation bulb into which tetrabromoethane (Sp. Gr. 2.96) had already been added. The heavy minerals separated by settlement from the rest of the sample, this process taking about 24 hours. The material that had deposited itself

at the base of the bulb was filtrated out into a beaker and the filtrate boiled dry. The residue was weighed and a strong magnet was then used to remove all magnetite particles from the residue. The residue was again weighed and from this value the amount of magnetite in the sample could be calculated. Gravenor *et al.* (1973) had found that of the magnetically separated particles just less than 5% were not magnetic. Bearing this in mind it was felt that considering all other possible laboratory errors this error could be ignored in this instance. Errors occurred where the sample separated in the fractionation bulb and in the removal of magnetic particles from the residue, but it was extremely difficult to reduce or estimate the effect of these errors. Initially it was thought that the magnetic particles once separated from the residue could be weighed but this proved impossible due to spillage and the small weight of magnetite recovered.

T A B L E 11

Till	Sample	Location	Initial Wt. 75u	Wt. of Magt.	% Magt.
Red	A	Milngavie	15.4970g	0.053g	0.342
Grey	B	Blackhill	9.5510g	0.054g	0.565
Red/Brown	C	Hamilton Hill	15.0606g	0.034g	0.226
Red	D	Baljaffray	16.0648g	0.057g	0.355
Grey	E	Ibrox	16.339g	0.096g	0.588
Average			=	0.415%	
Average (Red)			=	0.349%	
Average (Grey)			=	0.577%	

The percentage of magnetite recorded (Table 11) suggests that the grey till has a slightly higher percentage of magnetic particles, as will be borne out from magnetic strength figures given later. A fairly consistent percentage amount was found, the average for all the samples being 0.42%. This figure may be compared with the $\gg 1\%$ magnetite found by Gravenor et al. (1973, p.1076) for a till in southern Ontario.

ANALYSIS OF RESULTS

NATURAL REMANENT MAGNETISATION (NRM)

The natural magnetic remanence directions (Table 12)(Figs. 105, 106) of all the samples are much more scattered than the results derived on the Port Stanley till (Gravenor et al., 1973). The major reasons for this wide scatter is probably the effect of secondary magnetism which A.F. demagnetisation could reduce and the coarse-grained nature of the till. Although virtual pole positions of these uncleaned specimens were calculated, the wide scatter exhibited when they are plotted on a polar projection is of no significant value (Fig. 109). From Figure 106 it can be seen that the within-site variability is as great as the between-site variability. The significance of this variation in natural remanent magnetism remains uncertain. It would not be unreasonable to suggest however that the two tills were not markedly different in their scattered distributions. Since no significant distinction exists between the two tills it might be very tentatively suggested that they were deposited either at the same time or very close in time to one another.

SUBGLACIAL ENVIRONMENT IN WHICH GLASGOW'S TILLS WERE DEPOSITED

As well as measuring the natural remanent magnetism, the bulk

susceptibility of each sample was measured. The bulk susceptibility, as defined by Nagata (1961), is the ratio of the intensity of magnetisation produced in a material to the magnetising force or field intensity to which the material is subjected. The bulk susceptibility gives some measure of the magnetic content of the sample measured. By plotting the maximum and minimum axes of the susceptibility ellipsoid of each sample a stereographic plot of the magnetic anisotropy was constructed (Table 12, Fig. 107).

The minimum susceptibilities illustrated in Figure 108 are clustered around the vertical direction. This means that the maximum and intermediate susceptibility axes are nearly horizontal. This conclusion reveals that the magnetite particles in the samples are orientated with their long axes in the horizontal plane. This preferential alignment, similarly found by Gravenor et al. (1973), seems to indicate that the magnetic particles settled with this alignment on being released into a fluid slurry. The alignment would most likely seem to be the result of shear forces set up by the flow of the ice, in some manner similar to till fabric alignment and to alignments possibly inherited from the shear planes within the ice before the particles were released.

The above values of natural remanence magnetic intensity and the bulk susceptibility as a ratio of one to the other were used to calculate modified Koenigsberger values (Q) (Table 12). Stupavsky and Gravenor (1974, p.434) constructed a graph of Q values against the percentage weight of water in an experimentally constructed slurry (Fig. 110). In plotting the Q values found for the Glasgow tills it was possible, using the constructed line of Stupavsky and Gravenor, to calculate the percentage weight of water in the slurry that might have existed beneath the ice sheet that deposited the Glasgow tills

(Fig. 112). Stupavsky and Gravenor's graph of Port Stanley till can be used for the Glasgow tills because both tills most probably were deposited in their upper portions approximately 14,000 years B.P.

Stupavsky and Gravenor (1974, p.434) have shown that: "the present Earth's magnetic field is the approximate mean of the maximum and minimum (intensity) of the Earth's magnetic field for the past 9000 years which are respectively, 50% higher and 50% lower than the present intensity". Because the Q values for the magnetic intensities are directly proportional to the field, the calculated Q values for the extreme palaeointensity values of Glasgow till are 1.42 and 0.47 with a mean of 0.95 (Table 12). Therefore the Glasgow till acquired its natural remanent magnetism in a slurry composed of a minimum of approximately 36% and a maximum of 57% water by weight (Fig. 112). This is in contrast to the Port Stanley Till which acquired its palaeomagnetic characteristics in a slurry composed of a minimum of 28% and a maximum of 47% (Stupavsky & Gravenor, 1974, p.434).

EFFECTS OF MAGNETITE PARTICLE SIZE, OF WATER CONTENT AND OF WATER LAYER THICKNESS ON THE CALCULATED PALAEO-MAGNETIC VALUES

From the calculations made of maximum anisotropic susceptibilities, Q values, bulk susceptibility and the percentage of water by weight in a subglacial slurry certain characteristics of the subglacial environment can be suggested. Stupavsky and Gravenor have demonstrated that as the Q values increase, with increasing water content in a slurry, the bulk susceptibility values appear to decrease because of greater separation of the magnetic particles one from another. In the case of the Glasgow tills this inference is partly borne out by the graph of Q values against bulk susceptibilities (Fig. 113);

although the relationship is not particularly clear in the Glasgow tills. The reason for this poor relationship may be due to the size of the magnetite particles present in the Glasgow tills.

It has been clearly shown that the magnetite particle size may have a fundamental effect on the derived palaeomagnetic results (Gravenor et al., 1973; Stupavsky & Gravenor, 1974). Larger particles (>63 μ) tend to cause Q values to have less chance of being high while not affecting bulk susceptibility values to the same degree. Similarly Stupavsky and Gravenor have theorised that because the Port Stanley till has a well defined maximum susceptibility distribution this is evidence against there having been a water layer or very thin slurry of any great thickness (of the order of a few centimetres) present at the subglacial interface. The Glasgow tills in contrast reveal maximum susceptibility values that are fairly well scattered. From their experimental work on laboratory-produced slurries Stupavsky and Gravenor found that in slurried that were either very fluid or of no great thickness, large magnetite particles tended to exhibit scattered maximum susceptibility values.

It is therefore the writer's opinion that from the evidence already noted, of a water percentage in the subglacial slurry higher than in the Canadian example and of the poor relationship between the Q values and bulk susceptibility; the Glasgow tills contain magnetite particles larger than those of the Canadian till and that they were probably deposited through a much more fluid slurry. The skewed anisotropic fabrics, as will be discussed below, are further evidence for this hypothesis.

ANISOTROPIC MAGNETIC SUSCEPTIBILITY FABRICS

It is generally accepted that particles embodied in a moving

medium, yet free to rotate, will align themselves with their long axes parallel to the major direction of ice movement. Fuller (1964) used the magnetic susceptibility anisotropy of some tills as a rapid means of fabric determination. However since then this technique had rarely been used until Gravenor et al. (1973) noted its possibilities along with several fundamental drawbacks. They noted that as magnetite particles were released into a slurry only the smaller particles ($< 37 \mu$) were able to rotate freely in the magnetic field. Large particles tended to form "chainlike connections" one with another and to be less capable of rotation. Gravenor et al. (1973) have argued that in the typical poorly-sorted till the small magnetite particles will tend to reveal the palaeomagnetic field at the time of deposition. The larger particles, it is argued, exhibit either relict inherited orientations from the positions they held in the basal ice shear planes or, if they are released into a thick slurry where they would be incapable of free rotation, they would instead have been influenced by hydrodynamic forces tending to result in scattered orientation fabrics.

The anisotropic fabrics from the Glasgow tills reveal that of the 19 sites plotted only 3 (15.8%) were parallel to the known ice direction and drumlin orientations, a further 8 (42.1%) were sub-parallel to the ice direction and 7 (36.8%) were at right angles to the ice direction (Fig.108). Sample 13B from Maryhill B site (567 703) has a steep dip uncharacteristic of the other samples but is parallel to the direction of ice movement. These scattered fabrics may be the result of intricate ice movements around subglacial obstacles such as rock knobs or developing drumlins, of a random number of relict orientations inherited from the basal ice or of the vagaries of the hydrodynamic pressures externally and internally affecting the subglacial slurry

layer. These findings would seem to further substantiate Gravenor et al.'s results and support the conclusion that the magnetite particles within Glasgow's tills are dominantly larger than 37 μ and were deposited in a thick, highly fluid, slurry. It can therefore be concluded that in the use of magnetic susceptibility anisotropy as a technique of till fabric determination the reliability of orientations is limited without prior knowledge of magnetite particle sizes.

CONCLUSIONS

Although this investigation has derived several useful conclusions much remains to be done and tested in future research.

The evidence from the natural remanent magnetisation of the samples is such that it cannot be conclusively stated that the red and grey tills were deposited during the same narrow time period; but equally no differences between the two tills can be detected indicating different times of deposition.

The Glasgow tills, from the evidence of maximum and minimum susceptibilities and calculated Q values, were deposited as material released from the base of the ice mass by a melt-out process such that the particles constituting the till passed through a fluid slurry with between 36% and 57% by weight of water in that slurry. The importance of this water or slurry layer in lubricating the glacier cannot be underestimated (Chapter 14). Gravenor et al. (1973, p.1078) suggested that the effect of such a layer as a lubricant may have caused the ice sheet in the southern Ontario area to advance rapidly.

It appears highly probable that the most recently deposited till would be sufficiently permeable to allow some of the subglacial water to escape downwards, thence moving in the general direction of the

glacier margin. This movement of water would suggest either that hydrodynamic pressures were relatively high at the ice/slurry interface or that the deposited till had a surface skin of unconsolidated material, containing numerous open pores, acting as a kind of transient but effective aquifer. A picture of the subglacial environment that must have encapsulated a drumlin is therefore emerging.

The anisotropic fabrics, as noted, are only of limited value in allowing the direction of the major ice movements to be known. However these fabrics do indicate the thickness of and the effect of pressures on the slurry layer.

The Glasgow tills when compared to the southern Ontario tills are significantly different in certain respects. The samples of Glasgow till are all taken from drumlin till whereas the Canadian tills are part of a till sheet. The Glasgow tills contain a larger percentage of large magnetite particles. The particles appear to have been deposited in a slurry that was both thicker and of a more fluid nature. How important these differences are is difficult to assess until more work on both till sheets and drumlin till has been completed but they do tentatively hint that the subglacial environment of a drumlin may be somewhat different from that of a till sheet.

T A B L E 12

AVERAGE VALUES

No. of Samples	Q	Bulk Susceptibility (emu cm ⁻³)	Strength (emu cm ⁻³)
Total = 23	0.95	15.85 x 10 ⁻⁵	7.874 x 10 ⁻⁴
Red Till = 13	0.92	18.00 x 10 ⁻⁵	6.100 x 10 ⁻⁴
Grey Till = 10	0.98	13.05 x 10 ⁻⁵	10.170 x 10 ⁻⁴

TILL - ITS GEOTECHNICAL PROPERTIES

The geotechnical properties of till appear to be dependent upon the mode of till deposition, the lithology of the parent material, the pre-depositional history of the till material and the post-depositional processes and changes that the till has undergone (Dreimanis & Vagners, 1972). Since the formation of a drumlin is linked to a complex interaction between the ice, its bed and the material composing the till (Chap. 14), it is essential that the nature of the geotechnical properties of the till be known. The relationship between the above factors is closely dependent upon variations of and reactions to applied stresses. These stresses are largely created by the effect of the overlying, moving, ice mass. It therefore seems valuable to attempt to understand how till within drumlins reacts to stresses (cf. Chap. 6).

In studying the geotechnical properties of the till in Glasgow it was hoped that comparison between samples of red and grey till might further elucidate the relationship of these two tills to one another and to their respective parent materials.

PREVIOUS WORK

L. Goldthwait (1948, p.5) noted that "the density of till, at any given place or at any given depth, is unpredictable". Goldthwait rejected the theory of till overconsolidation as a consequence of ice overburden pressures (cf. Harrison, 1958). Instead he suggested that the consolidation value of a till is controlled by the water content at the time of consolidation. He also noted that till layers (cf.

Chap. 9) within the till were denser near the drumlin surface than at depth, thus substantiating his theory of till moisture content rather than ice overburden pressure controlling consolidation.

Easterbrook (1964, p.749), using void ratios and bulk densities, showed that different tills could be distinguished from one another.

Harrison (1958) made use of preconsolidation values of silt underlying till in central Indiana in order to construct past ice margins. More recent workers (Mathews & Mackay, 1960; Mathews, 1967,1974; Kazi & Knill, 1969, 1973; Sangrey, 1970; Greensmith & Tucker, 1971; Moran, 1971) have utilised the same idea. However, preconsolidation values cannot be easily converted to ice thicknesses since other processes, such as dessication, may cause overconsolidation. Therefore the use of preconsolidation values in the reconstruction of past ice sheet margins and thicknesses must remain tentative.

In discussing tills in New England, Linell and Shea (1960, p.278) pointed out that "it is possible that very small amounts of particular materials or minerals may have a decisive influence on the strength and other characteristics of a soil such as till". They discovered that illite, a clay mineral, had a peculiar influence on certain New England tills, causing sudden changes in till shear strength.

Several soil mechanics engineers have studied the tills within the Glasgow area (Busbridge, 1968; McKinlay, 1969; Anderson, 1970, 1974; Thorburn & Read, 1973; McKinlay et al., 1975). Their main conclusion is that till has a wide range of geotechnical properties. Busbridge has shown that the red till is often distinguishable from the grey till on the basis of shear strength, finding the values as shown in Table 13. McKinlay, in a more detailed study of unweathered and weathered till, found a remarkably uniform plasticity between all

tills measured. He also pointed out that till, being a material composed of a wide particle size range from clays to boulders, is difficult to test for shear strength values. The size of sample taken therefore becomes important. In an attempt to circumvent laboratory errors, McKinlay adopted in situ testing using a pressuremeter. The values of till shear strength using this in situ procedure gave results consistently 80 to 90% higher than those obtained in the laboratory. Recent work by McGown (pers. comm. 1975) has revealed that although sample testing sizes of 101.6mm (4") diameter gave better results than the previously normal 38.1mm (1½") diameter samples, sample sizes of 228.6mm (9") diameter only marginally improved the results obtained at the 101.6mm size.

T A B L E 13

	Average Till	Average Red Till	Average Grey Till
Shear Strength (Kg cm ⁻²)	1.08	0.69	1.46
Range		0.26-1.76	0.35-3.81

METHODS OF DETERMINATION AND RESULTS

In measuring the geotechnical properties of the till in Glasgow all samples were taken from a depth of at least 3m below ground surface in order to avoid the effect of weathering (Chap. 3). Samples were taken of red and grey till and from drumlin and non-drumlin locations. Measurements of compressibility and shear strength were carried out with the aid of members of the Civil Engineering Department of Strathclyde

University. Samples were taken by hand and by boring equipment and immediately transferred to the laboratory for testing or storage. In most instances several samples were taken at the same site to allow comparison and reduction of measurement errors.

PARTICLE SIZE DISTRIBUTION

The particle size distributions of both the red and grey tills were calculated using 20 samples of which 9 samples were red till. The samples were air dried and 200g of each sample were treated with hydrogen peroxide in order to remove organic matter. Particle size distribution was determined using a modification of the hydrometer method (Bouyoucos, 1934; Piper, 1950) using sodium hexametaphosphate as a dispersing agent. Each sample was agitated in a shaker for 18 hours and then washed into a litre cylinder, diluting to the litre mark. The laboratory temperature was noted and the hydrometer inserted after 3 minutes taking a reading after precisely 4 minutes to obtain the weight of silt and clay. After restirring of the suspension and standing for a further 2 hours a second reading was taken to obtain the clay content. The sand content is calculated as the difference of silt and clay from the original sample weight.

The results were plotted on a soil texture triangle (Fig. 114). This figure reveals that the fine fraction of the till ($<0.06\text{m}$) composes 20% to 60% of the till samples (cf. Thorburn & Read, 1973, p.322) and thus these tills may be regarded as typically multi-modal in particle size distribution (Dreimanis & Vagners, 1971, 1972; McGown, 1971).

On comparison of the samples of red till with grey till it can be seen from Figure 114 that the red till is occasionally sandier in texture but with a similar range of clay and silt size fractions. This analysis may be indicative of the coarser parent bedrock of the

red till (cf. Chap. 5).

NATURAL MOISTURE CONTENT

The moisture content of a soil (NMC) is the ratio of the mass of water (M_w) contained in the pores to the mass of the solid particles (M_s) expressed as a percentage. In determining the natural moisture content of the till 15 samples were taken at each of the following depths 3 to 6m, 6 to 15m and greater than 15m. The samples were brought back from the field in sealed polythene bags and were immediately weighed (M_t). They were then placed in an oven at 105°C for 12 hours and thereafter reweighed. The natural moisture content was then calculated using the following equation:

$$\text{NMC} = \frac{(M_t - M_s)}{M_s} \times 100 = \frac{M_w}{M_s} \times 100 \dots\dots\dots(13)$$

From Table 14 it can be seen that the natural moisture content varies with location and depth of sampling. The overall average value of moisture content was 12.0% (S.D. = 2.06%) with the average grey till having a moisture content of 12.2% and the red till having a value of 11.6%. As might be expected with increasing depth and thus increasing overburden pressure, moisture content tends to decrease (Boswell, 1961). The average moisture content between 3 and 6m was found to be 12.82% but reduced to 11.44% at depths greater than 15m. Since the red till is sandier it might be expected to have a higher moisture content when saturated (Terzaghi & Peck, 1967, p.28). In this group of samples, however, the converse was found, which may be the result of partial saturation, location and greater consolidation. In the main little distinction exists between the two tills.

TABLE 14

	N.M.C. (%)	Depth (m)	Location	Till
	11.10	3.38	West of Eden Lane	Grey
	14.10	4.27	Yorkhill	Grey
	12.60	4.27	Hillend Road	Grey
	12.60	4.50	Fergus Drive	Grey
	13.60	4.50	Cowcaddens	Grey
	15.40	4.57	Barmulloch	Grey
	12.00	4.88	Townhead	Grey
Average 12.82%	10.00	5.18	Townhead	Grey
	11.30	5.79	Yorkhill	Grey
	11.40	3.08	Acre Road	Red
	13.00	3.40	Milngavie	Red
	13.80	4.40	Baljaffray	Red
	12.40	5.15	Drumchapel	Red
	15.80	5.75	Temple Road	Red
	13.20	5.82	Canniesburn	Red
	19.20	6.01	Fergus Drive	Grey
	13.40	7.62	Yorkhill	Grey
	10.60	7.62	Charing Cross	Grey
	14.10	7.92	Jordanhill	Grey
	13.00	8.53	Pitt Street	Grey
	11.40	8.84	Yorkhill	Grey
	8.85	10.00	Hillend Road	Grey
Average 11.84%	11.20	10.00	Bothwell Street	Grey
	11.00	10.24	Townhead	Grey
	12.40	10.50	Greenfield	Grey
	7.00	6.10	Gilshochill	Red
	13.00	7.20	Temple Road	Red
	11.10	7.40	Drumchapel	Red
	11.90	9.20	Canniesburn	Red
	9.40	12.00	Baljaffray	Red
	12.00	15.24	Blythswood Square	Grey
	11.00	15.45	Woodside	Grey
	12.40	15.50	Bothwell Street	Grey
	11.00	15.75	Townhead	Grey
	14.00	16.12	Townhead	Grey
	10.60	16.15	Woodside	Grey
	12.90	16.79	Yorkhill	Grey
Average 11.44%	13.00	19.00	Bothwell Street	Grey
	11.40	20.50	Bothwell Street	Grey
	10.00	24.30	Pitt Street	Grey
	10.6	25.90	Hillkirk Street	Grey
	12.30	30.40	Yorkhill	Grey
	12.20	15.20	Drumchapel	Red
	7.40	15.40	Gilschochill	Red
	10.80	15.85	Sighthill	Red

Averages: Overall 12.00% Grey Till 12.20% Red Till 11.60%

NATURAL BULK DENSITY

This property of a soil may be defined as the ratio of the mass of soil to its volume (in its natural state) and is expressed in Kg cm^{-3} . This property defines the density at time of sampling and thus is a measure of solid particles, water filled voids and empty voids. In determining bulk density 20 till samples were taken from throughout the study area. The samples were all taken using steel bore casings (U4) that were either pushed into the till by a mechanical digger or were attached to boring equipment for sampling at depth. Eighteen samples were taken using the latter method in an attempt to take samples in an urban area that were uncontaminated. When the till was sampled the casing and sampled till were first weighed ($C_w + M_t$); then the till was removed and the casing weighed empty (C_w). Finally the sample volume was computed from the dimensions of the cylindrical casing (V_t). Using the following equation the Natural Bulk Density (B) was calculated:

$$B = \frac{(C_w + M_t) - C_w}{V_t} = \frac{M_t}{V_t} \dots\dots\dots(14)$$

The average bulk density was 0.23 Kg cm^{-3} (S.D. = 0.09 Kg cm^{-3}) and the average values for both the red and grey till were also 0.23 Kg cm^{-3} (Table 15). Although a textural difference may exist between the two tills the evidence of the bulk densities indicates that a considerable overlap in properties can be expected to occur between them (cf. Chap. 5).

ATTERBERG LIMITS

An important property of tills, since their behaviour depends upon it, is their consistency. In order to determine this property the Atterberg limits of 20 samples of red and grey till were calculated.

The liquid limit (LL) when the till is just liquid enough to flow was calculated as follows. A soil paste of air-dried, crushed till and water was made and placed in a Casagrande cup. The paste was then grooved and only when the groove just closed on the twenty-fifth blow of the cup was the water content of the paste calculated (see above). This value being taken as the liquid limit. The plastic limit (PL) is the state reached when the till is sufficiently moist to be plastic. This value was calculated as the water content of the till when, on repeated rolling of a small ball of till into a thread, the till crumbles when the thread is approximately 3mm in diameter. The plasticity index (PI) is the difference between these two limits (Table 16).

The overall average Atterberg Limits are as follows:

T A B L E 16

	LL	PL	PI
Average	27	14	13
S.D.	1.82	2.30	2.63

The difference of Atterberg Limits between samples of red and grey till were not significant indicating the similarity, in many locations, of the two tills.

The data were plotted on a plasticity chart (Terzaghi & Peck, 1967, p.41) revealing that all the tills sampled lie within the zone of low plasticity (CL) (Fig. 115). These findings are similar to those obtained for other till samples taken in Glasgow (cf. McKinlay, 1969, Fig. 2a). The low plasticity indicates that when stress is applied to the till it will not deform at first but only once a critical yield

stress is reached. This yield stress may be defined as the Cohesion (C) of the till (Wiun & Starzewski, 1972, p.149). In these particular tills this cohesion value can be therefore expected to be low.

COMPRESSIBILITY AND PRECONSOLIDATION

The compressibility of a given soil may be defined as its capacity to decrease in volume on application of stresses. A decrease in the volume of the soil specimen is equal to the decrease in the volume of its pores (voids) (Terzaghi & Peck, 1967). On removal of the stress the soil recovers and increases in volume but because of particle displacement and bonding the soil does not recover to its initial volume.

In order to determine the compressibility of the red and grey tills 4 samples were tested. The till samples (3.9cm in diameter) were extracted from a steel bore casing and mounted on a consolidating machine (oedometer) (Fig. 116). The sample is prevented from lateral expansion by the walls of the machine and rests on a ceramic plate thus allowing dissipation of pore water. The sample initial height (h_i) is determined (to ± 0.0001 cm) and its weight (to ± 0.01 g) prior to compression. The machine is then loaded incrementally and at each increment the height of the sample is measured. Sample heights were recorded after 0.5, 1, 2, 15, 30, 60 mins, and 4, 8, and 24 hours. The load was increased from 0 to 26 to 53 to 107 to 214 to 428 to 856 KN m^{-2} and then reduced to 53 to 0 KN m^{-2} .

In order to plot these determinations a graph of changing void ratios to applied stress was constructed (Figs. 117). To calculate the initial void ratio the following equation was utilised:

$$e_i = \frac{V_p}{V_s} = \frac{(G_{spw} - p_d)}{p_d} \dots\dots\dots(15)$$

where e_i is the initial void ratio of a sample, G_{spw} is the density of the material, p_d is the density after oven-drying, V_p is the volume of voids, and V_s the volume of solid particles.

Having derived e_i and the change in sample height Δh with loading and unloading the changing void ratio e_i can be calculated.

$$e_{i+1} = \Delta e_i - \frac{\Delta h_i (1 + e_i)}{h_i} \dots\dots\dots(16)$$

Two samples each of red and grey till were tested and gave characteristic compression curves for an overconsolidated soil (Figs. 118-120) (cf. Harrison, 1958; Sangrey, 1970). Till is overconsolidated because it has been, in the past, subjected to greater pressures than exerted by its present overburden.

The construction of these void ratio/pressure diagrams has, in the past, been used to calculate the preconsolidation values of a soil (Casagrande, 1936; Rominger & Rutledge, 1952; Schmertmann, 1955; Harrison, 1958; Sangrey, 1970; Kazi & Knill, 1973). The preconsolidation pressure (P_c) is the maximum pressure to which a sediment has been consolidated at any period in its history. The explanation for such overconsolidation in tills has been argued as being due to glacier ice pressures. However such overconsolidation may also be due to dessication and to the translocation of clay and silt particles (Terzaghi & Peck, 1967, p.73-4; Busbridge, 1968; Boulton & Dent, 1974). Since the amount of preconsolidation that can be directly attributable to glacier ice pressures is unknown, it seems unlikely that calculations of preconsolidation pressures without modification are of any value in constructing past glacier thicknesses and margins. The preconsolidation value is calculated using a graphical technique

(Fig. 121) described by Schmertmann (1955, p.1213). It was hoped that these determinations would have been valuable in understanding the overall ice pressures in a drumlin field and over a single drumlin but the inherent errors of the technique, as noted above, led to the abandonment of this analysis.

In attempting to derive preconsolidation values it was noted that the compression curves were shallower than might be expected (cf. Schmertmann, 1955, p.1224-5). It seems likely that all samples tested were "disturbed". This may be due to unavoidable disturbance of the samples during coring. McGown (pers. comm. 1974) has indicated that below sample diameters of 10cm results of other geotechnical tests have shown appreciable lower values.

SHEAR STRENGTH

This property may be defined as the maximum resistance that a soil can offer to a shear stress at a given point within itself. When this resistance is overcome continuous shear displacement occurs separating the soil into two parts. The soil is then said to have reached a state of failure (Terzaghi & Peck, 1967; Wilun & Starzewski, 1972).

Shear strength is defined as follows:

$$S_m = C + p \tan \phi \quad \dots\dots\dots(17)$$

where C is cohesion, p is the pressure on the material and ϕ is the angle of internal friction of the material. This equation has been resolved by Busbridge (1968) and McKinlay (1969) for tills in Glasgow to:

$$S_m = (c + K_o B h \tan \phi) (1 + \sin \phi) \quad \dots\dots\dots(18)$$

where K_o is defined as the "at rest" pressure ratio of the total horizontal stress to the total vertical stress and B is the Natural

Bulk Density. The value of K_0 for till has been established approximately as 1.5 using in situ testing (Busbridge, 1968).

To determine the till shear strength 20 samples (10.2cm in diameter) of red and grey till were sampled and triaxially tested. Each sample was placed in a triaxial compression apparatus (Fig. 122) in order to determine cohesion (C) and the angle of internal friction (ϕ). In using this apparatus 4 small samples of the same till sample were tested to compensate for laboratory errors. A thin rubber membrane was placed over the sample prior to testing, in order to isolate it from the cell water. The top and bottom ends of the sample were left uncovered and placed between non-draining plates. The cell was placed over the sample and filled with water to the required working pressure. The cell pressure was then increased by applying additional vertical stress in increments of 1.06, 2.85 and 4.10 Kg cm^{-2} with changes of cell pressure at stages of 0.7 to 1.43 to 2.14 Kg cm^{-2} at a rate of $2\% \text{ min}^{-1}$ until the shearing resistance of the sample was overcome. The cohesion and angle of internal friction were then calculated from the construction of a Mohr's Circle of Stress diagram (Fig. 123). This form of Triaxial Compression test is termed undrained in order to simulate, as near as possible, the conditions existing in situ within the highly impermeable till (Terzaghi & Peck, 1967, p.95).

Shear strength was then calculated by including the derived values of cohesion and angle of friction into equation (18). The shear strengths obtained (Table 15) are peak shear strengths and thus are slightly higher than the residual shear strengths of the till that are found when continuous deformation occurs over a considerable length of time as at the glacier bed (Skempton, 1964; Wilun & Starzewski, 1972).

T A B L E 17

	Average Till	Average Red Till	Average Grey Till
Shear Strength (Kg cm ⁻²)	1.92	1.99	1.87
S.D.	0.88		

The above average values of shear strength (Table 17) approximate closely to those found by other workers in the area. However because of the enormous variation in values found in close proximity to one another, for example, at Barmulloch where 2 samples gave a value of 1.32 and 3.13 Kg cm⁻² and throughout the thesis area, no broad correlations of shear strength variations could be made. Previously McKinlay (1969, p.6) had noted the similarity in values found between red and grey tills.

Little variation of shear strength with depth could be detected from the samples but McKinlay (1969, p.7) has noted a gradual increase in strength. How much the effect of overburden stresses influences these values cannot be easily ascertained because of the inherent problems in interpreting preconsolidation values. A further complication in till shear strengths is the effect of fissuring which will tend to reduce shear strength considerably (McGown et al., 1974).

The accuracy of shear strength values of till remains poor due to sampling disturbance, sample size, rate of strain during testing and the till matrix. To gain an accurate value for till shear strength, the complete till matrix must be tested. One method now being used is in situ testing, which has been reported as giving values 90% higher than determined in the laboratory (McKinlay, 1969; Radhakrishna

& Klym, 1974).

FINAL REMARKS

These geotechnical determinations reveal that the till in Glasgow is of low plasticity and is highly variable in its properties even over very short distances. By testing the till samples under applied stresses the nature of the deformation that the till undergoes can be observed.

Since the palaeomagnetic study revealed that the till in Glasgow had been apparently deposited as a fluid slurry with a moisture content in excess of 30%, the present till average moisture content of 12.0% indicates the considerable change that must have occurred in the rheological properties of the till following deposition. At moisture contents of > 30%, the till would have an exceedingly low cohesion value and an angle of friction of 0 degrees resulting in the till acting as a viscous material (Carson, 1971, p.66) having no yield stress and thus deforming under the slightest applied stress. This contrast in geotechnical properties in the till between the time of deposition and the present would seem to be fundamental to any theory of drumlin formation. Only till that was capable of withstanding shear stresses and of allowing pore water to dissipate could form the initial part to a drumlin that had no bedrock core (Chap. 14).

The differences that might have been expected to occur between samples of red and grey till are not present. It seems likely that although the red till has a tendency to be slightly sandier in patches, the two tills are identical in almost all the geotechnical properties measured. It can therefore be anticipated that drumlins whether composed of red or grey till should under similar glaciological conditions be of equivalent dimensions. Any variation in drumlin dimensions in

the Glasgow area can therefore be presumably regarded as more likely to have been caused by variations in glaciological conditions (cf. Chaps. 4, 14).

T A B L E 15

N.B.D. (Kg cm ⁻³ 10 ¹)	'C' (Kg cm ⁻² 10 ¹)	Depth (m)	Shear Strength (Kg cm ⁻²)	Location	Till	
2.37	13.35	10.0	5.80	2.00	Yorkhill	Grey
2.45	20.38	1.5	8.80	2.18	Yorkhill	Grey
2.25	9.14	9.0	4.30	1.32	Barmulloch	Grey
2.34	16.51	4.0	5.20	3.13	Barmulloch	Grey
2.33	18.85	0	4.20	1.89	Fergus Drive	Grey
2.17	8.66	0	4.80	0.87	Fergus Drive	Grey
2.15	11.59	2.5	7.90	1.33	Jordanhill	Grey
2.11	8.30	1.5	7.90	0.92	Jordanhill	Grey
2.30	30.98	0	2.75	3.10	Hillend	Grey
2.23	10.39	13.0	13.70	2.57	Garnet Hill	Grey
2.21	8.37	14.0	10.00	2.07	Garnet Hill	Grey
2.33	10.19	0	6.00	1.02	Greenfield	Grey
2.37	11.24	13.5	1.90	1.59	Peel Glen	Red
2.37	17.85	0.5	6.60	1.82	Drumchapel	Red
2.32	12.29	3.5	3.00	1.37	Drumchapel	Red
2.31	8.05	2.0	9.20	0.95	Canniesburn	Red
2.21	11.58	3.0	2.70	1.27	Acre Road	Red
2.21	15.46	0	3.10	1.55	Acre Road	Red
2.27	1.708	27.5	13.40	3.50	Gilshochill	Red
2.19	1.17	27.0	15.30	3.90	Gilshochill	Red

THE QUATERNARY IN GLASGOW

As previously discussed (Chap. 3) most of the glacial landforms and deposits within Glasgow are probably the result of the final period of glaciation (the late-Devensian). This last period of glaciation would seem, from the evidence of radiocarbon dates, to have begun sometime after 27,000 years B.P. (Rolfe, 1966), to have reached its maximum extension at around 18,000 years B.P. (Penny et al., 1969) and to have retreated from the lower Clyde valley before 12,650 years B.P. (Bishop & Dickson, 1970; Peacock, 1971), leaving the remainder of Scotland ice free probably by 12,500 years B.P. (Sissons, 1974, p.315). The Quaternary events in Glasgow have been discussed for over a century but still many problems remain unsolved, as previously outlined (Chap. 3). In re-examining the Quaternary evidence from the area, mapping the landforms and deposits, examining drift sections and collecting numerous borelog records for central Glasgow, it was hoped that new evidence might be found that would allow a better understanding of the events that occurred before, during and immediately after this last period of glaciation.

TILL AND DRUMLINS

In examining the pebble lithology (Chap. 5) of both the red and grey tills, in Glasgow, several conclusions were tentatively drawn. Firstly, although the two tills are distinctly different in colour (due to the silt and clay fraction) the lithologies of the pebble fraction of both tills are often almost identical. Secondly, an intermediate or intergrade till of a reddish-brown hue was found,

in several localities, lying along the supposed boundary (Clough et al., 1925; Jardine, 1973) between the two major tills. This intermediate till has many of the characteristics of both the red and grey tills. Thirdly, on mapping the distribution of the tills (Fig. 55) it was found that although the red till lay to the west and the grey till to the east of a line from Maryhill to Yoker, a few exceptions existed throughout the area (Chap. 8).

Till fabric studies (Chap. 6) of both red and grey till within drumlins and in inter-drumlin hollows revealed a marked easterly to south-easterly direction of ice movement. No fabric deviations that were any greater than normally found within samples, could be detected between samples of red and grey till.

Palaeomagnetic studies (Chap. 11) of both the red and grey till revealed that when the stereographic projections of each cored sample were plotted (Fig. 106) no discernible pattern could be noted that would separate the red till samples from those of the grey till. The only variation between the red and grey till cored samples was in their respective percentage magnetic contents (Table 11), there being a tendency for the grey till to be slightly higher in magnetite than the red till.

Differences in the geotechnical properties of the red and grey tills can largely be attributed to their marked textural differences. The red till was found to have a slightly higher sand fraction than the grey till and was therefore more permeable, had a lower bulk density and a lower shear strength (Chap. 12).

Morphometric analysis (Chap. 10) of the Glasgow drumlins revealed that, although a considerable standard deviation (16°) of drumlin orientation existed within this part of the drumlin field, the drumlins

in the areas of red till were similar in orientation to those in the areas of grey till. Distinct differences did, however, exist between drumlins in the red till area of Drumchapel/Milngavie and those of the grey till area of Springburn/Riddrie. The drumlins of the more westerly group were more elongate, had a higher density and were narrower and smaller in volume. These differences, however, are probably due to variations in ice pressure, ice velocity and drift availability (Chap. 14).

The borelog records, although revealing localised variations in till content, indicated no marked differences between red and grey till. The borelogs, however, did reveal that in only a very few instances was red till recorded directly overlying grey till while in other borelogs the converse was found (cf. Clough et al., 1925). Beneath the infilling deposits of the buried channel of the Clyde patches of till, described as grey, black, brown and reddish-brown, were located (Chap. 8). Of the 800 borelogs recording channel infill, 29% recorded this underlying till. In a further 3.4% of these specific borelogs till was recorded intercalated with the infilling deposits. The borelogs also revealed that till did not overlie the infilling deposits of the buried Clyde channel between Scotstoun in the west, and Bridgeton in the east. Similarly no infilling deposits were found beneath the till on the sides of the present Kelvin valley between Dawsholm Park in the north, and Yorkhill in the south. However from the borelog evidence, the investigation of sections and the examination of previous work it seems likely that the western extension of the Kelvin buried valley in the Bearsden/Garscadden/Drumchapel area had been infilled and later overlain with till and drumlins (Figs. 68,69) (Chap. 8).

The above evidence reveals that the red and grey till rather

than being of differing glacial periods are probably of the same single phase of glaciation and differ only on the basis of their parent material, the former being dominantly of Old Red Sandstone sediments and the latter of Carboniferous sediments. This conclusion is further substantiated by the continuity of drumlin orientations and pattern between the red till and grey till areas. The lower till beneath the buried channel infill (Fig. 53) may be of an earlier period within the final phase of glaciation or may be the remnants of an even earlier phase of glaciation.

The distribution of till, in Glasgow, in relation to the buried channels and their infilling deposits reveals that till was deposited probably after the buried channels were infilled. However the till may have been removed totally from above the infilling deposits in the Clyde valley and partially in the Kelvin valley either due to post-glacial subaerial stream erosion or because these two channels remained in use during the phase of till deposition.

BURIED CHANNELS AND THEIR INFILLING DEPOSITS

As already noted (Chap. 8) several buried bedrock channels are known to exist within the Glasgow area. Most of the evidence derived in this thesis relates to the buried channel of the Clyde. The Clyde buried channel and its infilling deposits would seem to be best explained as a subglacial tunnel valley with associated infill. The suggestion of a pre-glacial origin for channel and infill and of a link between the buried Clyde and Kelvin channel between Whiteinch in the south, and Drumry in the north, appear, on present evidence, to be unsubstantiated. If a subglacial origin is accepted for the buried channel of the Clyde it would seem likely that the flow of water in the channel

would have been from west to east during the last glaciation since subglacial meltwater will tend to flow away from areas of high pressure and was only reversed with final ice retreat from the lower Clyde estuary.

The cutting of this subglacial channel, by meltwater flowing subglacially under hydrostatic pressure, probably began much earlier in the Quaternary and may have been initiated because of the presence of a pre-glacial drainage system. Such depressions within the bedrock would cause meltwater to migrate towards these zones of lower pressure which thereafter would tend to be perpetuated by meltwater erosion (Nye, 1973, p.151). The presence of till within the deeper parts of the buried Clyde channel may be the result of in situ deposition or redeposition by the ice. In either instance much of this till was probably later removed as meltwater washed-out the bedrock channel.

Although it seems likely that the infilling deposits are of subglacial origin, when the process of infilling occurred remains unanswered. Considerable infilling seems to have occurred some time prior to till deposition but may have continued throughout the final stages of glaciation and deglaciation. Proglacial sedimentation in some form may have also occurred (Chaps. 3,8).

SUB TILL DEPOSITS

Although the buried channel infilling deposits may be regarded as sub till deposits other thin deposits were found scattered throughout the study area (Chap. 8)(Fig.54). These latter deposits range from coarse-textured gravels to finely laminated silts and clays. The possible origins of these deposits are complex. They may be in situ, redeposited or both and they may be subglacial, proglacial or a

combination of both. It seems likely from their scattered distribution that they are in the main due to subglacial deposition processes.

FLUVIOGLACIAL DEPOSITS AND MELTWATER CHANNELS

Very few deposits or landforms of fluvioglacial composition were noted (Chap. 3,8). Only in the eastern part of the study area close to the Shettleston/Baillieston district were spreads of fluvioglacial deposits found infilling meltwater channels and overlying till (Fig.76).

The presence of small terraces of fluvioglacial material on the sides of dry valleys and mis-fit streams, as at Garscadden (525 709), indicates the past existence of meltwater routes and groups of small meltwater channel systems.

The mapping of meltwater channels was complicated by the influence of the present drainage system that in many instances probably flows in the opposite direction to the meltwater streams. Meltwater channels, in the study area, fall into two distinct groups: 1) those along the flanks of the Kilpatrick Hills and 2) those within the drumlin field.

1) Along the steep sides of the eastern part of the Kilpatrick Hills (Fig. 4) several deep meltwater channels (> 15m) were mapped. At Edinbarnet (503 741) two major channels converge and descend steeply to Faifley where the confluent channel spreads out at around 115m O.D. Other channels exist in and around the Mains Plantation (530 743) and on the edges of Douglas Muir. All of these channels lie above the edge of the drumlin field and rapidly disappear on entering the drumlin field.

2) Within the drumlin field and at higher altitudes than the raised beach deposits are numerous meltwater channels often of considerable length (Fig. 4). Although many inter-drumlin hollows must have also

acted as routes for meltwater, many channels distinguished by their sinuosity, steep sides and dendritic pattern, can be observed. These channels are, in the main, shallow (5-10m deep) and have gentle gradients of less than 5 degrees. Many of these channels appear to begin on the sides or lee ends of drumlins (545 715) and continue into the inter-drumlin areas. It seems likely therefore that from the evidence of the size of these channels and their location that they were formed subglacially.

A group of meltwater channels was found to the north and south of Bearsden Station (543 718)(Fig. 4). These channels all trend roughly towards the east and disappear at the present flood plains of the River Kelvin and Allander Water. Within central Glasgow fewer meltwater channels were located probably due to the masking effect of buildings and made ground. In general the meltwater channels within the drumlin field appear to have contained subglacial streams flowing probably in a general easterly direction akin to the orientation of the drumlins. Many of these channels have since been utilised by subaerial streams.

Several major meltwater routes also appear to have existed within the study area. These routes would appear to have a complex history and are less clearly defined in terms of direction of meltwater movement and origin. These routes are 1) the Kelvin valley south of Dawsholm Park 2) the main valley of the Clyde and 3) the Bearsden/Garscadden Mains hollow (Fig. 4). The two last lie, in part, directly above the buried bedrock channels of the Clyde and Kelvin (Figs. 4,49). It seems likely that, if subglacial meltwater flowed along these buried channel routes, meltwater may have continued to flow when these bedrock channels were infilled since, in both instances, no drumlins were apparently deposited within these channels.

If meltwater did flow subglacially along these routes an easterly direction of flow seems likely. However during the final stages of deglaciation this direction may have been reversed if the ice-sheet did not retreat westwards down the Clyde valley (Sissons, 1974, p.330). If deglaciation was down valley, a large ice-dammed lake may have formed in the upper sections of the Clyde and Kelvin valleys. With final retreat these above meltwater routes may have been utilised by the escaping lake water as it flowed down-gradient towards the Clyde estuary.

The inference that the Kelvin valley, south of Dawsholm Park, was used as a meltwater route is based on three considerations. Firstly, no drumlins or till deposits were found within the valley. This evidence may indicate that this route was being used by meltwater during drumlin and till deposition. Secondly, several small meltwater channels, although hanging above the entrenched bedrock sections of the Kelvin, as at 557 697, appear to grade into the upper valley sides. Thirdly, the Kelvin river has throughout this section a bedrock bottom that passes beneath raised beach and infilling buried channel deposits at Partick Bridge and grades into the buried bedrock channel of the Clyde. This junction between these two routes seems to indicate that both routes were cut and being used simultaneously at some earlier time in their history. This link with the buried channel of the Clyde may indicate that subglacial meltwater flowed southwards along this lower section of the Kelvin valley. The Kelvin valley route may have acted, at some time before drumlin deposition, as a linking channel between the buried bedrock channels of the Clyde and Kelvin but this hypothesis can only be verified if the nature of the northern section of the Kelvin valley is examined using borelog records.

RAISED BEACHES

Although the raised beaches in this area were not studied in detail their upper limit and various surface beach levels were mapped (Fig. 4)(Chaps. 3,8). An upper limit of 26m within the Glasgow area was noted but is not in accordance with the marine limits of between 36 and 40m at Stirling, southern Loch Long, Glendaruel in Cowal, and southern Loch Fyne (Sissons, 1974, p.330). Since each of these locations is a similar distance from the main centre of the last ice-sheet similar altitudes might be expected (Sissons, 1976, Fig. 9.6, p.130). This not being so, in order to account for the different marine limit, a new mode of deglaciation in the Glasgow area has been tentatively suggested (Sissons, 1974, 1976).

THE POSSIBLE SEQUENCE OF EVENTS DURING
THE LAST GLACIATION AND DEGLACIATION IN GLASGOW

At present very little is known of the sequence of events prior to the retreat of the last major ice-sheet. The radiocarbon date of 27550 (+ 1370, -1680) B.P. obtained from a woolly rhinoceros bone found in fluvioglacial gravels beneath till at Bishopbriggs (Rolfe, 1966) is significant in dating the last known interstadial before the advance of the last ice-sheet into this area.

The nature of the landscape prior to this last ice advance cannot be ascertained with any accuracy due to a scarcity of deposits that can be definitely attributed to a date before this advance. Since the area had been previously glaciated it may be assumed that deposits similar to those now observed would have existed. Whether the buried channels of the Clyde and Kelvin were already cut to their final depths is unknown but probably major bedrock depressions at those locations

existed. The lower till underlying the infilling deposits lying directly on bedrock within the buried channel of the Clyde may be till of a previous glaciation and if so then the channel must have been cut prior to the last glaciation, although modification and recutting of the channel may have occurred in places with subsequent erosion of the lower till. If the buried valleys were infilled before this last ice advance it can be presumed that, on the advance of the ice, the channels were scoured-out, at least in part. The date from Bishopbriggs, if accurate, would tend to indicate that the fluvioglacial gravels, within which the bone was found, were laid down some considerable time after that date. Since these gravels appear to be closely related to the infilling deposits of the Kelvin/Bearsden buried channel it can be perhaps assumed that any buried channel infill prior to the final glaciation was removed and replaced with younger infill.

Evidence of the last ice advance into the Glasgow area is supplied by striae, and erratics, as previously noted (Chap. 3). The ice appears to have advanced eastwards blocking the lower Clyde estuary. Ice seems also to have advanced down the Vale of Leven and through the Strathblane Gap. With ice advance into the area it has been theorised, in the past, that an ice-dammed lake may have formed (Chap. 3). No deposits that can be specifically attributable to this lake could be found in the field or from borelog records. Several sub till deposits of uncertain origin composed of laminated clays and silts and fine sands were discovered, however, in scattered locations throughout the study area (Chap. 8). It has been suggested that the infilling deposits within the buried channels must have been cut into bedrock by an earlier ice-sheet. On subsequent retreat of the previous ice-sheet the channels must have been left free of infilling deposits.

Since the buried channels were left infilled after the retreat of the final ice-sheet it seems anomalous that such infilling would not have occurred on the retreat of a previous ice-sheet.

During the last glaciation in Glasgow subglacial meltwaters appear to have scoured-out and possibly deepened the buried channels of the Clyde and Kelvin/Bearsden. From the Rockhead map (Fig. 49) several bedrock gullies were detected along the sides of the Clyde buried channel. In particular the Kelvin valley, south of Dawsholm Park, appears to grade into the Clyde buried channel indicating perhaps that this bedrock channel carried subglacial meltwater at the same time as the Clyde buried channel.

When the major buried channels began to be infilled cannot be ascertained but it seems likely that infilling may have been a continuing process that at times was interrupted by phases of erosion and channel scouring. The major period of channel infilling appears to have preceded the deposition of till and formation of drumlins. In the case of the Kelvin/Bearsden buried channel, where till and drumlins overlie parts of the main channel infill, infilling of the channel appears to have almost ceased when till deposition began. However since no till overlies the Clyde buried channel it is possible that this major subglacial meltwater route may have remained open preventing any till being deposited in situ above the infilling deposits. The Kelvin bedrock channel, south of Dawsholm Park, contains no till deposits, or drumlins but has suffered the effects of post-glacial river erosion: however, no infilling deposits, other than south of Partick Bridge, could be detected. It is possible that this channel, transverse to the main direction of ice movement, may have existed as a zone of low pressure beneath the ice, acting as a meltwater route

(cf. Gjessing, 1966).

R. P. Goldthwait (1974, p.183) has proposed recently that "Except for early deposition in depressions, or spot deposition, basal till deposition occurs in the last few centuries of glaciation". He also states that "Basal till is deposited while the ice is thinning," . The process of till deposition cannot be an overall process affecting all parts of an area at the same time (cf. Chaps. 5,9). In some areas deposition would have occurred, erosion in others, but finally the whole of the study area was completely overlain with a till sheet. At some period of time during or prior to this phase of till deposition, subglacial melt-out deposition may have occurred. Sub till deposits of coarse gravels and sands scattered throughout the area may be evidence of such a process.

In the past the red and grey till have been regarded as being of differing glacial periods. However it seems more likely that these tills are only different in colour due to bedrock source differences. The evidence from the palaeomagnetic remanent magnetism of the two tills and the continuity of drumlins across the supposed red/grey till boundary appear to substantiate this theory.

The drumlins within the study area are in the up-ice section of a much larger drumlin field that stretches eastwards across central Scotland to West Lothian. Drumlin formation probably occurred at a late stage in the retreat of the last ice-sheet but it is difficult to ascertain without a study of the whole field being undertaken whether the complete drumlin field formed in a short period of time or whether drumlins formed progressively westwards as the ice margin retreated in that direction. From present-day evidence at ice margins the latter possibility seems the more likely (cf. Goldthwait, R.P.,

1974, p.166-7).

Drumlins were developed throughout the study area except in the zone in which the buried channel of the Clyde lay and in an area between Milngavie and the Wilderness Plantation in the floodplain of the river Kelvin (Fig. 4). The former area, if meltwater continued to flow along this route, would presumably have been unsuitable for drumlin formation. However, why no drumlins should form in the latter area is much more enigmatic. It is possible that the buried Kelvin channel joining the Carron channel to the east may have remained open until late in the phase of drumlin formation and till deposition but since the western extension to this channel, in the Garscadden area, appears to have ceased to function and been overlain with till this explanation remains tentative.

In the past it has always been assumed that since ice advanced across the Glasgow area to the east and south-east, the ice retreat would be to the west and north-west. On present evidence, however, it is possible that a different mode of deglaciation may have occurred in the Glasgow area (Sissons, 1974, p.330; 1976). As already mentioned when discussing the marine limit in Glasgow, this area has a marine limit (26m) that is lower than that of other areas a similar distance from the major centre of ice accumulation. This low marine limit in the Glasgow area may be explained if, when areas such as Loch Long, Glendaruel, Loch Fyne and Stirling were ice free, the Glasgow area, east of Gourock, still remained covered by ice. This ice may have possibly stagnated or slowly retreated through the Strathblane Gap and up the Clyde valley. Little evidence, other than the level of the marine limit, exists at present however to support this theory.

If ice had retreated in the manner previously hypothesised,

westwards down the Clyde estuary, a different set of events may have taken place. Firstly, an ice-dammed lake may have formed. This lake, for which there appears to be little stratigraphic evidence, would have remained presumably until the Clyde estuary became ice free or it may have drained subglacially.

It has been further suggested that while the ice margin stood in the Dumbarton/Greenock area, blocking the estuary mouth, the sea may have gained access to the then ice-free Glasgow area via the Lochwinnoch Gap (30m O.D.) (Peacock, 1971; Price, 1975). This theory, however, seems incompatible with the evidence that the marine limit in Glasgow is at only 26m O.D.

On present evidence therefore it seems more possible that at some stage in the retreat of the last ice sheet an area of ice became detached from its source in the western Grampians and remained either decaying in situ or slowly retreating in a direction other than previously suspected. The final deglaciation of the Glasgow area appears to have occurred sometime before $12,650 \pm 200$ years B.P.

FINAL REMARKS

This study of Quaternary events in the Glasgow area reveals that the last glaciation and deglaciation may have been somewhat different from that envisaged previously. No evidence appears to exist to support the theory of a glacial readvance to explain the occurrence of red till in the western half of the study area nor the idea of ice-dammed lakes having formed in and around Glasgow. From the evidence of the marine limit in Glasgow it seems likely that ice remained in this area while surrounding areas in the upper Forth valley and the sea lochs of the Cowal Peninsula became ice free. Evidence of ice retreat or in situ

stagnation is scanty within the study area but with further study in the surrounding areas clarification of the mode of deglaciation may be obtained.

DRUMLINS - A THEORY OF FORMATION

The theory developed in this chapter will attempt to explain the mechanism whereby drumlin material apparently agglomerates in specific locations. This theory will deal specifically with till drumlins that have no apparent bedrock core.

Many past theories (Chap. 4) have been developed from a consideration of the shape and location of drumlins with little attention being given to the material composing the drumlins. Although drumlin shape has been recognised as streamlined, developed in equilibrium with ice velocity and pressure, this shape is a final form and may be only indirectly related to the initial mass of till that formed the drumlin. Since as Muller (1974, p.189) has pointed out drumlin formation cannot ever be observed, all theories of origin must be based, in part, on inference and induction. With increasing knowledge, however of the subglacial environment and of the mechanics of till deposition such inferences may be less theoretical and more factually based.

Almost all drumlin theories in the past have been developed from an initial premise that the till that will form the drumlin is already deposited and is in a position to be moulded, or that the till is very rapidly deposited in large amounts due to some unknown mechanism and can be then drumlinised. If the mechanism of drumlin formation is subdivided into stages a clearer picture emerges of how a drumlin may form (Fig. 12⁴). Previous theories all appear to have their beginning sometime after the initial event of till deposition has occurred. It is intended in this chapter to attempt to suggest mechanisms whereby

this initial event of till agglomeration may occur.

During and after the formation of a drumlin, a large number of factors are involved (Fig. 125). Some of these factors may be of more importance to drumlin formation than others and some may be of importance at one or several stages in the formation of a drumlin. As Smalley and Unwin (1968, p.377) have noted the main problem in investigating drumlin formation is in choosing "the significant and avoiding the irrelevant" factors.

In previous chapters several of the above factors have been studied and their possible inter-relationships investigated. In the main it has been concluded that the till found within drumlins is similar in most aspects to the till in non-drumlin areas. Few relationships appear to exist between drumlins, drift thickness and bedrock topography. It is therefore likely that the intricate relationships that may have developed between glacier ice, till and water, in the subglacial zone, may be the most important factor in the initiation and final development of drumlins (cf. Smalley & Unwin, 1968).

TILL DEPOSITION

Since drumlins are usually composed of till, in explaining drumlin formation it must also be explained how till is deposited. Since drumlin till does not appear to be fundamentally different from other till deposits, it may be assumed that the mechanism of drumlin till deposition should be similar to that for the deposition of non-drumlin till.

The mechanism of till deposition, under a temperate ice mass, has been discussed by several writers (Peterson, 1969; Boulton, 1970, 1971; Mickelson, 1971; Nobles & Weertman, 1971; Goldthwait, R.P.,

1974) who have generally agreed that till is gradually deposited by the release of debris from the ice in response to basal melting. This melting process, under active temperate ice-sheets, is largely pressure melting. Nobles & Weertman (1971, p.122) have shown, using a simple equation (4)(Chap. 9) that heat sources, at the base of an ice-sheet, available for melting are derived from geothermal sources, (ca $35 \text{ cal cm}^{-1} \text{ yr}^{-1}$), from heat transmitted through the ice from the atmosphere, from the heat of friction and from latent heat sources, resulting in an average value of $80 \text{ cal cm}^{-1} \text{ yr}^{-1}$. Depending on the percentage of debris within the ice, a rate of till deposition of between 0.5 and 3 cm yr^{-1} might be expected to occur under normal circumstances (Chap.9).

DRUMLIN TILL

In relation to drumlin till deposition this rate of deposition appears to be too low. Work by R. P. Goldthwait (1974) and others, on present-day glaciers in Alaska, has shown that basal till which is main component of drumlins is deposited within the final few centuries before ice retreat from an area. A drumlin 50m high, under normal rates of till deposition, would take approximately 1,600 to 10,000 years to build-up; this time period seems contrary to Goldthwait's evidence. Investigations of till layers in a drumlin in Glasgow revealed layering, probably of an accretional nature, within the till (Chap. 9). These layers had a thickness range of 5 to 12cm. Although it could not be established whether these layers were annual or of a lesser or greater time period, it seems likely that they are at least minimal annual values if Goldthwait's concept of when till deposition occurs is correct. The tentative conclusion from this work would therefore be that rates of till deposition on a drumlin were

probably slightly above normal.

Further evidence of the nature of drumlin till deposition was supplied by palaeomagnetic investigations (Chap. 11). In comparison with non-drumlin till in southern Ontario (Stupavsky & Gravenor, 1974), the Glasgow till showed evidence of having been deposited in a fluid slurry with approximately a 10% higher percentage water content by weight. The implications of this higher water content were discussed in Chapter 11 and further substantiate the idea of higher till deposition rates (thus higher water contents) in drumlins.

Investigations of the areal distribution of pebble lithologies across the Glasgow drumlin field (Chap. 5) revealed the complex relationship that appears to exist between the processes of glacial erosion and deposition (cf. Clayton & Moran, 1974; Goldthwait, R.P. 1974). These processes rather than being separated into different areas appear to have co-existed and to have interacted throughout the drumlin field. Any drumlin theory developed must therefore allow for erosion and high rates of till deposition within close proximity to one another (cf. Muller, 1974).

THE CONCENTRATION OF DEBRIS IN BASAL ICE

To achieve a high rate of till deposition either over a broad area or in localised patches it is necessary for the basal ice to be either very heavily choked with debris over a considerable area or for very high concentrations of debris to exist in specific parts of the basal ice. Recent observations beneath temperate ice-sheets have revealed that dirt layers in the basal ice rarely exceed 15cm before clean, debris-free ice is found (Boulton et al., 1974, p.136). However, close to the margins of present day ice-sheets and glaciers that have

polar snouts large localised concentrations of debris have been observed (Goldthwait, R.P., 1951; Souchez, 1967, 1971; Moran, 1971; Hooke, 1973). The evidence of these debris concentrations has been in the form of shear moraines and flow tills. Moran (1971, p.134), Hooke (1973, p.424) and Clayton and Moran (1974, p.93) have argued that, for example, at point A in Figure 126 a large number of basal debris bands will stack themselves one on top of the other as a result of differential changes in ice velocity.

It is the opinion of several workers (Hooke, 1973; Clayton & Moran, 1974; Andrews, 1975) that the major Quaternary ice-sheets may have had polar snouts. However it seems unlikely that Britain with its temperate maritime climate would have had an ice sheet with a polar snout.

A further possibility that might allow large concentrations of debris in the basal ice zone would be short term changes in the basal ice temperatures. Baranowski (1970), Shaw (1972) and Shaw and Freschauf (1973) showed that if the zero isotherm descended beneath the base of the ice and into the underlying erodable material, this material could be incorporated into the basal ice and transported. If such basal ice temperature changes occurred in areas of thick underlying erodable material, large concentrations of debris would be incorporated into the ice and thus subsequently high rates of till deposition might occur.

Changes in basal ice temperatures may be either the result of climatic variations or thickness variations in the ice-sheet. Ice-sheets can be expected to thin due to ice extension on entering a less constricted area, to kinematic waves (Paterson, 1969), to surging (Weertman, 1962, 1966) or to changes in the nature of the underlying bed (Moran, 1971; Boulton, 1974; Boulton et al., 1974).

MECHANISM OF FORMATION

In order that a drumlin can remain at the interface between the ice and the glacier bed, the drumlin must be able to withstand the shear stresses applied to it by the overlying and moving ice mass. It can be further concluded that if a drumlin is to remain at this interface the shear strength (S_m) of the material composing the drumlin must be higher than the shear stresses (τ) applied on the drumlin material by the ice. As already noted, observations on present day tills indicate that the tills have a very high moisture content and are in the form of slurries that are easily deformed and squeezed (Okko, 1955; Peterson, 1969; Boulton, 1970; Mickelson, 1971; Boulton et al., 1974; Boulton & Dent, 1974; Clapperton, 1975). In order that this till be incorporated within a drumlin and be able to withstand the considerable shear stresses applied by the ice, it must undergo critical changes in its rheological properties. The till must change from being a fluid mixture of debris, water and ice to a non-fluid material of low water and ice content.

Two possible mechanisms may be suggested in which till could form into non-fluid agglomerations. Firstly, these agglomerations may develop from within a very thick mobile layer of till lying between the ice and underlying glacier bed; or secondly, these agglomerations may be the result of localised deposition caused by changing conditions in the subglacial zone. In the second mechanism no other till deposits need occur as was noted in northern Canada (Dean, 1953) and central Sweden (Lundqvist, 1970).

In both mechanisms of formation a basic principle of soil mechanics is applicable in the change from fluid slurry-like till to stable, resistant till. The shear strength of a material can be

defined as the inherent resistance of a material to deformation. Shear strength can be defined in terms of Coulomb's equation:

$$S_m = C + P \tan \phi \quad \dots\dots\dots(19)$$

where C is cohesion, P is pressure on the material and ϕ is the angle of internal friction (Chap. 12). If the voids in the material are filled with a liquid under stress (u_w), one part (p) of the pressure (P) is carried by the solid particles which have a finite $\tan \phi$ value; whereas the balance ($p - u_w$) is carried by the liquid phase which has a $\tan \phi$ of zero. Terzaghi (1948) derived the term "effective stress" to account for:

$$p = P - u_w \quad \dots\dots\dots(20)$$

and thus derived a "revised Coulomb equation"

$$S_m = C + (P - u_w) \tan \phi \quad \dots\dots\dots(21)$$

resolving to $S_m = C + p \tan \phi \quad \dots\dots\dots(17)$

It can be therefore seen that the shear strength of a material is controlled by the relationship between interparticle pressures (p) and pore pressures (u_w). In any saturated, unconsolidated material, the particle grain structure is more compressible than the pore water, causing excess, positive, porewater pressure. This excess porewater pressure begins to dissipate immediately by causing the water in the voids to flow along a path of least resistance toward an area of lower pressures. With the drainage of this porewater, increasing amounts of the applied stress are transferred to these particles. This change in the application of the stress results in an increase in interparticle stresses (p) thereby causing an increase in the shear strength of the material. A further increase in applied stress would cause a sequential increase in shear strength and further porewater dissipation.

At a specific stress level a material such as till, depending

on its grain size distribution and grain shapes, may become dilatant (Reynolds, 1885; Mead, 1925; Smalley & Unwin, 1968; Boulton et al., 1974). Dilatancy occurs in a material when the applied stress causes the particle grain structure to expand due to movement of particles in relation to one another, from side to side contacts to point to point contacts. This effect is usually manifested in an increase in volume, resulting in an increase in void spaces. When a saturated material becomes dilatant it has been shown that porewater pressures become negative causing a subsequent reduction in shear strength (Terzaghi & Peck, 1967).

The most important consideration in the increase in shear strength of any saturated material is the amount and rate at which excess porewater pressure can be dissipated and transferred to the grain structure. As Clayton and Moran (1974) have noted, the most rapid dissipation of excess pressure occurs in coarse-textured sediments where the flow path between areas of high and low pressure is short. The least rapid dissipation occurs in fine-textured sediments where the flow path is considerably longer. A further consideration is the compressibility of the material since coarse-grained sediments are much less compressible than fine-grained ones.

From the above observations the application of stresses to saturated till can be considered. Since the matrix of till is normally a fine-textured material it seems likely that flow paths will be exceedingly long and thus a tendency for fairly high excess porewater pressure to exist will persist when till is overridden by glacier ice. As the ice advances the drainage outlets for excess porewater will be steadily decreased causing these excess pressures to prevail unless otherwise dissipated. Boulton et al., (1974, p.141) have shown that

where no or limited drainage occurs in a fine-grained till, excess pore pressures being un-dissipated will cause a reduction in till shear strength finally leading to the till approaching a fluid state. However, if the till were to overlie a coarse-textured material or a subglacial drainage route that would both act as areas of pressure dissipation then this fine-grained material may become less fluid, increase its strength and no longer have an excess porewater pressure (Moran, 1971; Clayton & Moran, 1974, p.94; Boulton et al., 1974, p.140).

MECHANISM 1

If till has been accumulating beneath a glacier and above an impermeable bed such as unfractured bedrock or bedrock of low hydraulic conductivity a state may be reached where excess porewater pressures are produced. This may occur either due to increased subglacial melting and thus higher water content in the till or increased ice pressures due to ice advance over the deposited till. It has been considered that at this stage since the excess pore pressures cannot be dissipated very easily the till, sandwiched between the ice and impermeable bed, will become fluidised and its shear strength will be vastly reduced (Goldthwait, R.P., 1971, p.16; Boulton et al., 1974). At this stage the till will no longer remain stationary since the frictional stresses between the till and the ice and glacier bed will approach zero, and the till will flow.

It is envisaged that at this stage with the till flowing beneath the glacier the initial event in drumlin formation may occur. If parts of the fluid till were to be halted (see below) the surrounding fluid till would rapidly encompass and plaster around this stationary patch.

Any glaciological changes such as decreases in ice pressure that would affect the whole area of flowing till must therefore be discarded. Only a mechanism that would cause localised patches of till to become non-fluid while the remaining parts of the till remain fluid can be considered.

Since the till is flowing as a result of excess porewater pressures developed in the till because of pressures applied by the ice, any method of dissipating such pressures will cause the rheological change, noted above, to occur in the till. It has already been demonstrated by Moran (1971) and Boulton *et al.*, (1974) that areas of till underlain with coarse sands and gravels would allow drainage of this porewater. Also zones of highly shattered bedrock or jointed bedrock (Glückert, 1973) would act as areas of porewater dissipation. Subglacial bedrock or glacier bed depressions transverse to ice movement (Gjessing, 1966) and subglacial water channels would also act as areas of low pressure to which the porewater would migrate.

It is proposed that if till is flowing beneath an ice mass small local areas or narrow zones of low pressure could act as locations where the till could become non-fluid and develop, if the agglomeration was of sufficient size, into a proto drumlin. The non-fluid till would act as an obstruction around which more till would accrete.

MECHANISM 2

Investigations in boreholes (Gow, 1963) and directly at the glacier's sole (Kamb & La Chapelle, 1964; Vivien & Bocquet, 1973) have revealed that the theory of glacier sliding proposed by Weertman (1964) and Lliboutry (1965) is essentially correct. In order that a temperate ice mass can move over its bed a layer or sheet of water is necessary

at the interface between the moving ice mass and the glacier's bed. Much discussion has gone on as to whether this water layer is in sheets or discrete channels. When this water film is broken down or removed the ice mass grounds onto the glacier bed: friction between the ice and its bed changes from zero to a large figure causing pressure melting to occur. At this stage, of pressure melting, any debris in the basal ice is melted-out and thus deposited. By pressure melting the ice itself creates a water film whereby friction again becomes virtually zero and ice movement continues.

If this process of removal of water film and pressure melting could occur in areas beneath basal ice in which large concentrations of debris existed, large agglomerations of till could be rapidly produced in localised patches.

The relationship often alluded to between drumlins and terminal moraines (Chap. 4) may indicate not a close similarity in landform but in material source. Moran (1971) and Hooke (1973), as already noted, have envisaged large concentrations of debris in the areas up-ice of the glacier's snout (Fig. 126). If these large accumulations were to be melted-out then large amounts of till would be available for drumlin formation. If the lubricating water film could be drained into a permeable bed beneath the ice or into subglacial meltwater channels or if the water supply to the film could be reduced or cut off then the ice would be grounded and in a state of pressure melting. At this stage, with large amounts of debris being deposited in this subglacial marginal position, excess porewater pressures would immediately be built-up in the deposited till. If the mechanism that removed the water film could operate to remove the porewater, as envisaged in Mechanism 1, then the till would become non-fluid. At this stage,

if the agglomeration was of sufficient size, a proto drumlin could be created.

THE PROTO DRUMLIN - ITS INITIATION

Once the till has become non-fluid and becomes an obstruction at the basal ice/glacier bed interface two possibilities may occur. Firstly, if the agglomerated till is of too small a size or becomes rapidly dilatant (Radhakrishna & Klym, 1974), thus again increasing its porewater content, the till will be eroded or fluidized and removed. Secondly, if the agglomerated till is large enough to withstand the shear stresses applied by the ice and does not rapidly become dilatant, the till may remain in position. The second possibility is the state of initial drumlin formation.

When a stress is applied to a material, the stress is immediately passed to the particles and liquid in the voids. The intensity of the stress decreases through the material from beneath the point of application to zero at some distance from this point (Terzaghi & Peck, 1967, p.271). The following equation describes the dissipation of such stresses applied to a soil.

$$pv = q \left[1 - \left(\frac{1}{1 + \frac{R^2}{z^2}} \right)^{3/2} \right] \dots\dots\dots(22)$$

where pv is the stress at a depth z within a soil that has a load of q applied to it over a circular area of radius R . To find the depth at which the applied stress would equal the shear strength of the soil, the equation was resolved for z .

$$z = \frac{R}{\sqrt{2 \left[\left(1 - \frac{pv}{q} \right)^{2/3} - 1 \right]}} \dots\dots\dots(23)$$

In order to relate this equation to the stresses applied to a till body, the expected basal shear stresses under different thicknesses of ice were calculated using the following equation:

$$\gamma = p g h \sin \theta \dots\dots\dots(24)$$

where p is the density of ice, g is the acceleration due to gravity, h is the thickness of the glacier at that point and θ is the surface slope angle of the glacier. Table 18 illustrates the range of basal shear stresses found under 10m to 1000m of ice. Since these calculated values were used as the q value in equation (23), the stress at some depth z within the till (p_v) was assumed to be the shear strength value of the till. Values of till shear strength (Chap. 12) indicate considerable variability but range between 0.75 and 3.0 bars. Values of 0.75, 1.5 and 3.0 bars were therefore used as p_v values in equation (23).

TABLE 18

Ice Thickness (m)	Ice ($\theta=9^\circ$) Basal Shear Stress(T) (bars)	Depth (cm) within Till at which the Basal Shear Stress (T) is equal to the Till Shear Strength		
		0.75 bars	1.50 bars	3.00 bars
10	0.14	-	-	-
30	0.41	-	-	-
50	0.69	-	-	-
60	0.83	0.19	-	-
70	0.97	0.43	-	-
100	1.38	0.67	-	-
200	2.76	1.17	0.67	-
1000	13.80	2.43	2.00	1.33

With a 0.75 bar shear strength only at an ice thickness of 60m was the till shear strength exceeded by the basal ice stress. However the dissipation of this applied basal ice stress was calculated to equal the till shear strength at 0.19cm beneath the till surface. Other values of z are shown in Table 18 and illustrate the very rapid rate of stress dissipation that would occur within a till hummock at the ice/bed interface. These calculations show that initial enormous hummocks of till are not required in order to withstand the basal ice stresses.

With a till hummock (proto drumlin) acting as an obstruction at the ice/bed interface a fluctuation in basal ice pressures can be expected to occur over this hummock thereby inducing a related pattern of stresses within the hummock. From the above equation (22) of stress dissipation within a material it can be theorised that the distributions of stresses within a till hummock will be of a pattern similar to that shown in Figure 127. This figure (127a) illustrates the ice moving over the hummock in two dimensions with no cavity in the lee of the hummock (no cavitation). In Figure 127b a cavity in the lee of the hummock (cavitation) is shown. It can be seen from both figures that although the surface distribution of stresses varies with non-cavitation and cavitation, at depth within the hummock a large zone of till, lying close to the till/bed interface, remains almost totally unaffected by the basal ice stresses. This zone of low stressed till may constitute a 'core'. It can therefore be concluded on analysis of these figures that provided a till hummock is of a sufficient initial size to allow stress dissipation (nb. Table 17) no core of bedrock or frozen till is necessary for till to accumulate around.

In order to discover what the initial size of a till hummock must

be under varying conditions of basal stress, ice velocity and till shear strength, several equations used by Boulton (1974, p.67) on bedrock obstructions have been used. The background theoretical derivation to the equations used below has been developed by several workers (Nye, 1969, 1970; Boulton, 1974; Morland & Boulton, 1975). It can be shown that for any given hummock slope and ice velocity where no cavitation occurs the total normal pressure fluctuation across the obstruction is $2\Delta p$. Assuming that the material composing the hummock is an isotropic, linear elastic, material (Carson, 1971), with an assumed wavelength to amplitude ratio of 4/1 and with wavelengths greater than 10m, it can be shown that:

$$\Delta p \approx \frac{10 \eta V_i}{\lambda} \dots\dots\dots(25)$$

where η is the viscosity of ice assumed to be 1 bar year, V_i is the basal velocity of ice and λ the wavelength of the hummock. It can also be shown that if

$$\frac{\Delta p}{p g h} > 1 \dots\dots\dots(26)$$

then cavitation will occur in the lee of the hummock (Fig. 127b). Boulton (1974, p.64) states that "if cavitation occurs, the maximum shear stress (at the surface of the hummock) will occur immediately up-glacier of the point of closure, where there is a stress concentration". It can be concluded therefore that erosion of the till will be initiated in this position on a till hummock. At the point where ice overburden pressures cause the cavity to close, the till within the hummock will be stressed and thereby the shear strength of the till will increase.

In order to discover at what ice velocity and basal shear stress

the till within the hummock will be eroded and the hummock begin to be removed the following equations were utilised. In using these equations, failure was measured as a safety factor (SF) given by

$\frac{\text{Till strength}}{\text{Basal shear stress}}$ such that failure (erosion) will occur when

the safety factor is less than 1.0.

The equations are:

$$\text{a) Cavitation} \quad SF = \frac{S_m}{\left(\frac{1.253 V_i}{\lambda} + 0.188 pgh \right)} \quad \dots\dots(27)$$

$$\text{b) No Cavitation} \quad SF = \frac{S_m + (pgh - \frac{10.3 V_i}{h} \tan \phi)}{\frac{3.133 V_i}{\lambda}} \quad \dots\dots(28)$$

where S_m is the shear strength of the till and $\tan \phi = 0.7$, with the assumption that the till has a low permeability.

In testing these equations, wavelengths of 10, 50 and 100m were used, that is, hummock heights of 2.5, 12.5 and 25m, respectively. Till shear strengths of 0.75, 1.5 and 3.0 bars and basal ice velocities of 3.0, 30.0 and 300.0m per year (Paterson, 1969, p.77 and 128) were used as approximately normal values, although much higher till shear strengths and velocities may occur. Using the above values in equations 27 and 28 Figures 128 to 136 were plotted.

At basal ice velocities of $3m \text{ yr}^{-1}$ it can be seen from Table 19 that erosion (failure) will occur when a till shear strength of 0.75 bars and the hummock wavelength is 10m or less, or if the ice thickness is greater than 50m (Fig. 128). At a till shear strength of 1.5 bars and a velocity of $3m \text{ yr}^{-1}$ all hummock wavelengths, greater than or equal to 10m, will not be eroded. At an ice thickness of 30m all

hummocks, less than or equal to 10m, will be eroded. At an ice thickness of 90m all hummock wavelengths, greater than or equal to 50m, will be eroded (Fig. 129). At a till shear strength of 3.0 bars erosion will occur for all hummock wavelengths within the ice thickness range of 100 to 300m (Fig. 130).

At a basal ice velocity of 30m yr^{-1} , and a till shear strength of 0.75 bars only when cavitation ceases over hummock wavelengths of 50m and 100m and ice thickness increases to 500m will erosion cease due to decreasing basal shear stress (Fig. 131). When till shear strength is increased to 1.5 bars, hummocks of greater than or equal to 100m in wavelength will not be eroded until ice thickness increases to 30m (Fig. 132). When cavitation ceases hummock wavelengths of 50m and 100m will no longer be eroded after an ice thickness greater than or equal to 160m is reached (Fig. 132). At a till shear strength of 3.0 bars no erosion will occur for hummocks of 50 and 100m in wavelength except at an ice thickness of 100m when cavitation just ceases and the 50m hummock just descends below the safety factor limit but immediately returns on a non-cavitation state being reached with thicker ice (Fig. 133).

At a basal ice velocity of 300m yr^{-1} all till hummocks at any wavelength or till shear strength were within the failure zone (Figs. 134-6). Only at a hummock wavelength of 500m (height = 125m) was a Safety Factor of 1.24 reached, with a till shear strength of 3.0 bars, under 1m of ice.

As a first approximation the above analysis suggests that drumlins formed initially as agglomerations of till would most likely develop where the basal ice velocity ranges from 3 to 30m yr^{-1} and are unlikely to form under fast moving ice masses such as surging glaciers (cf.

Mathews, 1974). Similarly it would seem that hummocks would most readily form under ice thicknesses of less than 100m and greater than 400m, depending on the basal slip velocity. It can therefore be tentatively concluded that although drumlins are most likely to be landforms created near ice margins, drumlins may also form under considerable thicknesses of ice far removed from ice margins (cf. Lundqvist, 1970). It can also be seen from this analysis that till of a much higher shear strength could form hummocks under higher ice velocities and greater thicknesses of ice, whereas till of very low shear strength would under comparable ice conditions require to form initial hummocks of much greater wavelength and height (cf. Gravenor, 1974, p.52). This analysis may also confirm the hypothesis of progressive increase in drumlin height down-ice as changes in ice velocity and ice thickness occur.

THE PROTO DRUMLIN - ITS ESTABLISHMENT

Once the till hummock has withstood the basal ice stresses, the shear strength of the till will rapidly increase due to the gradual dissipation of pore water. At this point in the formation of the drumlin the dilatancy theory of Smalley and Unwin (1968) may be introduced since with increasing stress on the till, dilatancy in the till will occur. The increase in till strength will result in the establishment of the till hummock in situ making it more difficult for the ice to remove the obstruction the longer the obstruction remains at the ice/bed interface, provided that no rapid changes in ice velocity or thickness occur. Under normal ice conditions such sudden changes are unlikely to occur; therefore it can be assumed that once established a proto-drumlin, till hummock, will remain.

Boulton (1974, p.56-7) has shown that once an obstruction remains at the ice/bed interface subsequent abrasion will tend to be asymmetric causing a gradual migration of the hummock crest up-ice creating the true drumlin form (Fig. 90).

As well as an up-ice migration of the hummock crest, the hummock will become the nucleus around which further till deposits will accrete. As the ice passes over and around the proto drumlin, streamlining of the drumlin will take place and thus the beginnings of the characteristic drumlin shape will be produced. Once this shape begins to be produced and the moving ice begins to come into equilibrium with the drumlin further accretion may continue either until the drumlin size approaches the critical safety factor level, or the supply of fresh till is exhausted or glaciological changes occur.

IMPLICATIONS OF THE THEORY

The main implication behind this theory is that a route must exist to allow porewater dissipation before till will agglomerate. This route may be in the form of a bed of sand and gravel (cf. Goldthwait, R.P., 1974) (Fig. 67) as at Maryhill, a subglacial melt-water route (cf. Wright, H.E., 1973, p.254) such as the Kelvin and Clyde, or areas of shattered or jointed bedrock (Glückert, 1973). It might therefore be expected that by examining the locations of each individual drumlin possible routes of porewater dissipation would be discovered. Also a distribution pattern of a random to non-random nature can be expected.

The size of drumlins can be expected to vary in any area due to changing ice thicknesses and velocities. Although a lower limit for the size of a proto drumlin can be expected no upper limit can theo-

retically exist. Within any one area therefore several sizes of drumlins can be expected to exist side by side (Fig. 4).

Although it seems most likely that drumlins are formed in the ice marginal zone of ice thicknesses less than 100m, others may form under ice over 400m in thickness. Using an equation derived by Paterson (1969, p.146) to calculate the horizontal distance under the ice (L km) from the ice thickness (H m) where

$$H = 5 L^{0.5} \dots\dots\dots(29)$$

distances were calculated horizontally under the ice of less than 0.4km for an ice thickness of less than 100m and greater than 6.4km for an ice thickness of greater than 400m.

Since this theory demands no specific features with regard to drumlin internal material it can be expected that any material whether laminated clays (cf. Muller, 1974, p.199) or sands and gravels (cf. Lemke, 1958), once deposited from the basal ice in an agglomerated mass, may serve as a proto drumlin in the manner described above. It has been shown that with a sufficient size of hummock a core area of material develops without the necessity of having a bedrock or other form of in situ nucleus.

The mechanisms of drumlin formation described above are not related to the formation of fields of drumlins but to each individual drumlin. It is therefore implied that a drumlin can occur as an isolated landform without the necessity of swarms of adjacent drumlins occurring (cf. Flint, 1971). However it can equally be argued that if ice conditions of velocity and thickness are ideal and the nature of the bed capable of permitting porewater dissipation, then where material is available either as already deposited or as debris within a restricted zone of the basal ice (Moran, 1971) a drumlin field may

develop. Drumlin field development may however be a complex process that occurs over a considerable length of time and under varying boundary conditions (Chap. 4).

In deriving a theory of drumlin formation largely using existing knowledge, it can be visualised that hummocks of till that are of too small a wavelength/height ratio or of too low a shear strength would be deformed by the moving ice into featureless till sheets. This theory of drumlin formation therefore differs from accepted theories on till depositional mechanics only in the creation of a large enough hummock, of sufficient strength, probably beneath ice with a high debris content.

As Andrews (1975, p.131) has pointed out: "There is the possibility that different sets of processes develop an identical landform response". It seems consistent with much of the previous investigations of drumlins that many different factors combining in varying manners and degrees may react to produce a landform that is recognised as a drumlin. It is therefore necessary to recognise this complexity of processes when attempting to understand the creation of any landform and to expect several hypotheses to be consistent with the known evidence.

TABLE 19

λ	10			50			100						
	V_i	T_o	h	1	10	100	1000	1	10	100	1000		
3	0.75	0.610	0.547	0.260	0.040	2.88	1.83	0.39	0.05	5.360	2.590	0.420	0.050
	1.50	1.230	1.090	0.520	0.080	5.77	3.66	0.79	0.09	10.710	5.170	0.840	0.090
	3.00	2.460	2.190	1.050	0.120	11.53	7.32	1.58	0.18	21.430	10.340	1.680	0.180
30	0.75	0.060	0.060	0.060	0.030	0.30	0.29	0.25	8.16	0.610	0.550	0.260	18.560
	1.50	0.120	0.120	0.110	0.050	0.62	0.58	0.49	8.29	1.230	1.090	0.520	18.810
	3.00	0.250	0.250	0.220	0.100	1.24	1.17	0.98	8.54	2.460	2.190	1.050	19.310
300	0.75	0.006	0.006	0.006	0.005	0.03	0.03	0.03	0.02	0.064	0.062	0.055	0.030
	1.50	0.012	0.012	0.010	0.010	0.06	0.06	0.06	0.04	0.120	0.120	0.110	0.052
	3.00	0.025	0.025	0.024	0.020	0.13	0.12	0.12	0.07	0.250	0.250	0.220	0.100

$(V_i = m \text{ yr}^{-1}, T_o = \text{bars}, \lambda = m, h = m)$

B I B L I O G R A P H Y

- AARTOLAHTI, T. (1966) Koijarven-Urjalan drumliinikenttä. Terra 78, 42-51.
- ADAMS, J. I. (1961) Tests on glacial till. Proc. 14th Canadian Soil Mechanics Conf. Ottawa, 37-53.
- AHLMANN, H. W. (1935) Contribution to the physics of glaciers. Geogr. J. 86, 95-113.
- ALDEN, W. C. (1905) The Drumlins of south-eastern Wisconsin. U.S. geol. Surv. Bull. 273
- ALDEN, W. C. (1911) Radiation of glacial flow as a factor in drumlin formation. Bull. geol. Soc. Am. 22, 733-4.
- ALDEN, W. C. (1918) The Quaternary geology of S.E. Wisconsin. U.S. geol. Surv. Prof. Pap. 106.
- ALKIRE, B. D. and ANDERSLAND, O. B. (1973) The effect of confining pressure on the mechanical properties of sand-ice materials. J. Glaciol. 12, 469-82.
- ANDERSON, F. W. (1947) The fauna of the '100 feet beach' clays. Trans. Edinb. Geol. Soc. 14, 220-9.
- ANDERSON, R. C. (1955) Pebble lithology of the Marseilles Till Sheet in Northeastern Illinois. J. Geol. 63, 228-43.
- ANDERSON, R. C. (1957) Pebble and sand lithology of the major Wisconsin glacial lobes of the Central Lowland. Bull. geol. Soc. Am. 68, 1415-50.
- ANDERSON, W. F. (1970) Glacial geology with reference to the Glasgow district. Pub. No. Sm-01-70. Dept. Civ. Eng. Univ. Strathclyde.
- ANDERSON, W. F. (1974) Factors influencing the measured properties of Glasgow region till. Ground Engineering 7, 20-7.
- ANDREWS, J. T. (1971) Methods in the analysis of till fabrics. In Goldthwait, R.P. (ed). Till: a Symposium, Ohio, 321-7.
- ANDREWS, J. T. (1975) Glacial Systems. Belmont, California.
- ANDREWS, J. T. and KING, C. A. M. (1968) Comparative till fabrics and till fabric variability in a till sheet and a drumlin:

- A small-scale study. Proc. Yorks. geol. Soc. 36, 435-61.
- ANDREWS, J. T. and SHIMIZU, K. (1966) Three-dimensional vector technique for analysing till fabrics: discussion and Fortran program. Geogr. Bull. 8, 151-65.
- ANDREWS, J. T. and SMITHSON, B. B. (1966) Till fabrics of the cross-valley moraines of north-central Baffin Island, N.W.T., Canada. Bull. geol. Soc. Am. 77, 271-90.
- ARMSTRONG, J. E. (1949) Fort St. James Map - Area, Cassiar and Coast Districts, B.C. Geol. Surv. Can. Mem. 252.
- ARMSTRONG, J. E. and TIPPER, H. W. (1948) Glaciation in north-central British Columbia. Am. J. Sci. 246, 283-310.
- ARNEMAN, H. F. and WRIGHT, H. E. (1959) Petrography of some Minnesota tills. J. Sed. Petrol. 29, 540-54.
- ARONOW, S. (1959) Drumlines and related streamline features in the Warwick - Tokio area, North Dakota. Am. J. Sci. 257, 191-203.
- ASPEN, P. and JARDINE, W. G. (1968) A temporary exposure of Quaternary deposits at Renfrew, near Glasgow. Proc. geol. Soc. Glasg. 109, 35-7.
- BARANOWSKI, S. (1969) Some remarks on the origin of drumlins. Geographia Polonica 17, 197-208.
- BARANOWSKI, S. (1970) The origin of fluted moraines at the fronts of contemporary glaciers. Geogr. Ann. 52A, 68-75.
- BARNETT, F. M. and FINKE, P. G. (1971) Morphometry of landforms; drumlins. U.S. Army Natick Lab., Earth Sci. Lab., Tech. Rep. ES-63.
- BASSETT, D. A. (1958) Geological excursion guide to the Glasgow district. Geol. Soc. Glasg.
- BELL, D. (1871) On the aspects of Clydesdale during the Glacial Period. Trans. Geol. Soc. Glasg. 4, 63-9.
- BELL, D. (1874) Notes on the Glaciation of the West of Scotland, with references to some recently-observed instances of Cross Striation. Trans. Geol. Soc. Glasg. 4, 300-10.
- BELL, D. (1893) On the alleged proofs of Submergence in Scotland during the Glacial Epoch. - 1. Chapelhall, near Airdrie.

- Trans. Geol. Soc. Glasg. 9, 321-44.
- BELL, D. (1894) On the Glaciation of the West of Scotland.
Proc. Phil. Soc. Glasg. 22, 261-83.
- BELL, D. (1895) On the origin of certain granite boulders in the Clyde valley. Trans. Geol. Soc. Glasg. 10, 16-24.
- BENNIE, J. (1866) On the surface geology of Glasgow. Trans. Geol. Soc. Glasg. 2, 100-15.
- BENNIE, J. (1867) Further observations on the surface geology of Glasgow. Trans. Geol. Soc. Glasg. 2, 260-6.
- BENNIE, J. (1868) On the surface geology of the district round Glasgow, as indicated by the journals of certain bores. Trans. Geol. Soc. Glasg. 3, 133-48.
- BENNIE, J. (1891) On things new and old from the ancient lake of Cowdenglen, Renfrewshire. Trans. Geol. Soc. Glasg. 9, 213-25.
- BENNIE, J. (1896) On the occurrence of Peat with Arctic plants in boulder clay at Faskine near Airdrie, Lanarkshire. Trans. Geol. Soc. Glasg. 10, 148-52.
- BERGQUIST, S. G. (1941) The distribution of drumlins in Michigan. Pap. Mich. Acad. Sci. Arts. Lett. 28, 451-64.
- BETHUNE, R. (1879) Notes of proceedings. Trans. Geol. Soc. Glasg. 7, 291.
- BISHOP, A. W. et al. (1960) Factors controlling the strength of partly saturated Cohesive soils. A.S.C.E. Res. Conf. Shear Strength of Cohesive Soils, 503-32.
- BISHOP, M. S. (1960) Subsurface Mapping. New York.
- BISHOP, W. W. (1963) Lateglacial deposits near Lockerbie, Dumfriesshire. Trans. J. Proc. Dumfries Galloway nat. hist. antiq. Soc. 40, 117-32.
- BISHOP, W. W. (1970) Radiocarbon dates related to the Scottish late-glacial sea in the Firth of Clyde. Nature 227, 480-2.
- BLACK, R. F. (1966) Valdres glaciation in Wisconsin and upper Michigan. Great Lakes Res. Div. Univ. Mich. 15, 164-8.

- BLAIR, M. (1891) The surface geology of Paisley. Trans. Geol. Soc. Glasg. 9, 139-50.
- BLUCK, B. J. (1973) Excursion guide to the Geology of the Glasgow district. Geol. Soc. Glasg.
- BOLTON SEED, H. and CHAN, C. K. (1959) Thixotropic characteristics of compacted clays. Trans. A.S.C.E. 124, 894-925.
- BOSWELL, P. G. H. (1914) On the age of the Suffolk valleys and the buried channels of drift. Quart. J. Geol. Soc. 69, 581-620.
- BOSWELL, P. G. H. (1961) Muddy Sediments. Cambridge.
- BOULTON, G. S. (1967) The development of a complex supraglacial moraine at the margin of Sørbreen, Ny Friesland, Vestspitzbergen. J. Glaciol. 6, 717-35.
- BOULTON, G. S. (1968) Flow tills and related deposits on some Vestspitzbergen glaciers. J. Glaciol. 7, 391-412.
- BOULTON, G. S. (1970) On the origin and transport of englacial debris in Svalbard glaciers. J. Glaciol. 9, 213-29.
- BOULTON, G. S. (1970a) On the development of subglacial and melt-out tills at the margins of certain Svalbard glaciers. J. Glaciol. 9, 231-45.
- BOULTON, G. S. (1971) Till genesis and fabric in Svalbard, Spitzbergen. In Goldthwait, R.P. (ed.) Till: a Symposium, Ohio, 41-72.
- BOULTON, G. S. (1972) Modern Arctic glaciers as depositional models for former ice sheets. Quart. J. Geol. Soc. 128, 361-94.
- BOULTON, G. S. (1974) Processes and patterns of glacial erosion. In Coates, D.R. (ed.) Glacial Geomorphology, Binghampton, New York, 41-88.
- BOULTON, G. S. and DENT, D. L. (1974) The nature and rates of post-depositional changes in recently deposited till from south-east Iceland. Geogr. Ann. 56A, 121-34.
- BOULTON, G. S., DENT, D. L. and MORRIS, E. M. (1974) Subglacial shearing and crushing, and the role of water pressure in tills from south-east Iceland. Geogr. Ann. 56A, 135-45.

- BOULTON, G. S. and WORSLEY, P. (1965) Late Weichselian glaciation in the Cheshire-Shropshire basin. Nature 207, 704-6.
- BOUYOUCOS, G. J. (1934) The hydrometer method for making mechanical analysis of soils. Soil Sci. 38, 335.
- BREDEHOEFT, J. D. and HANSHAW, B. B. (1968) On the maintenance of anomalous fluid pressures: I - Thick sedimentary sequences. Bull. geol. Soc. Am. 79, 1097-1106.
- BREMNER, A. (1942) The origin of the Scottish river system. Scot. Geogr. Mag. 58, 15-20, 54-9, 99-103.
- BRETZ, J. H. (1969) The Lake Missoula floods and the channeled scabland. J. Geol. 77, 505-43.
- BRYCE, J. (1855) Geological notices of the environs of Glasgow, the shores of the Clyde and the island of Arran. Glasgow.
- BUDD, W. F. (1970) Ice flow over bedrock perturbations. J. Glaciol. 9, 29-48.
- BUDD, W. F. (1971) Stress variations with ice flow over undulations. J. Glaciol. 10, 177-95.
- BÜLOW, K. V. (1939) Einfluss von Eis und Untergrund auf Gefüge and Formen der Grundmoraine. Zeit. f. deutsche geol. Gesell. 91, 318-26.
- BURNS, J. (1871) On the surface deposits of the Clyde valley. Trans. Geol. Soc. Glasg. 4, 97-100.
- BUSBRIDGE, J. R. (1968) In-situ geotechnical characteristics of glacial till in the Glasgow area. Univ. of Strathclyde. M.Sc. thesis (unpubl.).
- CADELL, H. M. (1913) The story of the Forth. Glasgow.
- CAPPER, P. L. and CASSIE, W. F. (1949) The Mechanics of Engineering Soils. London.
- CARSON, M. A. (1971) The Mechanics of Erosion. London.
- CARRUTHERS, R. G. (1939) On northern glacial drifts: some peculiarities and their significance. Quart. J. Geol. Soc. 95, 299-333.
- CARRUTHERS, R. G. (1953) Glacial drifts and the undermelt theory. Newcastle.

- CASAGRANDE, A. (1936) The determination of the pre-consolidation load and its practical significance. Proc. 1st Int. Conf. Soil Mechanics. Paper D-34 (Vol. 3), 60-4.
- CHAMBERLIN, T. C. (1883) Preliminary paper on the terminal moraine of the second Glacial Epoch. U.S. geol. Surv. 3rd Ann. Rep., 291-402.
- CHAMBERLIN, T. C. (1894) Proposed genetic classification of Pleistocene glacial formations. J. Geol. 2, 517-38.
- CHAMBERS, R. (1848) Ancient Sea-Margins. Edinburgh.
- CHARLESWORTH, J. K. (1955) The late-glacial history of the Highlands and Islands of Scotland. Trans. R. Soc. Edinb. 62, 769-928.
- CHARLESWORTH, J. K. (1957) The Quaternary Era (2 vols.) London.
- CHARLESWORTH, J. K. (1967) The drumlins of East Down, Ireland. J. Glaciol. 6, 960-1.
- CHORLEY, R. J. (1959) The shape of drumlins. J. Glaciol. 3, 339-44.
- CHRISTIANNSEN, E. A. (1970) Physical environment of Saskatoon, Canada. Sask. Res. Coun. Nat. Res. Coun. Can.
- CHURCH, M. (1964) Streamlined, moulded forms - an essay in morphometry. Univ. of Toronto. B.A. thesis (unpubl).
- CLAPPERTON, C. M. (1970) The evidence for a Cheviot Ice Cap. Trans. Inst. Br. Geogr. 50, 115-27.
- CLAPPERTON, C. M. (1975) The debris content of surging glaciers in Svalbard and Iceland. J. Glaciol. 14, 395-406.
- CLAPPERTON, C. M., GUNSON, A. R. and SUGDEN, D. E. (1975) Loch Lomond Readvance in the eastern Cairngorms. Nature 253, 710-2.
- CLARK, P. J. and EVANS, F. C. (1954) Distance to nearest neighbour as a measure of spatial relationship in populations. Ecology 35, 445-53.
- CLAYTON, L. and MORAN, S. R. (1974) A glacial process-form model. In Coates, D.R. (ed.) Glacial Geomorphology, Binghamton, New York, 89-120.
- CLOSE, M. H. (1867) Notes on the general glaciation of Ireland. Roy.

Geol. Soc. Ireland J. 1, 207-42.

- CLOUGH, C. T. et al. (1925) The geology of the Glasgow district. Mem. geol. Surv. Scot.
- COLE, J. P. and KING, C. A. M. (1968) Quantitative Geography. London.
- COOPE, G. R. (1962) Coleoptera from a peat interbedded between two boulder clays at Burnhead, Airdrie. Trans. Geol. Soc. Glasg. 24, 279-85.
- COOPE, G. R., MORGAN, A. and OSBORNE, P. J. (1971) Fossil coleoptera as indicators of climatic fluctuations during the last glaciation in Britain. Palaeogeogr., Palaeoclimatol., Palaeoecol. 10, 87-101.
- COWAN, W. R. (1968) Ribbed moraine: Till fabric analysis and origin. Can. J. Earth Sci. 5, 1145-59.
- CRAIG, R. (1874) On the section on the Crofthead and Kilmarnock Railway, in Cowden Glen, Neilston, Renfrewshire. Trans. Geol. Soc. Glasg. 4, 17-32.
- CROLL, J. (1870) On two river channels buried under drift, belonging to a period when the land stood several hundred feet higher than at present. Trans. Edinb. Geol. Soc. 1, 330-45.
- CROLL, J. (1875) Climate and Time in their Geological Relations - A theory of secular changes of the Earth's climate. London.
- CROSBY, I. B. (1934) Evidence from drumlins concerning the glacial history of Boston basin. Bull. geol. Soc. Am. 45, 135-58.
- CROSSKEY, H. W. (1865) On the Tellina calcarea bed at Chappel Hall, near Airdrie. Quart. J. Geol. Soc. 21, 219-21.
- CROSSKEY, H. W. (1871) Recent researches into the Post-Tertiary geology of Scotland. Proc. Phil. Soc. Glasg. 7, 92-102.
- CROSSKEY, H. W. and ROBERTSON, D. (1867) The Post-Tertiary fossiliferous beds of Scotland (part I). Trans. Geol. Soc. Glasg. 2, 283-91.
- CROSSKEY, H. W. and ROBERTSON, D. (1869) The Post-Tertiary fossiliferous beds of Scotland (part II). Trans. Geol. Soc. Glasg. 3, 321-41.
- CROSSKEY, H. W. and ROBERTSON, D. (1874) On the Post-Tertiary

- fossiliferous beds of Scotland. Trans. Geol. Soc. Glasg. 4, 241-54.
- CROXTON, F. E. and COWDEN, D. J. (1965) Applied General Statistics. London.
- CROZIER, M. J. (1975) On the origin of the Peterborough drumlin field: testing the Dilatancy theory. Can. Geogr. 14, 181-95.
- CUSHING, E. J. (1963) Origin of pseudostratification and interlayering in glacial tills. Geol. Soc. Am. Spec. Pap. 76, 38.
- CUSHING, E.J. (1967) Late - Wisconsin pollen stratigraphy and the glacial sequence in Minnesota. In Cushing, E.J. and Wright, H.E. (eds.) Quaternary Paleoecology, New Haven, Conn., 59-88.
- DAVIS, W. M. (1884) The distribution and origin of drumlins. Am. J. Sci. 28, 407-16.
- DEAN, W. G. (1953) The drumlinoid landforms of the "Barren Grounds", N.W.T. Can. Geogr. 3, 19-30.
- DEANE, R. E. (1950) Pleistocene geology of the Lake Simcoe District, Ontario. Geol. Surv. Can. Mem. 256.
- DEEGAN, C. E. et al. (1973) The superficial deposits of the Firth of Clyde and its sea lochs. I.G.S. Rep. 73/9.
- DEERE, D. V. and SHAFFER, P. R. (1956) Plasticity studies of Till intruded into jointed limestone in Fairmount Quarry, Illinois. Trans. Ill. Acad. Sci. 49, 121-8.
- DEMOREST, M. (1939) Glacial movement and erosion, a criticism. Am. J. Sci. 237, 594-605.
- DE QUERVAIN, A. and SCHITTER, E. (1920) Das Zungenbecken des Biferten Gletschers. Denkschriften d. schweiz naturf. 55
- DICK, R. (1870) On the discovery of a "sand dyke" or old river channel running north to south from Kirk of Shotts to Wishaw, Lanarkshire. Trans. Edinb. Geol. Soc. 1, 345-52.
- DICKSON, J. H., JARDINE, W. G. and PRICE, R. J. (1976) Three Late-Devensian sites in west-central Scotland. Nature 262, 43-4.
- DOELL, R. R. and COX, A. (1961) Paleomagnetism. In Landsberg, H.F. and

- Van Miegheem, J. (eds.) Advances in Geophysics, New York.
- DOORNKAMP, J. C. and KING, C. A. M. (1971) Numerical Analysis in Geomorphology. London
- DOUGALL, J. (1865) On ancient sea margins around Glasgow. Trans. Geol. Soc. Glasg. 2, 30-3.
- DRAKE, L. D. (1968) Till studies in New Hampshire. Ohio State Univ. Ph.D. thesis (unpubl.).
- DRAKE, L. D. (1971) Evidence for ablation and basal till in east-central New Hampshire. In Goldthwait, R.P. (ed.) Till: a Symposium, Ohio, 73-91.
- DREIMANIS, A. (1961) Tills of southern Ontario. In Legget, R.F. (ed.) Soils in Canada, Roy. Soc. Can. Spec. Pub. 3, 80-96.
- DREIMANIS, A. (1969) Selection of genetically significant parameters for investigation of tills. Zeszyty Naukowe Uniwersytetu im Mickiewicza w. Poznaniu, No.8.
- DREIMANIS, A. and REAVELY, G. H. (1953) Differentiation of the lower and the upper till along the north shore of Lake Erie. J. Sed. Petrol. 23, 238-59.
- DREIMANIS, A. and TERASMAE, J. (1958) Stratigraphy of Wisconsin glacial deposits of the Toronto area, Ontario. Proc. Geol. Assoc. Can. 10, 119-35.
- DREIMANIS, A. and VAGNERS, U. J. (1965) Till-bedrock lithologic relationships. I.N.Q.U.A. 7th Int. Congr. Gen. Sess., 110-1.
- DREIMANIS, A. and VAGNERS, U. J. (1969) Lithologic relation of till to bedrock. In Quaternary Geology and Climate. I.N.Q.U.A. 7th Congr. 16, 93-8.
- DREIMANIS, A. and VAGNERS, U. J. (1971) Bimodal distribution of rock and mineral fragments in basal tills. In Goldthwait, R.P. (ed.) Till: a Symposium, Ohio, 237-50.
- DREIMANIS, A. and VAGNERS, U. J. (1972) The effect of lithology upon texture of till. In Yatsu, E. and Falconer, A. (eds.) Research methods in Pleistocene geomorphology, Guelph, 66-82.

- DRON, R. W. (1915) Notes on a buried river channel at Motherwell. Trans. Geol. Soc. Glasg. 15, 1-3.
- DUNLOP, R. (1888) Notes of proceedings. Trans. Geol. Soc. Glasg. 8, 357.
- DYSON, J. L. (1952) Ice-ridged moraines and their relation to glaciers. Am. J. Sci. 250, 204-11.
- EASTERBROOK, D. J. (1964) Void ratio and bulk densities as means of identifying Pleistocene tills. Bull. geol. Soc. Am. 75, 745-50.
- EBERL, B. (1930) Die Eiszeitenfolge im nördlichen Alpenvorlande. Augsburg.
- EBERS, E. (1926) Die bisherigen Ergebnisse der Drumlin-forschung. Eine Monographie der Drumlins. Neus. Jahrbuch für Min. Geol. Palaon. 53B, 153-270.
- EBERS, E. (1937) Zur Entstehung der Drumlins als. Stromlinien Körper. Neus. Jahrbuch für Min. Geol. Palaon. 78B, 200-39.
- Economic Geology of the Central Coalfield, Area 5 (Glasgow East, Chryston, Glenboig and Airdrie). (1926) Mem. geol. Surv. Scot.
- EDEN, R. A. et al. (1969) Submarine examination of lower Carboniferous strata on inshore regions of the continental shelf of south-east Scotland. Mar. Geol. 7, 235-51.
- EDEN, W. J. (ed.) (1973) Proc. Nat. Conf. on Urban Eng. Terrain Problems. Nat. Res. Coun. Can. Tech. Mem. 109.
- ELDER, S. et al. (1935) The drumlins of Glasgow. Trans. Geol. Soc. Glasg. 19, 285-7.
- ELSON, J. A. (1961) Geology of tills. Proc. 14th Canadian Soil Mechanics Conf. Ottawa, 5-35.
- EMBLETON, C. and KING, C.A.M. (1968) Glacial and Periglacial Geomorphology. London
- ESKOLA, P. (1933) Tausend Geschiebe aus Lettland. Ann. Acad. Sci. Fenicae 39A, No.5.
- EVENSON, E. B. (1970) A method for 3-dimensional microfabric analysis of tills obtained from exposures or cores. J. Sed Petrol. 40, 762-4.

- EVENSON, E. B. (1971) The relationship of macro- and micro fabric of till and the genesis of glacial landforms in Jefferson County, Wisconsin. In Goldthwait, R.P. (ed.) Till: a Symposium, Ohio, 345-66.
- EVERETT, W. (1976) Ice-movement direction from drumlin morphology: comments on the paper by Gravenor, C.P. (J. Glaciol. 13, 45-54.) J. Glaciol. 17, 158-9.
- FAIRCHILD, H. L. (1907) Drumlin structure and origin. Bull. geol. Soc. Am. 17, 702-6.
- FAIRCHILD, H. L. (1929) New York drumlins. Proc. Roch. Acad. Sci. 7, 1-37.
- FEININGER, T. (1971) Chemical weathering and glacial erosion of crystalline rocks and the origin of till. U.S. geol. Surv. Prof. Pap. 750-C, 65-81.
- FITZPATRICK, E. A. (1963) Deeply weathered rock in Scotland, its occurrence, age and contribution to soils. J. Soil Sci. 14, 33-43.
- FITZPATRICK, E. A. (1965) An interglacial soil at Teindland, Morayshire. Nature 207, 621-2.
- FITZPATRICK, E. A. (1972) The principal Tertiary and Pleistocene events in northeast Scotland. In Clapperton, C.M. (ed.) North-East Scotland: geographical essays, 1-4.
- FLINT, R. F. (1947) Glacial geology and the Pleistocene Epoch, New York.
- FLINT, R. F. (1957) Glacial and Pleistocene Geology. New York.
- FLINT, R. F. (1971) Glacial and Quaternary Geology. New York.
- FOLK, R. L. (1971) Genesis of longitudinal and oghurd dunes elucidated by rolling upon grease. Bull. geol. Soc. Am. 82, 3461-8.
- FOOKES, P. G. (1965) Orientation of fissures in stiff overconsolidated clay of the Siwalik System. Geotechnique 15, 195-206.
- FOOKES, P. G. and DENNESS, B. (1969) Observational studies of fissure patterns in Cretaceous sediments of south-east England. Geotechnique 19, 453-77.

- FOOKES, P. G. and WILSON, D. D. (1966) The geometry of discontinuities and slope failures in Siwalik clay. Geotechnique 16, 305-20.
- FRANCIS, E. H. et al. (1970) The geology of the Stirling district. Mem. geol. Surv. Scot.
- FULLER, M. D. (1964) A magnetic fabric in till. Geol. Mag. 99, 233-7.
- FYLES, J. G. (1963) Surficial geology of Victoria and Stefansson Islands, District of Franklin. Geol. Surv. Can. Bull. 101.
- GALLOWAY, R. W. (1961) Ice wedges and involutions in Scotland. Biul. Peryglac. 10, 169-93.
- GEIKIE, A. (1863) On the phenomena of the glacial drift of Scotland. Trans. Geol. Soc. Glasg. 1, 1-190.
- GEIKIE, A. (1865(1st ed.), 1887 (2nd ed.), 1901 (3rd ed.))
The Scenery of Scotland. London
- GEIKIE, J. (1871) On denudation in Scotland since Glacial Times. Trans. Geol. Soc. Glasg. 3, 54-74.
- GEIKIE, J. (1874 (1st ed.), 1877 (2nd ed.), 1894 (3rd ed.))
The Great Ice Age. London.
- GEMMELL, A. M. D. (1973) The deglaciation of the island of Arran, Scotland. Trans. Inst. Br. Geogr. 59, 27-39.
- GEORGE, T. N. (1958) The geology and geomorphology of the Glasgow district. In Miller, R. and Tivy, J. (eds.) The Glasgow Region, 17-61.
- GEORGE, T. N. (1960) The stratigraphical evolution of the Midland Valley. Trans. Geol. Soc. Glasg. 24, 32-107.
- GEORGE, T. N. (1965) The geological growth of Scotland. In Craig, G.Y. (ed.) The Geology of Scotland, Edinburgh, 1-47.
- GILLBERG, G. (1955) Den glaciála utvecklingen inom Sydsvenska Högländets västra randzon. Geol. För. Stockh. Förh. 77, 481-524.
- GILLBERG, G. (1965) Till distribution and ice movement on the northern slopes of the south Swedish Highlands. Geol. För. Stockh. Förh. 86, 433-84.
- GJESSING, J. (1966) On "plastic scouring" and 'subglacial erosion'. Norsk geogr. Tidsskr. 20, 1-37.

- GLEN, J. W., DONNER, J. J. and WEST, R. G. (1957) On the mechanism by which stones in till become orientated. Am. J. Sci. 255, 194-205.
- GLINICKA, J. L. et al. (1936) Über die Ausdehnung der Rückzugsphasen der baltischen Vereisung in Narocz - see - Gebiet. Trav. Inst. Geol. Geogr. Univ. Wilno. 24.
- GLÜCKERT, G. (1973) Two large drumlin fields in Central Finland. Fennia 120.
- GODARD, A. (1965) Recherches de Geomorphologie en Ecosse du Nord-Ouest. Paris.
- GOLDTHWAIT, J. W. (1924) Physiography of Nova Scotia. Geol. Surv. Can. Mem. 140.
- GOLDTHWAIT, L. (1948) Glacial till in New Hampshire. Min. Res. Surv. N.H. State Plan. Dev. Comm. 10.
- GOLDTHWAIT, R. P. (1960) Study of ice cliff in Nunatarssuaq, Greenland. U.S. Army Cold Reg. Res. Engng. Lab. Tech. Rept. 39.
- GOLDTHWAIT, R. P. (1971) Introduction to till, today. In Goldthwait, R.P. (ed.) Till: a Symposium, Ohio, 3-26.
- GOLDTHWAIT, R. P. (1974) Rates of formation of glacial features in Glacier Bay, Alaska. In Coates, D.R. (ed.) Glacial Geomorphology, Binghamton, New York, 163-85.
- GOODLET, G. A. (1960) Mid-Carboniferous sedimentation in the Midland Valley of Scotland. Trans. Edinb. Geol. Soc. 17, 217-40.
- GOW, A. J. (1963) Results of measurements in the 309 meter bore hole at Byrd Station Antarctica. J. Glaciol. 4, 771-84.
- GRAVENOR, C. P. (1951) Bedrock source of tills in south-western Ontario. Am. J. Sci. 249, 66-71.
- GRAVENOR, C. P. (1953) The origin of drumlins. Am. J. Sci. 251, 674-81.
- GRAVENOR, C. P. (1957) Surficial geology of the Lindsay-Peterborough area, Ontario, Victoria, Peterborough, Durham and Northumberland Counties, Ontario. Geol. Surv. Can. Mem. 288.
- GRAVENOR, C. P. (1974) The Yarmouth drumlin field, Nova Scotia, Canada. J. Glaciol. 13, 45-54.

- GRAVENOR, C. P. and BAYROCK, L. A. (1961) Glacial deposits of Alberta. In Legget, R.F. (ed.) Soils in Canada, R. M. Soc. Can. Spec. Pub. 3, 33-50.
- GRAVENOR, C. P. and MENELEY, W. A. (1958) Glacial flutings in central and northern Alberta. Am. J. Sci. 256, 715-28.
- GRAVENOR, C. P. and STUPAVSKY, M. (1974) Magnetic susceptibility of the surface tills of southern Ontario. Can. J. Earth Sci. 11, 658-63.
- GRAVENOR, C. P., STUPAVSKY, M. and SYMONS, D. T. A. (1973) Paleomagnetism and its relationship to till deposition. Can. J. Earth Sci. 10, 1068-78.
- GREENSMITH, J. T. and TUCKER, E. V. (1971) Overconsolidation in some fine-grained sediments; its nature, genesis and value in interpreting the history of certain English Quaternary deposits. Geol. en Mijnbouw 50, 743-8.
- GREGORY, J. W. (1915) The Tweed valley and its relation to the Clyde and Solway. Scot. Geogr. Mag. 31, 478-86.
- GREGORY, J. W. (1915a) The Geology of the Glasgow district, "The Glacial Geology of the district". Proc. Geol. Assoc. 26, 158-64.
- GREGORY, J. W. and CURRIE, E. D. (1928) The vertebrate fossils from the glacial and associated post-glacial beds of Scotland in the Hunterian Museum, University of Glasgow. Mon. geol. Dept. Hunterian Mus. Glasg. Univ. 2.
- GREGORY, S. (1971) Statistical Methods and the Geographer. London
- GROSS, D. L. and MORAN, S. R. (1971) Grain-size and mineralogical gradations within tills of the Allegheny Plateau. In Goldthwait, R.P. (ed.) Till: a Symposium, Ohio, 251-74.
- HANSEN, K. (1971) Tunnel valleys in Denmark and northern Germany. Bull. Geol. Soc. Den. 20, 295-306.
- HANSEN, W. R. (1956) Geology and mineral resources of the Hudson - Maryland Quadrangles, Mass., U.S.A. U.S. geol. Surv. Bull. 1038, 62-7.
- HARRIS, S. A. (1967) Origin of part of the Guelph drumlin field and

- the Galt and Paris moraines, Ontario. Can Geogr. 11, 16-34.
- HARRIS, S. A. (1968) Till fabrics and the speed of movement of the Arapahoe Glacier, Colorado. Prof. Geogr. 20, 195-8.
- HARRIS, S. A. (1969) The meaning of till fabrics. Can. Geogr. 13, 317-77.
- HARRISON, P. W. (1957) A clay-till fabric: its character and origin. J. Geol. 65, 275-308.
- HARRISON, W. (1958) Marginal zones of vanished glaciers reconstructed from the pre-consolidation values of overridden silts. J. Geol. 66, 72-95.
- HARRISON, W. (1960) Original bedrock composition of Wisconsin till in central Indiana. J. Sed. Petrol. 30, 432-46.
- HEIDENREICH, C. (1964) Some observations on the shape of drumlins. Can. Geogr. 8, 101-7.
- HILL, A. R. (1968) An analysis of the spatial distribution and origin of drumlins in North Down and South Antrim, Northern Ireland. Queen's Univ., Belfast. Ph.D. thesis (unpubl)
- HILL, A. R. (1971) The internal composition and structure of drumlins in North Down and South Antrim, Northern Ireland. Geogr. Ann. 53A, 14-31.
- HILL, A. R. (1973) The distribution of drumlins in Co. Down, Ireland. Ann. Am. Assoc. Geogr. 63, 226-40.
- HILLEFORS, Å. (1973) The stratigraphy and genesis of stoss- and lee-side moraines. Bull. geol. Inst. Univ. Uppsala 5, 139-54.
- HÖGBOM, A. G. (1905) Studien in nordschwedischen Drumlinlandschaften. Bull. geol. Inst. Univ. Uppsala 6, 175-99.
- HOLLINGWORTH, S. E. (1931) The glaciation of western Edenside. Quart. J. Geol. Soc. 87, 281-359.
- HOLMES, A. (1966) Principles of Physical Geology. Edinburgh.
- HOLMES, C. D. (1941) Till fabrics. Bull. geol. Soc. Am. 52, 1299-1355.
- HOLMES, C. D. (1952) Drift dispersion in west-central New York, Bull. geol. Soc. Am. 63, 993-1010.

- HOLMES, C. D. (1960) Evolution of till-stone shapes in central New York. Bull. geol. Soc. Am. 71, 1645-60.
- HOOKE, Le B. R. (1970) Morphology of the ice-sheet margin near Thule, Greenland. J. Glaciol. 9, 303-24.
- HOOKE, Le B. R. (1973) Structure and flow in the margin of the Barnes Ice Cap, Baffin Island, N.W.T., Canada. J. Glaciol. 12, 423-38.
- HOPKINS, W. (1852) On the granitic blocks of the South Highlands of Scotland. Quart. J. Geol. Soc. 3, 20-36.
- HOPPE, G. (1951) Drumlins i Nordöstra Norbotten. Geogr. Ann. 33, 1299-1354.
- HOPPE, G. (1952) Hummocky moraine regions, with special reference to the interior of Norbotten. Geogr. Ann. 34, 1-72.
- HOPPE, G. (1959) Glacial morphology and Inland Ice recession in northern Sweden. Geogr. Ann. 41, 193-212.
- HOPPE, G. (1963) Subglacial sedimentation, with examples from northern Sweden. Geogr. Ann. 45, 41-9.
- HOPPE, G. and SCHYTT, V. (1953) Some observations on fluted moraine surfaces. Geogr. Ann. 35, 105-15.
- HORBERG, C. L. (1945) A major buried valley in east-central Illinois and its regional relationships. J. Geol. 53, 349-59.
- HORBERG, C. L. (1950) Bedrock topography of Illinois. Ill. Geol. Surv. Bull. 73.
- HOWELL, F. T. (1973) The sub-drift surface of the Mersey and Weaver catchment and adjacent areas. Geol. J. 8, 285-96.
- HUGHES, T. (1973) Glacial permafrost and Pleistocene Ice Ages. 2nd Int. Conf. on Permafrost (Yakutsk, U.S.S.R.), Nat Ac. Sci., 213-23.
- JAHNS, R. H. (1943) Sheet structure in granites: its origin and use as a measure of glacial erosion in New England. J. Geol. 51, 71-98.
- JAMIESON, T. F. (1865) On the history of the last geological changes in Scotland. Quart. J. Geol. Soc. 21, 161-203.

- JARDINE, W. G. (1965) Note on a temporary exposure in central Glasgow. Scot. J. Geol. 1, 221-4.
- JARDINE, W. G. (1967) The post-glacial marine transgression at Girvan, Ayrshire. Trans. Inst. Br. Geogr. 42, 181-2.
- JARDINE, W. G. (1968) Letters to the Editors: The "Perth" Readvance. Scot. J. Geol. 4, 185-7.
- JARDINE, W. G. (1969) Quaternary deposits at Garscadden Mains, Glasgow. Proc. Geol. Soc. Glasg. 110, 51-3.
- JARDINE, W. G. (1973) The Quaternary geology of the Glasgow district. In Bluck, B.J. (ed.) Excursion guide to the Geology of the Glasgow district, Geol. Soc. Glasg., 156-69.
- JARDINE, W. G. (1974) Form and age of late Quaternary shorelines and coastal deposits of south-west Scotland: critical data. Quaternaria 14, 103-14.
- JARDINE, W. G. and MOISLEY, H. A. (1967) Note on a temporary exposure of Quaternary deposits at Scotstoun House, Glasgow. Proc. Geol. Soc. Glasg. 108, 25-7.
- JARDINE, W. G. and PEACOCK, J. D. (1973) Scotland. In Mitchell, G.F. et al. (eds.) A correlation of Quaternary deposits in the British Isles, Geol. Soc. Lond. Spec. Rept. 4, 53-9.
- JEWTUCHOWICZ, S. (1956) Structure des drumlins aux environs de Zbojno. Acta geogr. Univ. Lodz. 7, 1-74.
- JOHANSSON, H. G. (1968) Striae and fabric analysis in a moraine exposure in Västerbotten, northern Sweden. Geol. För. Stockh. Förh. 90, 205-12.
- JOHANSSON, H. G. (1972) Moraine ridges and till stratigraphy in Västerbotten, northern Sweden. Sv. geol. Unders. C66.
- JOHNSON, A. M. (1970) Physical Processes in Geology. San Francisco.
- JOHNSON, W. H. et al. (1971) Till stratigraphy of the Danville Region, east-central Illinois. In Goldthwait, R.P. (ed.) Till: a Symposium, Ohio, 184-216.
- JONES, R. L., BEAVERS, A. H. and ALEXANDER, J. D. (1966) Mineralogical and physical characteristics of till in moraines of La Salle

- County, Illinois. Ohio J. Sci. 66, 359-68.
- KAISER, R. E. (1962) Glacial till in north-central New York. J. Sed. Petrol. 32, 502-13.
- KAMB, B. and LA CHAPELLE, E. (1964) Direct observation of the mechanism of glaciers sliding over bedrock. J. Glaciol. 5, 159-72.
- KARROW, P. F. (1973) Bedrock topography in south-western Ontario: a progress report. Proc. Geol. Assoc. Can. 25, 67-77.
- KAURANNE, L. K. (1960) A statistical study of stone orientation in glacial till. Comm. Geol. de Finlande Bull. 188, 87-97.
- KAZI, A. and KNILL, J. L. (1969) The sedimentation and geotechnical properties of Cromer Till, between Happisburgh and Cromer, Norfolk. Quart. J. Eng. Geol. 2, 63-86.
- KAZI, A. and KNILL, J. L. (1973) Fissuring in glacial lake clays and tills on the Norfolk coast, United Kingdom. Eng. Geol. 7, 35-48.
- KINAHAN, G. H. and CLOSE, M. H. (1827) General Glaciation of Iar - Connaught.
- KING, C. A. M. (1974) Morphometry in glacial geomorphology. In Coates, D.R. (ed.) Glacial Geomorphology, Binghamton, New York, 147-62.
- KIRBY, R. P. (1968) The ground moraines of Midlothian and East Lothian. Scot. J. Geol. 4, 209-20.
- KIRK, W. and GODWIN, H. (1963) A lateglacial site at Loch Droma, Ross and Cromarty. Trans. R. Soc. Edinb. 65, 225-49.
- KLOHN, E. J. (1965) Elastic properties of dense glacial till. Can. Geotech. J. 11, 116-40.
- KOTEFF, C. (1974) The morphologic sequence concept and deglaciation of southern New England. In Coates, D.R. (ed.) Glacial Geomorphology, Binghamton, New York, 121-44.
- KRUGER, F. C. (1937) A sedimentary and petrographic study of certain glacial drifts of Minnesota. Am. J. Sci. 34, 345-63.
- KRUGER, J. (1970) Till fabric in relation to direction of ice movement; a study from the Faska Banke, Denmark. Geogr. Tidsskr. 69, 133-70.
- KRUGER, J. (1973) Operator variance in orientation measurements in till

- macro-fabric analyses. Bull. geol. Inst. Univ. Uppsala 5, 117-25.
- KUPSCH, W. O. (1955) Drumlins with jointed boulders near Dollard, Saskatchewan. Bull. geol. Soc. Am. 66, 327-38.
- LASCA, N. P. (1970) The drumlin field of south-eastern Wisconsin. Wisc. Univ. Geol. Nat. Hist. Surv. Inf. Circ. 15, E1-E13.
- LEGGET, R. F. (1973) Cities and Geology. New York.
- LEGGET, R. F. (1974) Glacial landforms and civil engineering. In Coates, D.R. (ed.) Glacial Geomorphology, Binghamton, New York, 351-74.
- LEMKE, R. W. (1958) Narrow linear drumlins near Velva, North Dakota. Am. J. Sci. 256, 270-83.
- LEOPOLD, L. B., WOLMAN, M. G. and MILLER, J. P. (1964) Fluvial Processes in Geomorphology. San Francisco.
- LINDSAY, J. F. (1970) Clast fabric of till and its development. J. Sed. Petrol. 40, 629-41.
- LINELL, K. A. and SHEA, H. F. (1960) Strength and deformation characteristics of various glacial tills in New England. A.S.C.E. Res. Conf. Shear Strength of Cohesive Soils, 275-314.
- LINTON, D. L. (1933) The origin of the Tweed drainage system. Scot. Geogr. Mag. 49, 162-75.
- LINTON, D. L. (1940) Some aspects of the evolutions of the rivers Earn and Tay. Scot. Geogr. Mag. 56, 1-11, 69-79.
- LINTON, D. L. (1951) Problems of Scottish scenery. Scot. Geogr. Mag. 67, 65-85.
- LINTON, D. L. (1955) The problem of tors. Geogr. J. 121, 470-87.
- LINTON, D. L. (1963) The forms of glacial erosion. Trans. Inst. Br. Geogr. 33, 1-28.
- LLIBOUTRY, L. (1968) General theory of subglacial cavitation and sliding of temperate glaciers. J. Glaciol. 7, 21-58.
- LO, K. Y. (1970) The operational strength of fissured clays. Geotechnique 20, 57-74.

- LOTAN, J. E. and SHETRON, S. C. (1968) Characteristics of drumlins in Leelanau County, Michigan. Pap. Mich. Acad. Sci. Arts Lett. 53, 79-89.
- LUNDQVIST, G. (1935) Blockundersökningar, Historic och Metodik. Sv. geol. Unders. (Ser.) 390.
- LUNDQVIST, J. (1970) Studies of drumlin tracts in central Sweden. Acta Geogr. Lodziensia 24, 317-26.
- LUNDQVIST, J. (1974) Outlines of the Weichsel glaciation in Sweden. Geol. För. Stockh. Förh. 96, 327-39.
- MCCALLIEN, W. J. (1937) Late-glacial and early post-glacial Scotland. Proc. Soc. Antiq. Scot. 71, 174-206.
- MACCLINTOCK, P. and DREIMANIS, A. (1964) Reorientation of till fabric by overriding glacier in the St. Lawrence Valley. Am. J. Sci. 262, 133-42.
- MCGINNIS, L. D. (1968) Glaciation as a possible cause of mineral deposition. Econ. Geol. 63, 390-400.
- MCGOWN, A. and RADWAN, A. M. (1975) The presence and influence of fissures in the boulder clays of west-central Scotland. Can. Geotech. J. 12, 84-97.
- MCGOWN, A. SALDIVAR-SALI, A. and RADWAN, A. M. (1974) Fissure patterns and slope failures in till at Hurlford, Ayrshire. Quar. J. Eng. Geol. 7, 1-26.
- MACGREGOR, M. and RITCHIE, J. (1940) Early glacial remains of reindeer from the Glasgow district. Proc. R. Soc. Edinb. 60, 322-32.
- MCKENZIE, G. D. (1969) Observations on a collapsing kame terrace in Glacier Bay National Monument, south-east Alaska. J. Glaciol. 8, 413-25.
- MCKENZIE, G. D. (1970) Glacial geology of Muir Inlet, south-east Alaska. Inst. Polar Studies Rept. 25.
- MACKENZIE, J. (1818) Regarding the remains of an Elephant found in Ayrshire. Mem. Wernerian Nat. Hist. Soc. 2, 662.
- MACKINDER, H. J. (1902) Britain and the British Seas London.

- McKINLAY, D. G. (1969) Engineering properties of boulder clays. Eng. Group Reg. Meeting Univ. Strathclyde, Geol. Soc. Lond. Pap. 3.
- McKINLAY, D. G., TOMLINSON, M. J. and ANDERSON, W. F. (1975) Observations on the undrained strength of a glacial till. Geotechnique 24, 503-16.
- McLELLAN, A. G. (1969) The last glaciation and deglaciation of central Lanarkshire. Scot. J. Geol. 5, 248-68.
- MacNEILL, R. H. (1965) Variation in the content of some drumlins and tills in south-west Nova Scotia. Mar. Sed. 1, 16-9.
- McPHERSON, H. J. and GARDNER, J. S. (1969) The development of glacial landforms in the vicinity of Saskatchewan Glacier. Can. Alpine J. 52, 90-6.
- MADSEN, V. et al. (1928) Summary of the geology of Denmark. Dan. geol. Unders. 5.
- MANGERUD, J. (1972) Radiocarbon dating of marine shells, including a discussion of apparent age of recent shells from Norway. Boreas 1, 143-72.
- MANNERFELT, C. M. (1945) Några Glacialmorfologiska Fornelement. Geogr. Ann. 27, 1-239.
- MANNERFELT, C. M. (1949) Marginal drainage channels as indicators of the gradients of Quaternary ice caps. Geogr. Ann. 31, 194-9.
- MARK, D. M. (1974) On the interpretation of till fabrics. Geology 2, 101-4.
- MARSLAND, A. (1971) The shear strength of stiff fissured clays. Building Res. Stat. Pap. 21/71.
- MARTIN, J. O. (1903) A study of the drumlin area of New York State. Cornell Univ. M.S. thesis (unpubl.)
- MATHEWS, W. H. (1964) Water pressure under a glacier. J. Glaciol. 5 235-40.
- MATHEWS, W. H. (1967) Profiles of late Pleistocene glaciers in New Zealand. N.Z. J. Geol. Geophy. 10, 146-63.
- MATHEWS, W. H. (1974) Surface profiles of the Laurentide ice sheet in

- its marginal areas. J. Glaciol. 13, 37-44.
- MATHEWS, W. H. and MACKAY, J. R. (1960) Deformation of soils by glacier ice and the influence of pore pressures and permafrost. Trans. R. Soc. Can. 54, 27-36.
- MEAD, W. J. (1925) The geologic role of dilatancy. J. Geol. 33, 685-98.
- MICKELSON, D. M. (1971) Glacial geology of the Burroughs Glacier area, southeastern Alaska. Inst. Polar Studies Rept. 40.
- MICKELSON, D. M. (1973) Nature and rate of basal till deposition in a stagnating ice mass, Burroughs Glacier, Alaska. Arctic and Alpine Res. 5, 17-27.
- MILLER, J. W. (1970) Drumlins in the Oswego, Weedsport and Auburn, New York Quadrangles. Syracuse Univ. Ph.D. thesis (unpubl.).
- MILLER, J. W. (1972) Variations in New York drumlins. Ann. Am. Assoc. Geogr. 62, 418-23.
- MILTHERS, K. (1942) Indicator boulders in Denmark. Den. geol. Surv. Bull. 69, 122-8.
- MINELL, H. (1973) An investigation of drumlins in the Narvik area of Norway. Bull. geol. Inst. Univ. Uppsala 5, 133-8.
- MITCHELL, B. D. and JARVIS, R. A. (1956) The soils of the country round Kilmarnock. Mem. Soil Surv. Scot.
- MITCHELL, G. F. (1952) Late-glacial deposits of Garscadden Mains, near Glasgow. New Phytol. 50, 277-86.
- MITCHELL, G. F. (1960) The Pleistocene history of the Irish Sea. Advn. Sci. 17, 313-25.
- MOAR, N. T. (1969) Late Weichselian and Flandrian pollen diagrams from south-west Scotland. New Phytol. 68, 433-67.
- MORAN, S. R. (1971) Glaciotectonic structures in drift. In Goldthwait, R.P. (ed.) Till: a Symposium, Ohio, 127-48.
- MORLAND, L. W. and BOULTON, G. S. (1975) Stress in an elastic hump: the effects of glacier flow over elastic bedrock. Proc. R. Soc. Lond. 344A, 157-73.
- MORT, F. W. (1918) The rivers of south-west Scotland. Scot. Geogr. Mag.

34, 361-8.

- MULLER, E. H. (1963) Geology of Chautauqua County, New York. N.Y. State Mus. Bull. 392.
- MULLER, E. H. (1974) Origins of drumlins. In Coates, D.R. (ed.) Glacial Geomorphology, Binghamton, New York. 187-204.
- MURDOCH, J. B. (ed.) (1904) The Geology and Palaeontology of the Clyde Drainage Area. Geol. Soc. Glasg.
- MUTANEN, T. (1971) An example of the use of boulder counting in lithologic mapping. Bull. geol. Soc. Fin. 43, 131-40.
- NECHAY, V. (1927) Les sediments glaciaires dans le pays de Dobrzyn. Bull. Serv. Geol. de Pologne.
- NEILSON, J. (1896) On the occurrence of marine organisms in the boulder clay of the Glasgow district. Trans. Geol. Soc. Glasg. 10, 273-7.
- NEILSON, J. (1903) The geology of the Clyde "Crannogs". Trans. Geol. Soc. Glasg. 12, 273-89.
- NIINI, H. (1964) Bedrock and its influence on the topography in the Lokka-Porttipahta Reservoir District, Finnish Lapland. Fennia 90, 5-54.
- NOBLES, L. H. and WEERTMAN, J. (1971) Influence of irregularities of the bed of an ice-sheet on deposition rate of till. In Goldthwait, R.P. (ed.) Till: a Symposium, Ohio, 117-26.
- NYE, J. F. (1965) Stability of a circular cylindrical hole in a glacier. J. Glaciol. 5, 505-7.
- NYE, J. F. (1969) The effect of longitudinal stress on the shear stress at the base of an ice-sheet. J. Glaciol. 8, 207-13.
- NYE, J. F. (1970) Glacier sliding without cavitation in a linear viscous approximation. Proc. R. Soc. Lond. 315A, 381-403.
- NYE, J. F. (1973) Water at the bed of a glacier. Symposium on the Hydrology of Glaciers, Int. Ass. Sci. Hydrol. Pub. 95, 189-94.
- OKKO, V. (1955) Glacial drift in Iceland, its origin and morphology. Comm. Geol. de Finlande Bull. 170, 1-133.
- OLAVSSON, E. and SVENONIUS, B. (1975) Past changes in the geomagnetic field caused by glaciation and deglaciation. Boreas 4, 55-62.

- OLSSON, I. U. (1974) Some problems in connection with the evaluation of C^{14} dates. Geol. För. Stockh. Förh. 96, 311-20.
- ORME, A. R. (1967) Drumlins and the Weichsel Glaciation of Connemara. Ir. Geogr. 5, 262-74.
- PARTHASARATHY, A. and BLYTH, F. G. H. (1959) The superficial deposits of the buried valley of the River Devon near Alva, Clackmannan, Scotland. Proc. Geol. Assoc. 70, 33-50.
- PATERSON, I. B. (1974) The supposed Perth Readvance in the Perth district. Scot. J. Geol. 10, 53-66.
- PATERSON, W. S. B. (1969) The physics of glaciers. Oxford.
- PATERSON, W. S. B. (1970) The sliding velocity of the Athabasca Glacier, Canada. J. Glaciol. 9, 55-63.
- PEACH, A. M. (1909) Boulder distribution from Lennoxton, Scotland. Geol. Mag. 46, 26-31.
- PEACH, B. N. and HORNE, J. (1930) Chapters in the Geology of Scotland. London.
- PEACOCK, J. D. (1971) Marine shell radiocarbon dates and the chronology of deglaciation in Western Scotland. Nature 230, 43-5.
- PENNINGTON, W. and BONNY, A. P. (1970) Absolute pollen diagram from the British Late-Glacial. Nature 226, 871-3.
- PENNY, L. F. and CATT, J. A. (1967) Stone orientation and other structural features of tills in east Yorkshire. Geol. Mag. 104, 344-60.
- PENNY, L. F., COOPE, G. R. and CATT, J. A. (1969) The age and insect fauna of the Dimlington silts, east Yorkshire. Nature 224, 65-7.
- PETERSON, D. N. (1969) Glaciological investigations on the Casement Glacier, southeast Alaska. Ohio State Univ. Ph.D. thesis (unpubl.)
- PETERSON, D. N. (1970) Glaciological investigations on the Casement Glacier, southeast Alaska. Inst. Polar Studies Rept. 36.
- PHEMISTER, T. C. and SIMPSON, S. (1949) Pleistocene deep weathering in north-east Scotland. Nature 164, 318-9.

- PIPER, C. S. (1950) Soil and Plant Analysis. Adelaide.
- PISKIN, K. and BERGSTROM, R. E. (1967) Glacial drift in Illinois: thickness and character. Ill. Geol. Surv. Circ. 416.
- PREST, V. K. (1962) Surficial geology and soils of the Montreal area. Proc. 15th Can. Soil Mechanics Conf. Ottawa, 163-85.
- PREST, V. K. (1968) Nomenclature of moraines and ice flow features as applied to the glacial map of Canada. Geol. Surv. Can. Pap. 67-57.
- PRICE, R. J. (1960) Glacial meltwater channels in the upper Tweed drainage basin. Geogr. J. 126, 483-9.
- PRICE, R. J. (1963) The glaciation of a part of Peeblesshire, Scotland. Trans. Edinb. Geol. Soc. 19, 325-48.
- PRICE, R. J. (1973) Glacial and Fluvio-glacial Landforms. London.
- PRICE, R. J. (1975) The glaciation of West Central Scotland - a review. Scot. Geogr. Mag. 91, 134-45.
- PUTNAM, D. F. and CHAPMAN, L. J. (1943) The drumlins of southern Ontario. Trans. R. Soc. Can. 37, 75-88.
- RADHAKRISHNA, H. S. and KLYM, T. W. (1974) Geotechnical properties of a very dense glacial till. Can. Geotech. J. 11, 396-408.
- RAGAN, D. M. (1968) Structural Geology, an introduction to geometrical techniques. New York.
- RAMSDEN, J. and WESTGATE, J. A. (1971) Evidence for reorientation of a till fabric in the Edmonton area, Alberta. In Goldthwait, R.P. (ed.) Till: a Symposium, Ohio, 335-44.
- READE, T. M. (1882) On the relation of the glacial deposits of the Clyde and Forth to those of the north-west of England and north of Ireland. Trans. Geol. Soc. Glasg. 6, 264-76.
- REED, B., GALVIN, C. J. and MILLER, J. P. (1962) Some aspects of drumlin geometry. Am. J. Sci. 260, 200-10.
- REPO, R. and TYNNI, R. (1971) Observations on the Quaternary geology of an area between the Second Saulpausselkä and the ice-margin formation of central Finland. Bull. geol. Soc. Fin. 43, 185-202.

- REYNOLDS, O. (1885) On the dilatancy of media composed of rigid particles in contact. Phil. Mag. (5th Ser.) 20, 469-81.
- RICHEY, J. E. et al. (1930) The geology of North Ayrshire. Mem. geol. Surv. Scot.
- RICHTER, K. (1929) Studien uber fossile Gletscherstruktur. Z. Gletscherkunde 17, 1-37.
- ROBERTS, M. C. and MARK, D. M. (1970) The use of trend surfaces in till fabric analysis. Can. J. Earth Sci. 7, 1179-84.
- ROBERTSON, D. (1877) Notes on a Post-Tertiary deposit of shell-bearing clay, on the west side of the railway tunnel at Arkleston. Trans. Geol. Soc. Glasg. 5, 281-7.
- ROBIN, G. de Q. (1955) Ice movement and temperature distribution in glaciers and ice sheets. J. Glaciol. 2, 523-32.
- ROLFE, W. D. I. (1966) Woolly rhinoceros from the Scottish Pleistocene. Scot. J. Geol. 2, 253-8.
- ROMINGER, J. F. and RUTLEDGE, P. C. (1952) Use of soil mechanics data in correlation and interpretation of Lake Agassiz sediments. J. Geol. 60, 160-80.
- ROSE, J. (1975) Raised beach gravels and ice wedge casts at Old Kilpatrick, near Glasgow. Scot. J. Geol. 11, 15-21.
- ROSE, J. and LETZER, J. M. (1975) Drumlin measurements: a test of the reliability of data derived from 1:25,000 scale topographic maps. Geol. Mag. 112, 361-71.
- ROSENQVIST, I. TH. (1975) Chemical investigations of tills in the Numedal. Geol. För. Stockh. Förh. 97, 284-6.
- ROTHLISBERGER, H. (1972) Water pressure in intra- and subglacial channels. J. Glaciol. 11, 177-203.
- RUDBERG, S. (1958) Some observations concerning mass movement on slopes in Sweden. Geol. För. Stockh. Förh. 1, 114-25.
- RUSSELL, I. C. (1895) The influence of debris on the flow of glaciers. J. Geol. 3, 823-32.
- RUSSELL, I. C. (1907) Drumlins of Michigan. Bull. geol. Soc. Am. 17, 707.

- SANGREY, D. A. (1970) Evidence of glacial readvance over soft layered sediments near Kingston, Ontario. Can. J. Earth Sci. 7, 1331-9.
- SAVAGE, W. Z. (1968) Application of plastic Flow analysis to drumlin formation. Syracuse Univ. M.S. thesis (unpubl.)
- SCHEIDEGGER, A. E. (1970) Theoretical Geomorphology. Berlin.
- SCHMERTMANN, J. H. (1955) The undisturbed consolidation behaviour of clay. Trans. A.S.C.E. 120, 1201-33.
- SCHNEIDER, A. F. (1961) Pleistocene geology of the Randall region, central Minnesota. Minn. Geol. Surv. Bull. 40.
- SCHUMM, S. A. and SHEPHERD, R. G. (1973) Valley floor morphology: evidence of subglacial erosion. Area 5, 5-9.
- SHALER, N. S. (1889) The geology of Cape Ann, Massachusetts. U.S. geol. Surv. 9th Ann. Rept., 529-611.
- SHALER, N. S. (1893) The conditions of erosion beneath deep glaciers, based upon a study of the boulder train from Iron Hill, Cumberland, R.I. Harvard Coll. Mus. Comp. Zoo. Bull. 16, 185-225.
- SHAW, J. (1971) Mechanism of till deposition related to thermal conditions in a Pleistocene glacier. J. Glaciol. 10, 363-73.
- SHAW, J. (1972) Sedimentation in the ice-contact environment with examples from Shropshire (England). Sedimentology 18, 23-62.
- SHAW, J. and FRESCHAUF, R. C. (1973) A kinematic discussion of the formation of glacial flutings. Can. Geogr. 17, 19-35.
- SHILTS, W. W. (1973) Glacial dispersal of rocks, minerals and trace elements in Wisconsinan till, southeastern Quebec, Canada. In Black, R.F. et al. (eds.) The Wisconsinan Stage, Geol. Soc. Am. Mem. 136, 189-219.
- SHOTTON, F. W. et al. (1970) Birmingham University radiocarbon dates (IV). Radiocarbon 12, 385-99.
- SHREVE, R. L. (1972) Movement of water in glaciers. J. Glaciol. 11, 205-14.
- SIMPSON, E. S. (1962) A ground-water mechanism for the deposition of glacial till. Int. Geol. Cong. Copenhagen Sect. 21, 103-7.

- SIMPSON, J. B. (1933) The late-glacial readvance moraines of the Highland Border west of the River Tay. Trans. R. Soc. Edinb. 57, 633-45.
- SISSONS, J. B. (1958) Supposed ice-dammed lakes in Britain with particular reference to the Eddleston valley, southern Scotland. Geogr. Ann. 40, 159-87.
- SISSONS, J. B. (1960) Erosion surfaces, cyclic slopes and drainage systems in southern Scotland and northern England. Trans. Inst. Br. Geogr. 28, 23-38.
- SISSONS, J. B. (1961) A subglacial drainage system by the Tinto Hills, Lanarkshire. Trans. Edinb. Geol. Soc. 18, 175-93.
- SISSONS, J. B. (1962) A reinterpretation of the literature on late-glacial shorelines in Scotland, with particular reference to the Forth area. Trans. Edinb. Geol. Soc. 19, 83-99.
- SISSONS, J. B. (1963) The Perth Readvance in central Scotland. Scot. Geogr. Mag. 79, 151-63.
- SISSONS, J. B. (1964) The Perth Readvance in central Scotland. Scot. Geogr. Mag. 80, 28-36.
- SISSONS, J. B. (1966) Relative sea-level changes between 10,300 and 8,300 B.P. in part of the Carse of Stirling. Trans. Inst. Br. Geogr. 39, 19-29.
- SISSONS, J. B. (1967) The Evolution of Scotland's Scenery. Edinburgh
- SISSONS, J. B. (1967a) Glacial stages and radiocarbon dates in Scotland. Scot. J. Geol. 3, 375-81.
- SISSONS, J. B. (1968) Letter to the Editors: The Perth Readvance. Scot. J. Geol. 4, 185-7.
- SISSONS, J. B. (1969) Drift stratigraphy and buried morphological features in the Grangemouth, Falkirk-Airth area, central Scotland. Trans. Inst. Br. Geogr. 48, 19-50.
- SISSONS, J. B. (1971) The geomorphology of Central Edinburgh. Scot. Geogr. Mag. 87, 185-96.
- SISSONS, J. B. (1972) The last glaciers in part of the south-east Grampians. Scot. Geogr. Mag. 88, 168-81.

- SISSONS, J. B. (1974) The Quaternary in Scotland: a review.
Scot. J. Geol. 10, 34-7.
- SISSONS, J. B. (1974a) A late-glacial ice-cap in the central Grampians, Scotland. Trans. Inst. Br. Geogr. 62, 95-114.
- SISSONS, J. B. (1976) The Geomorphology of the British Isles - Scotland. London.
- SISSONS, J. B., CULLINGFORD, R. A. and SMITH, D. E. (1966) Late-glacial and post-glacial shorelines in south-east Scotland.
Trans. Inst. Br. Geogr. 39, 9-18.
- SISSONS, J. B. and GRANT, A. J. H. (1972) The last glaciers in the Lochnagar area, Aberdeenshire. Scot. J. Geol. 8, 85-93.
- SISSONS, J. B. and RHIND, D. W. (1970) Drift stratigraphy and buried morphology beneath the Forth at Rosyth. Scot. J. Geol. 6, 272-84.
- SISSONS, J. B. and SMITH, D. E. (1965) Raised shorelines associated with the Perth Readvance in the Forth valley and their relation to glacial isostasy. Trans. R. Soc. Edinb. 66, 143-68.
- SISSONS, J. B. and WALKER, M. J. C. (1974) Late-glacial site in the central Grampian Highlands. Nature 249, 822-4.
- SKEMPTON, A. W. (1964) Long-term stability of clay slopes.
Geotechnique 14, 77-102.
- SLATER, G. (1929) Structure of drumlins on southern shore of Lake Ontario. N.Y. State Mus. Bull. 281, 3-19.
- SMALLEY, I. J. (1966) Drumlin formation: a rheological model.
Science 151, 1379-80.
- SMALLEY, I. J. and UNWIN, D. J. (1968) The formation and shape of drumlins and their distribution and orientation in drumlin fields. J. Glaciol. 7, 377-90.
- SMITH, J. (1838) On the composition of the till near Glasgow.
Edinb. New Phil. J. 25, 383.
- SMITH, J. (1839) On the climate of the Newer Pliocene Tertiary Period.
Proc. Geol. Soc. 3, 118.

- SMITH, J. (1850) On the occurrence of marine shells in the stratified beds below the till. Quart. J. Geol. Soc. 6, 386-8.
- SMITH, J. (1862) Researches in Newer Pliocene and Post-Tertiary Geology. Glasgow.
- SMITH, John (1893) The Great Ice Age in the Garnock Valley. Trans. Geol. Soc. Glasg. 9, 151-91.
- SMITH, John (1898) The drift or glacial deposits of Ayrshire. Trans. Geol. Soc. Glasg. 11 (Supplement).
- SMITH, John (1902) On the boulder clay at Hamilton Hill, north of Glasgow. Trans. Geol. Soc. Glasg. 12, 65.
- SODERMAN, L. G. et al. (1968) Field and laboratory studies of modulus of elasticity of a clay till. Highway Res. Rec. 243, 1-11.
- SOMMERVILLE, J. (1905) Notes. Trans. Geol. Soc. Glasg. 12, 265.
- SOONS, J. M. (1960) The sub-drift surface of the lower Devon valley. Trans. Geol. Soc. Glasg. 24, 1-7.
- SOUCHEZ, R. A. (1967) The formation of shear moraines, an example from South Victoria Land, Antarctica. J. Glaciol. 6, 837-43.
- SPROULE, J. C. (1939) The Pleistocene geology of the Cree Lake region, Saskatchewan. Trans. R. Soc. Can. 33, 101-9.
- STALKER, A. (1960) Ice-pressed drift forms and associated deposits in Alberta. Geol. Surv. Can. Bull. 57, 1-38.
- STARK, J. (1902) The surface geology of the Falls of Clyde district. Trans. Geol. Soc. Glasg. 12, 52-7.
- STEERS, J. A. (1973) The Coastline of Scotland. Cambridge.
- STOKES, J. C. (1958) An esker-like ridge in process of formation, Flatisen, Norway. J. Glaciol. 3, 286-9.
- STRANGWAY, D. W. (1970) History of the Earth's Magnetic field. New York.
- STUPAVSKY, M. and GRAVENOR, C. P. (1974) Water release from the base of active glaciers. Bull. geol. Soc. Am. 85, 433-6.
- STUPAVSKY, M., GRAVENOR, C. P. and SYMONS, D. T. A. (1974) Paleomagnetism and magnetic fabric of the Leaside and Sunnybrook tills near Toronto, Ontario. Bull. geol. Soc. Am. 85, 1233-6.

- SVENSSON, H. and FRISEN, R. (1964) Rock morphology and glacier movement in a limestone area on the Island of Oland. Sv. Geogr. Årsbok 40, 19-30.
- SYNGE, F. M. (1952) Retreat stages of the last ice-sheet in the British Isles. Ir. Geogr. 2, 168-71.
- TARLING, D. H. (1972) Principles and Applications of Palaeomagnetism. London.
- TARR, R. S. (1894) The origin of drumlins. Am. Geologist, 18, 393-407.
- TAYLOR, F. B. (1907) Distribution of drumlins and its bearing on their origin. Bull. geol. Soc. Am. 17, 726 (abs.).
- TAYLOR, F. B. (1931) Distribution of drumlins and its bearing on their origin. Bull. geol. Soc. Am. 42, 201.
- TERZAGHI, K. (translation 1943 (1st ed.), 1948 (2nd ed.)) Theoretical Soil Mechanics. New York.
- TERZAGHI, K. and PECK, R. B. (1967) Soil Mechanics in Engineering Practice. New York.
- THORBURN, S. and REID, W. M. (1973) Stability of slopes in lodgement till within the Glasgow district. Civ. Eng. Public Works Rev. 68, 321-5.
- THORNBURY, W. D. (1969 (2nd ed.)) Principles of Geomorphology, New York.
- THWAITES, F. T. (1937 (1st ed.), 1941 (2nd ed.), 1963 (Rev. ed.)) Outline of Glacial Geology. Ann Arbor, Michigan.
- TRAINER, F. W. (1973) Formation of joints in bedrock by moving glacial ice. U.S. geol. Surv. J. Res. 1, 229-35.
- TRENHAILE, A. S. (1971) Drumlins: their distribution, orientation and morphology. Can. Geogr. 15, 113-26.
- TRENHAILE, A. S. (1975) The morphology of a drumlin field. Ann. Assoc. Am. Geogr. 65, 297-312.
- UPHAM, W. (1889) The structure of drumlins. Proc. Boston Soc. Nat. Hist. 24, 127-228.
- UPHAM, W. (1892) Conditions of accumulation of drumlins. Am. Geologist 10, 339-62.
- UPHAM, W. (1898) Drumlins in Glasgow. Am. Geol. 21, 335-43.

- USSING, N. V. (1903) Om Jyllands Hedesletter og Teorierne om deres Dannelselse: Copenhagen. Overs. K. danske. Vid. Selsk Forh. 2, 99-165.
- VERNON, P. (1966) Drumlins and Pleistocene ice flow over the Ards Peninsula/Strangford Lough area, Co. Down, Ireland. J. Glaciol.
- VIRKKALA, K. (1951) Glacial geology of the Suomussalmi area, East Finland. Comm. Geol. de Finlande Bull. 155.
- VIRKKALA, K. (1952) On the bed structure of till in eastern Finland. Comm. Geol. de Finlande Bull. 157, 97-109.
- VIRKKALA, K. (1960) On the striations and glacier movements in the Tampere region, southern Finland. Soc. Geol. de Finlande Compte Rendus 32, 159-76.
- VIRKKALA, K. (1963) On ice marginal features in southwestern Finland. Comm. Geol. de Finlande Bull. 210.
- VIVIAN, R. and BOCQUET, G. (1973) Subglacial cavitation phenomena under Glacier d'Argentiere, Mont Blanc, France. J. Glaciol. 12, 439-52.
- VONDER HAAR, S. P. and JOHNSON, W. H. (1973) Mean magnetic susceptibility: a useful parameter for stratigraphic studies of glacial till. J. Sed. Petrol. 43, 1148-51.
- VON ENGELN, O. D. (1938) Glacial geomorphology and glacier motion. Am. J. Sci. 235, 426-40.
- VON WEYMARN, J. and EDWARDS, K. J. (1973) Interstadial site on the Island of Lewis, Scotland. Nature 246, 473-4.
- WALKER, M. J. C. (1973) The nature and origin of a series of elongated ridges in the Morley Flats area of the Bow Valley, Alberta. Can. J. Earth Sci. 10, 1340-6.
- WALLACE, J. (1902) Notes on a recent excavation in Sauchiehall. Trans. Geol. Soc. Glasg. 12, 79-80.
- WEERTMAN, J. (1957) On the sliding of glaciers. J. Glaciol. 3, 33-8.
- WEERTMAN, J. (1961) Equilibrium profile of Ice Caps. J. Glaciol. 3, 953-64.
- WEERTMAN, J. (1964) The theory of glacier sliding. J. Glaciol. 5, 287-303.
- WEERTMAN, J. (1966) Effect of a basal water layer on the dimensions

- of ice sheets. J. Glaciol. 6, 191-207.
- WEERTMAN, J. (1969) Lubrication mechanism of glacier surges. Can. J. Earth Sci. 6, 929-41.
- WEERTMAN, J. (1970) A method for setting a lower limit on the water layer thickness at the bottom of an ice sheet from the time required for upwelling of water into a borehole. Int. Assoc. Sci. Hydrol. 86, 69-73.
- WEERTMAN, J. (1972) General theory of water flow at the base of a glacier or ice sheet. Rev. Geophys. Space Phys. 10, 287-333.
- WEERTMAN, J. (1973) Position of ice divides and ice centers on ice sheet. J. Glaciol. 12, 353-60.
- WELLS, A. K. (1960) Cyclic sedimentation: a review. Geol. Mag. 97, 389-403.
- WEST, R. G. and DONNER, J. J. (1956) The glaciations of East Anglia and the East Midlands: a differentiation based on stone orientation measurements of the tills. Quart. J. Geol. Soc. 112, 69-91.
- WESTGATE, J. A. (1968) Linear sole markings in Pleistocene till. Geol. Mag. 105, 501-5.
- WILLMAN, H. B. et al. (1963) Mineralogy of glacial tills and their weathering profiles in Illinois Part I - Glacial tills. Ill. Geol. Surv. Circ. 347.
- WILLMAN, H. B. et al. (1966) Mineralogy of glacial tills and their weathering profiles in Illinois Part II - Weathering profiles. Ill. Geol. Surv. Circ. 400.
- WILSON, J. T. (1938) Drumlins of south-west Nova Scotia. Trans. R. Soc. Can. 32, 41-7.
- WILSON, M. J. et al. (1972) Occurrence of interstratified kaolinite - montmorillonite in some Scottish soils. Clay Minerals 9, 435-7.
- WILUN, Z. and STARZEWSKI, K. (1972) Soil Mechanics in Foundation Engineering - Vol. I. London.
- WOLDSTEDT, P. (1935) Über den stratigraphischen Wert von Geschiebeuntersuchungen in Norddeutschland. Z. der deutsch. Geol. Gesell.

87, 360-9.

- WOLDSTEDT, P. (1952) Die Entstehung der Seen in den ehemals vergletscherten Gebieten. Eiszeit v. Gegenwart 2, 146-53.
- WOLDSTEDT, P. (1961, 1965) Das Eiszeitaler. Stuttgart.
- WOODLAND, A. W. (1970) The buried tunnel valleys of East Anglia. Proc. Yorks. Geol. Soc. 37, 521-78.
- WRIGHT, H. E. (1957) Stone orientation in Wadena drumlin field, Minnesota. Geogr. Ann. 39, 19-31.
- WRIGHT, H. E. (1962) Role of the Wadena lobe in the Wisconsin glaciation of Minnesota. Bull. geol. Soc. Am. 73, 73-100.
- WRIGHT, H. E. (1973) Tunnel valleys, glacial surges and subglacial hydrology of the Superior lobe, Minnesota. In Black, R.F. et al. (eds.) The Wisconsinan Stage, Geol. Soc. Am. Mem. 136, 251-76.
- WRIGHT, J. (1896) Boulder clay, a marine deposit. Trans. Geol. Soc. Glasg. 10, 270-2.
- WRIGHT, W. B. (1912) The drumlin topography of south Donegal. Geol. Mag. 9, 153-9.
- WRIGHT, W. B. (1937 (2nd ed.)) The Quaternary Ice Age. London.
- WRIGHT, W. B. and CLOUGH, C. T. (1906) Summary of Progress of Geological Survey. Geol. Surv. Scot., 95-6.
- WYATT, R. J. (1971) New evidence for drift-filled valleys in north-east Leicestershire and south Lincolnshire. Bull. Geol. Surv. Great Brit. 37, 29-55.
- WYATT, R. J. et al. (1971) Drift-filled channels on the Leicestershire - Lincolnshire border. Bull. Geol. Surv. Great Brit. 37, 57-79.
- YATSU, E. (1966) Rock Control in Geomorphology. Tokyo.
- YOUNG, J. (1869) Notes on the section of strata in the Gilmorehill Quarry, and boulder clay on the site of the new University buildings, Glasgow. Trans. Geol. Soc. Glasg. 3, 298-310.
- YOUNG, J. (1874) On the probably source of certain boulders in the till of the Glasgow district. Trans. Geol. Soc. Glasg. 4, 259-63.

- YOUNG, J. and CRAIG, R. (1871) Notes on the occurrence of seeds of freshwater plants and arctic shells, along with the remains of Mammoth and Reindeer, in beds under the boulder clay at Kilmaurs. Trans. Geol. Soc. Glasg. 3, 310-21.
- YOUNG, J. and GEIKIE, J. (1870) Discussion on the buried valleys of Clyde and Kelvin. Trans. Geol. Soc. Glasg. 4, 76-84.
- YOUNG, J. A. T. (1969) Variations in till microfabric over very short distances. Bull. geol. Soc. Am. 80, 2343-52.