GENETIC INFLUENCES ON THE NATURE AND PROPERTIES OF BASAL MELT OUT TILLS

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A THESIS SUBMITTED FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY IN THE DEPARTMENT OF
CIVIL ENGINEERING, UNIVERSITY OF STRATHCLYDE, GLASGOW.

FEBRUARY, 1975.

VOLUME 1

TEXT

SUMMARY.

The glacier regime is described and the classifications of glacier types are outlined. The modes of acquisition and transportation of the debris in glaciers is considered and the deposition process briefly considered. The various systems of classification of unstratified and stratified drift are given and the several morphological expressions of the unstratified drift are described.

The crushing mechanism producing basal tills, of which the materials studied are examples, is reviewed in terms of their transportation environment in the glacier. The mechanical crushing of rocks is also considered and the particle size distribution laws developed to describe the products of this industrial process considered for application to glacial comminution products. The nature of glacial comminution is then further reassessed in terms of the shape of particles developed by the process.

A full description of the locations of study sites and samples included in the investigations is then given including a detailed description of the local geological and glaciological environments where these are known.

Previous investigations of the textural variations in tills are reviewed and the sampling and testing techniques for particle size distribution are outlined. The textural variations measured, or previously reported for Scottish, Norwegian, American and Canadian Pleistocene tills are analysed and compared to the measured variations in tills taken from three active modern glaciers in Norway,

Iceland and Antarctica. These variations are then interpreted in terms of the mode of formation of the tills. Close correlations between these glacial products and industrial crushing products are thus shown to exist.

Based on this, it is suggested that till variability can be much more easily understood if the material is treated as two size fractions mixed in variable proportions. The size fractions in any one till are then found to be fairly consistent with the mix proportions varying often very locally. Lithological variations are, however, found to have much less effect than might be expected.

The organisation of the particulate matter in the tills is then considered in terms of the mode of deposition of the basal melt out tills. The orientation of clasts in the tills were measured in the field. This study was then extended in the laboratory using the contact goniometer to include the orientation of particles down to the sand size grade. Further qualitative studies using the Scanning Electron Microscope then extended the appreciation of the particle organisation down to the clay size particles. This attempt at determining the nature of particle organisation at all size levels was then proven to be most useful in determining the actual mechanisms operating during deposition. Essentially it was shown that the clasts react to the englacial stress field whereas the fines are organised during the melt out process and record in a more sensitive manner than the clasts, the stress history of the till during and after deposition.

Some of the microfabrics in the tills were found to be very open and

field data on in-situ density confirmed both the variability and the very low densities that can be found in the tills. Investigations of the factors influencing achieved density when recompacting tills showed that the variations in grading in these soils could be as important as differences in compactive effort. It is suggested that for engineering situations where quality control of compaction is required it is necessary to include gradational variations in the assessment procedures otherwise variations in compactive effort will be masked.

A review of the factors affecting permeability and shear strength of soils was also undertaken with particular reference to the tills. Detailed investigation of some tills were undertaken and comparisons made to recorded data for tills used in Norwegian and Canadian dams. The interrelated influences of grading, density and particle arrangement were shown to critically affect permeability and shear strength and a system of classification based on percentage fines and the identity of the fines was suggested which attempted to include many of the variables. Limited success was met with respect to permeability but none with shear strength, the many other variables influencing the tills strength properties overriding the basic parameters used in the system. The use of percentage fines and the identification of the coarse and fine fractions in the tills was still however shown to be the best means of understanding the variations within any one till.

The inherent variations in the basal melt out tills were therefore shown to be attributable to their modes of formation and deposition and by recognising the fundamental nature of the till composition and particle organisation it is considered that a better understanding of the variations has been achieved.

ACKNOWLEDGEMENTS.

The author wishes to express his gratitude to Professor D.G. McKinlay B.Sc., Ph.D., F.I.C.E., F.G.S. who supervised this research and whose help and valuable criticism have been of great assistance.

Also thanks are due to Laing Barden B.Sc., M.Sc., Ph.D., D.Sc., F.I.C.E., F.G.S., formerly Professor of Soil Mechanics in this Department for his advice and his assistance when initiating the electron microscopy work.

Particular thanks are due also to Edward Derbyshire, B.Sc., Ph.D., Reader in Physical Geography at University of Keele who has worked closely with the author on the modern glacial till investigations and with whom he visited the Breidamerkurjokull and Blaisen Glaciers.

During the course of the work a number of students assisted with field and laboratory work and the author wishes to particularly thank Alex. A. McArthur, M.Sc., M.I. Mun. E. and Kennedy Collins, B.Sc.

Assistance in the field and laboratory work was also given by the technicians in the Soil Mechanics Laboratories under the supervision of Mr. Donald Mitchell. Particular thanks are however due to Mr. Robert Dolan who was associated with these investigations from their beginning.

Acknowledgement is also made of the assistance given to the author by the Argyll County Engineer, Mr. J. Smith, B.Sc., M.I.C.E. and by Mr. J. McMahon, B.Sc., M.I.C.E., Deputy Chief Civil Engineer of the Forestry Commission. Grateful thanks are also due to Mr. Rene Audy of Piette, Audy, Leopinay, Betrand and Lemieux, Consulting

Engineers, Quebec and Mr. Arne Sande, Norwegian Geotechnical Institute for data they provided on Canadian and Norwegian tills, respectively.

Thanks are also due to Miss Valerie I. Paterson who had the difficult task of typing the draft of the manuscript and to Mrs. Irene G. Collins who very carefully and neatly typed the thesis. Also the author wishes to thank Miss Marion Simpson and her staff in the University Drawing Office for their assistance in preparing many of the figures and photographs.

Finally the author wishes to thank his wife, Beatrice and his family for their understanding and encouragement to carry out and complete this research project.

CONTENTS.

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CHAPTER 1. INTRODUCTION.

A large proportion of Scotland is covered by superficial deposits derived by the action of glaciers that covered the area until only 8,000 to 10,000 years ago. These so called drift deposits consist of a wide range of materials with different particle size distributions, densities and particle arrangements. Some of the soils are derived by glacio-fluvial action and some are the direct products of ice action, which latter are called tills. In the central belt of Scotland the tills are normally very dense, well graded soils formed by the direct action of ice into numerous streamlined hills called drumlins. In the Highlands and Southern Uplands of Scotland, the tills are usually much looser and less well graded although they are also formed into small hills. These deposits are generally much less regular in shape than the drumlins and are called moraines.

In the mountainous areas where the morainic mounds of tills are to be found, the rainfall is often very high and these tills prove difficult to construct over or with in roadworks and dams. Indeed it was the difficulties experienced by the Author when a site engineer on roadworks in the County of Argyll that initiated his interest in these soils. However, the Scottish morainic tills are not unique and the present study is not restricted to Scotland. Similar tills from other geographical areas, principally Norway and North America have been included in the investigation. As part of this wider study, research was undertaken into the detailed mechanism of deposition of the tills at the margins of two active glaciers, Breidamerkurjokull in Southern Iceland and Blaisen in

Southern Norway.

The problems encountered by the Author when constructing roadworks in the County of Argyll were, however, associated with the very loose nature of some of the deposits and the variability in the grading from one location to the next. The effect of these factors was to cause difficulties in obtaining satisfactory, consistent subgrade conditions for the road in both cutting and fill areas, and to cause slope stability to be a highly unpredictable element in the construction. The Author therefore recognised the need for the provision of an adequate means of classifying tills and of predicting the influence on engineering behaviour of the likely variations in particle size distribution, density and particle organisation in the tills.

Previous attempts at classifying similar tills have been carried out in both geological and engineering terms. Krumbein (1953) Shepps (1958), Chryssafopoulas (1963) and others have determined gradational parameters which they considered would allow till sheets to be differentiated. Beskow (1951) and Bernell (1957) based their appreciation of till behaviour on rather complex relationships between gradation or plasticity characteristics and engineering behaviour. No particular regard for the geological nature of the tills was, however, taken in these investigations whereas Jarnefors (1952), Elson (1961) and Dreimanis and Vagner (1965, 1969, 1971) have looked more fundamentally at the problem and their investigations suggest that there is the possibility of rationalising these highly variable soils. It is with the objective of developing these fundamental approaches and suggesting means of rationalising till behaviour that this study is made.

The investigations forming the study fall into three main themes. Firstly, the mode of formation of the tills is considered in some detail and analogies between glacial comminution and the industrial crushing of rock debris are made which permit the development of a means of recognising the fundamental nature of the granulometric composition of the tills. By so recognising the basic nature of the tills the characteristic variability of their overall gradings may be better assessed and indeed they are shown to be explained almost entirely in terms of the glacial process which led to their formation.

Secondly, the mode of deposition of the melt out tills is considered in detail. Field studies on the tills at the two modern glaciers visited have been combined with laboratory studies on undisturbed samples obtained from these modern tills and with laboratory studies of Pleistocene tills, to develop a better understanding of the resulting particle organisation at all size levels in the soils. To carry out this work, study techniques and classification systems have been developed to describe and quantify the fabric viewed. For the field studies, use is made of a light weight contact goniometer to study englacial and melt out stone fabrics and with the added use of a dry brushing technique on air-dried specimens, the same apparatus is used to study the orientation of particles down to the sand size grade in the laboratory. The organisation of the finer particles in the tills is viewed using the Scanning Electron Microscope with magnifications up to 20,000 x. Therefore an assessment of particle organisation from stones down to clay sizes has been possible. A critical reappraisal of the mode of deposition of tills and the associated formation of moraines is then undertaken and modifications to previously accepted theories of depositional processing are presented.

Thirdly, based on the finding of the studies of the fundamental granulometric nature of the tills and of the nature of their particle organisation, consideration is given to the variation of some engineering properties. The engineering properties considered are the compactibility of the tills their permeability, and their shear strength.

Based on the data obtained in these investigations an attempt has then been made to suggest a means of classifying or at least improving the understanding of the inherent variability of the tills.

CHAPTER 2. GLACIERS, GLACIAL PROCESSES AND LANDFORMS.

2.1. THE GLACIAL THEORY.

About 15 million km^2, or 10 per cent of the earth's land area, are presently covered by ice, with Antarctica and Greenland accounting for 96 per cent of the total ice cover, Flint (1971). According to the most recent evidence, more than three times this area, some 47 million km^2 was covered at the maximum extent of the Pleistocene glaciation. Both the Antarctic and Greenland ice sheets differed little in extent from their present sizes, for they were limited, as now, by calving into deep water, Embleton and King (1969). Therefore, the ice sheets once extended much further south, in Europe and North America, in the Northern Hemisphere and further north in the Southern Hemisphere. The extent of the Pleistocene glaciations, and most probably there were four or five major stages, has, however, only become known gradually.

The glacial theory was, in fact, based principally on the occurrence of erratic boulders and secondarily on deposits of till and other features. Erratics and till had long been known, but the prevalent theories of their origin had been based in the 17th and 18th centuries on the idea of transport by water. Early in the 19th century the concept of numerous icebergs floating down from the polar ice caps across universal waters, dropping foreign boulders was popularised by W. Buckland and others. The universal flood necessary for such an occurrence was identified with the biblical Noachian flood. Later, Buckland was converted to the glacial theory by L. Agassiz. Agassiz was not the originator of the glacial theory, nor did he add much new to it, but has acceptance and publication, Agassiz (1840), of the ideas on widespread glaciation developed by Venetz, Bernhardi, de Charpentier and others, did much to establish the theory.

Agassiz first visited Britain in 1840 and carried out some field work with W. Buckland and C. Lyell and suggested that Britain like Switzerland had been glaciated. The glacial theory did not receive much further support, however, until the 1860's when Ramsay (1860), Jamieson (1862) and Geikie (1863) published papers in support of the glaciation of Britain. These early workers have been followed by numerous others from all of whose investigations and reports, the complexities of the glacial processes have been unfolded.

It is now known that major ice ages have occurred in the Pre-Cambrian, the Permo - Carboniferous and the Pleistocene periods of earth's history. The Pleistocene is thought to have been initiated some 1.5 to 2.0 million years ago by sudden falls of world temperatures and that the ice sheets reached their maximum extents, not during the last (Wurm, Weichsel, Wisconsinan) glaciation, but with earlier glacial periods, possible the Riss (Saale, Illinoian). The causes of these ice ages are still the subject of speculation but most probably a number of factors were involved including changes in land-mass altitude, short-term changes in the receipts of solar radiation resulting from varying geometrical relationships of earth and sun, and longer term changes in quality and quantity of solar emission, Embleton and King (1968).

2.2. TYPES OF GLACIER.

2.2.1. Glacier Regime.

Glacier regimes are concerned with the gain or loss of snow in a glacier and the two essential factors that make this up are the accumulation and the ablation, the gain and loss of mass respectively. Accumulation includes all those processes by which solid ice and snow are added to a glacier or ice sheet and ablation refers to all the processes by which ice and snow are lost from the glacier. The processes that cause ablation include melting, evaporation, calving, wind erosion, and removal of snow or ice by avalanches.

The budget year is the most important unit of time when glacier regime is being considered. The budget year runs from the time when ablation has reached its maximum extent after the summer season of one year until the same state in the following year. The period need not be an exact calendar year. In the ablation area, all the material gained that year is lost before the end of the budget year. The loss in temperate glaciers, especially, takes place largely by surface melting. The melting occurs mainly in the lower parts of the glacier during the summer season, although some ablation may go on at low levels throughout the whole of the year in some glaciers. In polar areas such as the Antarctic ice sheet calving is the most important process of ablation.

From the point of view of glacier activity, however, the actual amounts of accumulation and ablation are just as important as the mass balance between accumulation and ablation. Where the amount of snow added to a glacier is high, the glacier will be active, as in the case of the glaciers of south Iceland and Norway. But where the accumulation is very small and ablation equally low because of extremely low temperatures, glaciers will tend to move slowly in relation to their dimensions and geomorphologically be less active. The net balance between accumulation and ablation thus determines the movement of the glacier front and causes variations in ice thickness whilst the total amounts of accumulation and ablation in part determine the degree of glacial activity. The overall erosive and depositional effects of a glacier are thus complex and variable when considered over an extensive period.

2.2.2. Classification of Glacier Types.

Ahlmann (1948) suggested three methods of classifying ice masses which may all be related to their activity. He suggested a thermal classification, a dynamic classification and a morphological classification.

2.2.2.1. Thermal Classification.

Thermal classification of glaciers produces two fundamental types; temperate and cold (or polar) glaciers. Temperate glaciers are at pressure melting point throughout their thickness, except in the winter season when the uppermost layers may be temporarily colder. The important point concerning this type of ice mass is that melt water can be present throughout. Many of the glaciers in the Alps, Southern Scandanavia and Iceland are temperate in character. This type of glacier, because meltwater exists at its bed, flows fairly easily over the rock. Such glaciers move faster than polar glaciers and the erosive action is probably enhanced by this.

Polar glaciers differ in very important respects from temperate glaciers and Ahlmann (1948) found it necessary to sub-divide this type into two: the sub-polar type and the high polar type. This differentiation is based mainly on their "firn" characteristics, where firn is compact granular snow more than one year old produced by a process of recrystallization. In the accumulation area of sub-polar glaciers, the glacier consists of crystalline firn down to a depth of 10 to 20 m. In summer the surface can melt and water can be present. In the high polar glaciers there is no melting on the surface of the accumulation area and the firn remains well below freezing point even in the summer season. Thus firnification is a very slow process. A very important feature of such polar ice masses is therefore the absence of meltwater at depth in the ice. Melt streams where they occur flow on the surface of the ice. At the base of the glacier the ice is well below pressure melting point and the ice is frozen to the bedrock on which it is resting. This of course greatly influences the manner in which the ice moves over its bed and significantly reduces the amount of erosion achievable by the glacier.

Various modifications have been suggested to Ahlmann's classification system as numerous complications have been discovered. Court (1957) proposed the terms permelting, refreezing and nonmelting be used instead of temperate, sub-polar and high polar, respectively. These newer terms were meant to signify that glaciers were either permeated by meltwater throughout, had a layer in which water refreezes below a surface melting or never experiences melting on the surface. He also suggested that the whole of an ice mass need not fall into one category. Just as complications arose with Ahlmann's classifications so Court's classification was not found to completely characterise ice masses without problems. It is therefore generally agreed that Ahlmann's classification be used, but it is also recognised that the whole of an ice mass need not necessarily fall into a single category.

2.2.2.2. Dynamic Classification.

As stated above the dynamic activity of a glacier is influenced by its thermal characteristics but as was previously stated in section 2.2.1., the dynamic activity is also closely associated with its regime or mass balance. Ahlmann's (1948) classification of glaciers based on their dynamic activity consists of three main types: active, passive or inactive and dead glaciers. Active glaciers are normally fed by a continuous ice stream from an accumulation zone that may lie in a cirque basin or on a plateau. Some active glaciers are classed as regenerated as they are entirely fed by ice avalanches falling from an upper accumulation area onto lower ground. Some glaciers can maintain active dynamic movement even with a negative mass balance, the total mass budget being the most important factor in determining the relative activity of a glacier.

Where the mass budget is small a glacier may become passive. This may occur on the low side of a mountain range or where the slopes are gentle. The ice under these conditions although it is replenished by snow accumulation is not dynamically active. Dead ice is not necessarily immobile, as defined by Ahlmann, it is ice which in fact receives no supply from an accumulation area. Dead ice is thus slowly wasting and its movement, if any, is restricted to that dependent on the slope of its bed.

2.2.2.3. Morphological Classification of Ice Masses.

The morphological classification of ice masses is based on their size and the characteristics of their environment. Altitude in relation to the areal distribution of ice is essentially the important factor. On this basis the classifications suggested are:

a) Niche, wall sided or cliff glacier

b) Cirque glacier

c) Valley glacier - Alpine type

d) Valley glacier - outlet type

e) Transection glacier

f) Piedmont glacier

g) Floating glacier tongues and ice shelves

h) Mountain ice-cap

i) Glacier, cap or lowland ice-cap

j) Continental ice-sheet.

Niche glaciers consist of triangular wedges of ice, often with a slightly convex surface, lying in shallow funnel shaped hollows in the upper parts of hillsides. They develop on steep slopes (up to 42 degrees) and are often associated with rock benches, formed where harder rock outcrops. These glaciers probably originate as snow patches, which rest between the steep rock slope and the scree beneath. The cirque glaciers are genetically similar but larger than the niche glaciers and may in fact be described as a developed form of them.

There are four elements in a well developed cirque. First, there are head and side walls, steep and usually shattered; second, there is the rock floor, showing evidence of smoothing and polishing; third, near the junction of the head wall and cirque floor there is sometimes a projecting node of rock, Lewis (1938); fourth, there is a lip to the basin, convexly rounded and often shattered on the down valley side. When the snow line falls below the elevation which substantiated the cirque, the ice of the cirque can move out of its basin to form a valley glacier. Sometimes, the ice of several cirques combine to form the valley glacier as is common in the Alps and has given rise to the term Alpine type to describe this form of valley glacier.

Outlet type valley glaciers are similar in their lower reaches to Alpine type valley glaciers but are fed from an ice cap and not from an individual or series of cirque basins. The outlet glaciers draining from ice caps in Antarctica, Iceland and Norway which are studied in this thesis, are good examples of this type.

Transection glaciers are those which occupy much of a mountain group from which glaciers flow down in several directions into a system of radiating valleys. The accumulation area is at a high elevation but is not large enough to be called a mountain ice cap or the mountains are too deeply dissected to allow the ice cap to form.

Piedmont glaciers form when the valley glacier advances out from the containing mountain walls into a lowland beyond. As the glacier spreads out it maintains a sufficient thickness and surface slope to enable uphill flow across hollows to occur. This type of glacier is characterised by its relatively large area at its lowest altitude.

Floating ice tongues are presently restricted to high latitudes where glaciers can reach to sea level. The form that the floating part takes depends on the surrounding coastal relief. Where the glacier is confined within a valley, the floating part is no wider than the grounded part. The glacier loses mass by calving, thus creating ice bergs. These narrow tongue glaciers differ greatly from the floating ice shelves in size. Ice shelves are more characteristic of the Antarctic, a good example being the Ross shelf. The material of these shelves is partly derived from the outward flow of their inland ice sheets but it is mainly supplied by accumulation on their upper surfaces. These ice shelves spread out and move under their own weight. They melt from below over most of their area, a process assisted by brine soaking.

Mountain ice-caps are accumulation areas from which outlet glaciers flow to lower levels. They usually rest on upland plateau surfaces. Lowland ice caps or Glacier caps on the other hand, develop at fairly low levels on flattish country often in the high arctic.

There are only two so called continental ice sheets at present, namely, the Greenland and the Antarctic ice sheets. The Antarctic ice sheet is vastly greater than the Greenland ice sheet and is, in fact, similar in size to the maximum extent of the Laurentide ice sheet of the Pleistocene and approximately twice the size of the European ice sheet at its maximum.

2.3. ACQUISITION OF DEBRIS BY GLACIERS.

In mountainous regions fragments of rock produced by frost shattering fall down the precipitous valley sides and accumulate on glacier surfaces to form moraine ridges. Most rock debris in ice sheets is not, however, obtained by this process but is accumulated by the processes of glacial abrasion and quarrying (or plucking), acting along the sides and base of the glacier.

Abrasion is caused by the accumulation of soil and rock debris in the base of a glacier which is then dragged across the rock surface by the glacier. Glacial quarrying is the lifting out and removal of blocks of bedrock by the glacier. It is probable that basal meltwater running into joint planes causes frost splitting of the rock, Carol (1947), however, the mechanical process of ice freezing onto rock projections also has the effect, when the glacier moves, of pulling blocks of rock away from their foundations. The pressure changes as the glacier moves over the rock may also lead to stress effects with consequent opening up of joints, and loosening of blocks of rock, Lewis (1954). Another important factor may be bedrock shattering by a period of deep freezing prior to ice advance.

Well jointed rocks are known to be more susceptible to glacial quarrying than massive rocks and even relatively soft rocks, if not well jointed, may resist ice erosion by plucking. Generally, but with local exceptions, far more rock is removed by quarrying than by abrasion, Flint (1971).

2.4. TRANSPORTATION OF DEBRIS.

The rock particles in glaciers constitute glacial drift in transport and individually are described as inclusions whilst collectively they are termed the glacier load, Flint (1971). The load is concentrated mainly at the contact between glacier and bed rock, and transported either sub glacially or englacially. However, accumulations of drift, called moraines, can occur on the surfaces of the glaciers, derived in the manner described in Section 2.3. On a simple valley glacier these moraines occur along its lateral margins, at the outcrops of steeply dipping, drift rich zones within the ice. These are lateral moraines. On a compound valley glacier, the junction of two lateral moraines creates a medial moraine. Such tributary units and moraines maintain their identity as they flow in close contact down the valley.

From observation of modern glaciers and investigation of deposited drift the transportation mechanism of the basal drift can be inferred. Firstly, glaciers usually carry only a minor proportion of the load as coarse fragments far beyond the place where they were picked up. This is shown by the close relationship between the composition of the coarse fragments in the drift and that of the local bedrock. Most rock fragments forming the drift are crushed and worn down to small sizes over very short distances.

A small proportion of the rock fragments do, nevertheless, travel long distances and these fragments are usually found to consist of hard, resistant minerals and have few joints or other surfaces of weakness. They usually have survived over such long distances at the expense of considerable loss of size by attrition and have generally travelled englacially in positions where there were few other rock fragments to abrade them. Secondly, observations possible only in glaciers where the ice is flowing against the slope of the land, reveal that some rock fragments, surviving long enough to be carried long distances, are lifted through considerable heights above their inferred places of origin in the bedrock, Flint (1971). This vertical component of transport is presumed to result from oblique upward shear in the zone of net ablation while the stones were embedded in basal ice.

2.5. DEPOSITION OF DEBRIS BY GLACIERS.

2.5.1. Classification of Unstratified and Stratified Drift.

Glacial drift includes a complex inter-related series of sediments such as glacial, fluvio-glacial, glacio-lacustrine and glacio-marine sediments. Strict classification of these presents a rather complex problem to which there are a number of suggested solutions. Most classifications, however, are based on one or more of the following: sedimentary character, relationship of sediment to the ice and the forms of deposit. Nevertheless two basic sub-divisions of drift can be identified on the basis of the medium of deposition, namely whether the drift was deposited by the ice itself, or laid down by melt water. Very generally, these sub-divisions may be set out as unstratified and stratified drift, and their main characteristics summarised as follows:

GLACIAL DRIFT

Unstratified	Stratified
Ice deposited	Water deposited
Unsorted (particle size)	Sorted
Angular unwashed rock particles	Washed
Striated particles	Rounded rock particles
Wide variety of rock types	Wide variety of rock types

(after Price, 1973)

Of course, in the complicated glacial environment, it is often very difficult to establish the medium of deposition solely from the sedimentary characteristics of the end product when identified as above, and often in any glacial deposit, more than one medium of deposition has been operative. The principle medium of deposition is, however, closely related to the environment of deposition and from this viewpoint it is possible to add a means of classifying the unstratified and stratified deposits, as follows:

Unstratified Drift	Stratified Drift
Sub-glacial	Ice-contact:
Supra-glacial	Sub-glacial
Marginal	Supra-glacial
	Englacial
	Marginal
	Proglacial:
	Fluvial
	Lacustrine
	Marine

(after Price, 1973)

A further factor which may also be included to give better identification of drift deposits, is an evaluation of the condition of the ice mass at the time of deposition, namely, whether the ice was active or stagnant. Unfortunately it is very often difficult to diagnose the glacialogical conditions at the time of deposition, as the judgement may require, for Pleistocene deposits, to be based on sedimentary and morphological data alone. This sub-division is not, therefore, always practical. The major distinction made between deposits of whether they were laid down by and from the ice itself, with only relatively small amounts of assistance from meltwater or were laid down after transport, even if only over very short distances, by melt-water are, however, generally operable and useful.

The subject material of this study being unstratified drift, no further reference to the complex classification or depositional processing of stratified drift will be made.

2.5.2. Deposition of Unstratified Drift or Till.

The most common unstratified drift contains a mixture of particle sizes from boulders to clay and is best called till. The term, till, was widely used in Scotland well before the Glacial Theory was established, to describe "a kind of coarse obdurate land", the soil developed on the stoney clay that covers much of Scotland. The earliest detailed areal glacial studies published in Britain (e.g. Geikie 1863) were Scottish, hence the Scots term came into wide use. The English term boulder clay, put forward a little later at a time when boulder referred to a clast of any size rather than its present restricted usage, is still widely used but is much less acceptable as it infers certain sedimentalogical characteristics not always apparent in the materials it describes.

Till may be deposited by a glacier in the following three ways:

a) At the base of the glacier as Basal Till

b) On or from its surface as Ablation Till

c) Underneath ice shelves as Waterlaid Till

after Dreimanis (1974)

(a) Basal till, which is often termed lodgement till (Flint, 1971) may in itself be deposited by three principal modes as:

i) basal melt out till

ii) lodgement till (sensu stricto)

iii) deformation till.

i) Basal meltout till may be deposited at the base of actively moving or stagnant temperate ice by slow melting (up to 1 cm of ice per year) due to geothermal heat, Boulton (1970, 1972). The till deposited by this mode was termed subglacial ablation till by Elson (1961). Because of the load of overlying ice, the basal meltout till is usually denser than ablation meltout till, (defined later), but not as dense as lodgement till (defined later), Dreimanis (1974).

ii) Lodgement till (sensu stricto) is formed by plastering on, or lodgement, under an actively moving glacier. This process usually involves pressure melting, heat from shear friction and comminution of rock fragments, and geothermal heat together providing just sufficient meltwater to lodge and compact the variously sized particles to their optimum density, and so least porosity. Such dense till consisting mainly of crushed rocks and minerals, is called comminution till by Elson (1961). The process of lodgement may create joints and fissures in the till during deposition and subsequently on stress relief when the ice stagnates and melts, McGown et al (1974) and Radwan (1974).

iii) Deformation till derives from blocks and slices of bedrock and underlying sediments which have been deformed by glacial thrust in-situ, or transported for short distances only, Elson (1961). These tills have not undergone prolonged glacial comminution and compaction like lodgement tills and contain only very small amounts of far travelled materials. The primary structure of the original materials is usually still recognisable but it is generally deformed by shearing, faulting, folding, overthrusting, injections, etc. Deformation till is often less dense than lodgement till due to the original material having relatively higher porosity or by increase of this original porosity during shearing and crushing.

b) Ablation till is deposited from supra glacial or englacial drift either on or adjacent to a stagnant glacier or in the terminal zone of an active though shrinking glacier, Dreimanis (1974). The resulting till is loose and less compact than basal till and its texture and shapes of clasts reflect its supraglacial or englacial transport. Clayey and silty ablation tills may acquire compactness by post depositional processing, e.g. dessication. Angularity of clasts may be due not only to supra glacial transport, but also to repeated freezing and thawing during and after deposition.

Ablation till may form as follows:

i) Melt out till in situ on the surface of the glacier.

ii) Flow till.

i) Ablation melt out till is usually described as ablation till and is derived from supra glacial drift only from the lateral and medial moraines of mountain glaciers. It is particularly coarse textured, loose and its clasts are usually angular with a fabric unrelated to glacial movement. This till may also be derived from englacial drift by slow ablation on the glacier surface. In such circumstances it closely resembles basal melt out till in its composition and fabric but generally less compact unless it has undergone post depositional processing which increases its density.

ii) Flowtill is usually derived from ablation melt out till which has moved down the glacier surface or from the surface portion of a basal till on a slope which has liquified and flowed, Hartshore (1958). Depending on its derivation, flowtill resembles in its composition either supra glacial, englacial or basal drift. The non glacial flow causes the clasts to orient parallel and transverse to the flow direction which may or may not be the same as the glacial movement. In very mobile and liquid flows, clasts tend to sink towards their base and also stratification develops while semi-plastic flow produces little stratification. If the movement of flowtill is merely a down slope creep, then down slope shear planes and fissures may develop. With these fabric features and the parallel oriented clasts these tills can often resemble basal tills, Dreimanis (1974).

c) Waterlaid till is deposited beneath floating ice shelves by sedimentation of drift material from the base of a melting glacier, with the admixture of glacio-lacustrine or glacio-marine sediments. It corresponds in part to para-till as described by Harland et al (1966) and to some glacio-marine sediments and so called lacustro-tills and lacustrine ablation materials. It may grade, laterally or vertically, into basal, particularly deformation till, wherever the glacier is grounded, or into dominantly glacio-lacustrine or glacio-marine sediments containing dropstones. The term waterlaid till is only applied then to drifts in which the till like material dominates. The clast fabric is mostly random, unless a mudflow has occurred.

2.6. THE MORPHOLOGY OF TILL DEPOSITS.

Till and stratified drift are often found in intimate contact or grading from one to the other within glacial deposits, making a clear cut distinction between till and stratified drift difficult. Distinction between morphological units primarily associated with till or with stratified drift is very often even more difficult to make, again because of mixtures and gradations. Thus the description of till deposits based on their morphological expression covers those deposits in which till is the principal component but is not necessarily the sole component. Other features in which till may exist in a minor role are not described.

Drift deposits which do consist primarily of till and which possess their initial constructional form are known as Moraines and it is with the detailed nature of these that this section deals.

2.6.1. Ground Moraine

The early term moraine profunde, was translated into the German, grundmorane and so into the English, ground moraine. It is now used to define moraine having low profile devoid of transverse linear elements, Flint (1971). It may consist entirely of basal till or it may have a capping of supra-glacial till, ablation till or flow till. The thickness of the till sheet is usually of the order of tens of metres but if more than one till sheet is present, the combined thickness of the till sheets may be in excess of one hundred metres, Price (1973). A thick till cover tends to mask the underlying bedrock topography and the existence of pre-glacial valley systems, although there are obviously some instances where bedrock ridges will protrude above the general level of ground moraine.

2.6.2. Fluted Ground Moraine.

In some areas the till sheet has distinct lineations parallel to the former direction of glacier movement and is described as fluted ground moraine. The surface in such a situation may have a local relief of only a few metres with maximum amplitudes reaching tens of metres. Henderson (1958) and Lemke (1958) have described the existence of such ridges in Pleistocene deposits in North America and Dyson (1952), Hoppe and Schytt (1953) and Lemke (1958) have observed these same features in front of modern active glaciers. Lemke observed the existence of transverse recessional moraine and other deposits superimposed on these linear ridges and Hoppe and Schytt proved that the flutes extended beneath the glacier and were associated with till accumulation on the lee side of boulders. The importance of the boulders in the mechanism involved in the development of fluted ground moraine was also pointed out by Dyson (1952).

When fluting is of the order of tens of metres in local relief it is often very difficult to establish whether the moraine was laid down in the form of flutes or whether it and the underlying sediments or rock head have been eroded by an ice advance after the till deposition. Small flutes with amplitudes of a few metres are believed to be produced by squeezing of till at high moisture contents into cavities developed on the lee side of boulders or into basal crevasses, Dyson (1952) and Hoppe and Schytt (1953). However, it is often difficult to decide both for small and large flutes whether depositional or erosional processes are involved and some investigations suggest that both processes may be involved.

2.6.3. Drumlins.

The term drumlin is of Gaelic origin being derived from druim, a word used to describe a mound or rounded hill. It refers to a wide variety of features from isolated rounded hills up to 60 m in height to low gentle swells grouped together in large numbers. Normally drumlins are grouped in fairly large numbers and have a length to breadth ratio of 2.5:1 extending up to 3 or 4:1, but in some instances very long narrow features have also been referred to as drumlins, Embleton and King (1968).

Lemke (1958) described the ridges in fluted ground moraine as narrow linear drumlins and Gravenor (1953) suggested that drumlins and such flutings resulted from the same process.

However, drumlins do not always consist simply of streamlined ground moraine and in fact, normally contain a wide variety of stratified drift and widely varying proportions of solid rock.

Although drumlins vary considerably in most of their major characteristics, such as elongation, spacing, size and constituent materials, they do have an essential common feature, which is their streamlined form. A number of variations in the formation process have been suggested all of which explain this essential feature but two theories dominate. In particular it is suggested that drumlins are formed by erosion of pre-existing drift cover or that they are formed by subglacial accumulation of till in streamlined form. Of these two, the depositional explanation is the more common Chamberlain (1883), Goldthwait (1924), Flint (1971), Vernon (1966) and Hill (1971). The complex character of drumlins, however, does not suggest a simple depositional mechanism and it seems quite likely that drumlin formation is polygenetic. On the basis of all the data available at that time, Gravenor (1953) suggested that the most important features of drumlins could be summarised as follows:

a) Drumlins may consist of clay till, sandy or loamy till, rock or pre-existing drift.

b) Drumlins may frequently have lenses or layers of stratified drift which may be faulted or folded.

c) Rock drumlins may be formed side by side with other varieties and have the same shape.

d) Many glaciated areas do not support drumlins.

e) Drumlins exist in fields wider than most other moraines and rarely occur singly.

f) Drumlins have a streamlined shape with the steep end pointing up glacier.

g) Laminations may or may not be present.

h) Some drumlins have cores but most do not.

i) The long axes of the drumlins are parallel to the direction of ice movement.

j) They are found behind terminal moraines which mark approximately the outer limit of ice advance.

2.6.4. Moraine Ridges.

Glaciers and ice sheets may deposit till in the form of ridges and these may be classified in a number of ways. A classification system based on the relationship between the moraine ridges and the direction of movement of the ice that formed them has been suggested by Prest (1968). Gravenor and Kupsch (1959) and others have stressed the dynamic character of the ice from which the moraines were formed and have therefore sub-divided ridges on the basis of whether they are active or stagnant ice forms. Hoppe (1952) and Andrews (1963) have used the overall morphology or locations in terms of other relief features in their classifications. Price (1973) has chosen to classify the moraine ridges according to the process of their formation and it is this latter system which is adopted here.

According to Price (1973), there are at least three processes capable of producing moraine ridges: dumping, pushing and squeezing. In some cases of moraine ridge formation, more than one of these processes may operate. In such circumstances the dominant this ice cored moraine survives the process of down wastage eventually the ice core will melt out and a moraine with concave slopes will result. Several variations are possible depending on the dip of the bed of debris and the slope of the ice surface. Ridges produced in this way are unlikely to be larger than a few metres.

Dumping of materials along the lateral margins of valley glaciers produces lateral moraines but some doubt exists as to the percentage of till material in lateral moraines and the percentage derived by weathering and mass wastage. Nevertheless it is widely agreed that dumping of surface and englacial drift is an important component process in the formation of lateral moraines.

Dumping of material from the ice surface may occur in open crevasses or other re-entrants in the ice. The accumulating of material in the ice walled channels allows a ridge to develop,which when the ice melts forms a ridge.

The development of both single and complex ridges (hummocky moraine) from debris accumulated on the surface of an ice mass has been described by Boulton (1967). He outlined how a series of debris bands result in irregular ablation surfaces and when the debris is deposited an area of hummocky moraine is produced. The composition of these ridges of course depends on the composition of the debris bands from which they are derived.

2.6.4.2. Moraine Ridges Produced by Pushing.

Gwynne (1942), Dyson (1952), Okko (1955) and Hewitt (1967) have all process is then often difficult to determine and the external form and internal character of the moraine may not readily reveal the process of formation. Also in some cases the process of formation may not be the most important process involved. The environment at deposition, for example, may be the most significant factor or alternatively the structure of the ice depositing the till may be the most important single feature. In general, however, it is possible to use the approach of Price (1973) to classify most moraine ridges.

2.6.4.1. Moraine Ridges Formed by Dumping.

Debris often occurs on the surface of glaciers and ice sheets in their frontal zones. This debris may have been transported on the surface or have been brought to the surface along shear planes or crevasses. The mechanism by which the debris is actually brought to the surface along the margins of a cold ice mass has been the subject of considerable debate, Weertman (1961), but once the material does arrive on the ice surface the stages in the development of the moraine ridges are clearly understood, Goldthwait (1951) Souchez (1966) and Hooke (1970).

Outcrops of debris trending roughly parallel to the glacier margin are not uncommon. Depending on the nature of the material the slope of the ice surface, the structures in the ice and the presence or absence of melt water streams on the ice surface, the type of moraine that is produced varies widely. In some cases a ridge of debris is accumulated above a wasting ice surface and the ice beneath, by being so protected, melts slower than clean ice. If described ice masses pushing till to form a moraine ridge. The moraines so produced tend to have convex slopes of which the distal slope is the steepest. The internal fabric of these push moraines often shows signs of faulting and thrusting. If distinct faults are present, it is likely that the drift was frozen when the moraine was formed.

2.6.4.3. Moraine Ridges Produced by Squeezing.

Moraine ridges of this type are produced by the movement of tills with high moisture contents, as a result of pressure induced from an overburden of ice or pressure differences within an ice sheet. Hoppe (1952), Gravenor and Kupsch (1959) and Stalker (1960) have provided a great deal of data relating to the formation of such ridges and all emphasised the importance of sub-glacial deposition by the squeezing process for the formation of these ridges.

Price (1970), on the basis of observations in south-east Iceland suggested that semi-liquid till could also be squeezed out from beneath a glacier to produce ridges parallel to ice margins and reflect any irregularities it may possess. The semi-liquid till builds up into a ridge with its distal side steepest because of the drag effect of the basal layers. The pressure that produced the movement in the till, Price suggests, is derived from above as the glacier or broken off parts of it, sink into the semiliquid till with its obviously very low bearing capacity.

The development of moraine ridges both in the sub-glacial and proglacial environment is only poorly understood and undoubtedly some moraines are produced by a combination of dumping, pushing and squeezing. The environment in which the deposition takes place, can change rapidly over short times and short distances. Also the structures in the ice may or may not greatly influence the mode of formation. Indeed moraine ridges may be developed from either the direct deposition by an ice mass or from post depositional transport of the material.

CHAPTER 3. CRUSHING MECHANISM PRODUCING BASAL TILLS

3.1. INFLUENCE OF TRANSPORTATION ENVIRONMENT.

An ice sheet may accumulate materials by erosion, mechanical weathering, landslides and many other processes. As previously discussed in Chapter 2, this material may be transported by the ice in three distinct environments: supraglacially, englacially and sub-glacially. The supraglacial materials are transported on the surface of the ice and rarely are they abraded or crushed during this. The sub-glacial, basal, materials, which are predominantly acquired by erosion and abrasion of the bedrock, may very quickly become incorporated in the ice as englacial debris, or be transported along the base of the ice as basal debris. The larger particles in the englacial material tend to be isolated in the ice and further crushing, comminution, does not occur. Silt and clay size grains, are not distributed evenly through the ice, the ice crystals tending to expel impurities of these dimensions, Elson (1961). The fines thus collect in globules of water within and between ice crystals and as wet coatings to pebbles and larger stones, maintaining their wet environment by virtue of their surface energy. Thus englacial debris is so transported up through the glacier along flow lines eventually outcropping on the surface and forming ablation till.

If the basal materials are carried along at the base of the ice they very often come into contact with other particles or the bedrock, and a grinding process takes place in which the larger fragments are reduced by crushing and abrasion to a range of finer particles. The materials so produced are those which are later deposited as basal till either beneath the active ice or by basal melting of the ice.

3.2. MECHANICAL CRUSHING OF ROCKS

3.2.1. The Crushing Process.

On many occasions, the as dug or as blasted rock from a quarry requires to be subjected to further processing in order to attain the required degree of fineness. In such processing, the rock fragments are subjected to further comminution in order to attain the required degree of fineness. In such processing, the rock fragments are subjected to a mechanical force great enough to break them into many smaller pieces. This fracturing process may be based on pressure alone and is known as crushing, or it may be based on abrasion, causing the fragments to be gradually worn down to smaller pieces. In fact, rarely is there a clear demarcation between crushing and abrasion although generally in industrial plants crushing is used down to approximately 5 mm fragment size and abrasion is preferred thereafter.

A simple appreciation of the grinding process is presented by Herden (1960) when considering a unit cube or rock which is broken into perfect, smaller cubes in successive stages, at each of which, the length of side of the newly formed cubes is exactly half those of the previous stage. For such a circumstance, it is easily shown that the combined surface area of the cubes doubles with each halving of the cube edges. Actual grinding of course differs from this theoretical model in two respects. Firstly, not every particle is broken from one stage to the next, but there is a certain probability of a particle being comminuted as grinding proceeds by one stage and secondly, the parts into which a particle is broken are by no means equal. At any given stage then the particles are not uniform in size, but have a size frequency distribution depending upon both the grinding equipment and the properties of materials.

The mean particle sizes at successive stages of a grinding operation are generally found to form a series of decreasing values. Due to the homogenizing effect of grinding, the size range also decreases from one stage to the next. Studies by Alling (1944) on the crushing of quartz, microcline, tourmaline and garnet samples, initially with approximately symmetrical bell-shaped size distribution curves, yielded the following results:

a) After a short time in a rotating mill, a secondary peak developed in the small size ranges and the primary peak was reduced and shifted towards the small size, Fig. 3.1.

b) The originally angular grains became slightly rounded and the sphericity increased.

c) As the milling continued, the primary peak of the size distribution declined and the secondary became dominant.

d) Both roundness and sphericity showed maxima at certain medium particle sizes which with time of grinding, either did not change or shifted somewhat towards the smaller sizes. This shift was pronounced for roundness of garnet particles and for sphericity of tourmaline.

e) Quartz reduced in size at the fastest rate, microcline next, followed by tourmaline and lastly by garnet. The Mohs hardness did not therefore seem to be the controlling factor.

3.2.2. The Form of the Particle Size Distribution Produced by Grinding.

No mill is able to grind a product to grains of even approximately equal size. All that is generally achieved from prolonged grinding is the reduction in average particle size combined with a reduction in size range. Martin (1923) proposed a law connecting the increase in the number of particles with the change in average particle diameter. According to him, the frequency curve (number of particles at a given time plotted against mean diameter) follows the "Compound Interest Law":

$$y = a.\exp(-bx) \quad \text{................ Eq3.1}$$

where y represents the ratio of increase $\partial N/\partial x$ in the number N of particles per unit increase of diameter at the point where the mean diameter is x and a and b are constants depending upon the material.

Although the data Martin produced on the grinding of sand was a close fit for his formula, Mellor (1923) indicated that the formula was in fact only applicable to substances which fracture in a uniform manner and others, like mica and felspar which fracture in a much more complicated manner would follow a more involved relationship. Further investigations by Kolmogoroff (1941), Kottler (1950), Irani (1959) and others have in fact suggested that the form of the particle size distribution produced by grinding is a log normal distribution.

3.2.3. The Log-normal Distribution Law.

The most popular statistical law is the "Gaussian" normal law but as Kottler (1950) indicated, this law and the so called "truncated" normal law cannot realistically be applied to particle size distribution as they infer particles of a negative dimension. The log-normal law has, however, been widely applied by several investigators, Irani and Callis (1963). It has been shown that if the particle size distribution obtained by crystallisation or crushing gives a straight line on a numbers basis when using a log-probability plot, the size distribution by weight or surface area is a parallel straight line on the same co-ordinates.

3.2.3.1. Derivation of the Log-normal Distribution Law.

In general, it can be assumed that the size M of a particle grows or diminishes according to the relationship:

$$\frac{dM}{dt} = \phi(M) \quad \text{.................... Eqn3.2}$$

where ϕ (M) can be expressed as:

$$\phi(M) = \frac{K\,(M - M_o)\,(M_\infty - M)}{(M_\infty - M_o)} \quad \text{..... Eqn3.3}$$

M_o and M_∞ are respectively the minimum and maximum sizes formed and K is the velocity constant of formation that can be either positive or negative depending on whether the particles are growing or are being crushed.

As M approached M_o or M_∞ it becomes time independent because $f(M)$ becomes zero. Since time does not have any starting point, the time units of growth or crushing can be either lengthened or shortened abritrarily. This results in a justification for assuming that times of growth or crushing of particles are normally distributed. Assuming a unit standard deviation , the normal distribution of time is represented by

$$f(t) = \frac{1}{\sqrt{2\pi}} \exp\left(\frac{-t^2}{2}\right) \quad \text{................ Eqn.3.4}$$

If Equations 3.2. and 3.3. are combined then

$$t = a + b.\ln\left[\frac{(M - M_o)(M_\infty - M_o)}{(M_\infty - M)}\right] \quad \text{....... Eqn.3.5}$$

where a and b are constants. And from Equations 3.4. and 3.5.

$$f(M) = \frac{1}{\sqrt{2\pi}\ \ln\sigma} \exp\left\{-\left[\frac{\ln.\ \frac{(M - M_o)(M_\infty - M_o)}{(M_\infty - M)\ M}}{\sqrt{2}\ \ln\sigma}\right]^2\right\} \quad \text{. Eqn.3.6}$$

where σ and $\bar{M}$ can be assumed to be arbitrary constants related to a and b.

If the special case is considered where $M_o \doteq 0$ and M_∞ is very large Equation 3.6. reduces to the "simple" log-normal distribution law:

$$f(M) = \frac{1}{\sqrt{2\pi}\ \ln\sigma} \exp\left\{-\left[\frac{\ln\left(M/\bar{M}\right)}{2\ \ln\sigma}\right]^2\right\} \quad \text{............ Eqn.3.7}$$

It can in fact be shown that $\bar{M}$ and σ are not arbitrary constants, but represent the geometric mean size and geometric standard deviation, respectively. Therefore it is possible to define $\bar{M}$ and σ. The geometric mean size is:

$$\bar{M} = \sqrt[n]{M_1 \cdot M_2 \cdots\cdots M_n} \quad \text{Equ.3.8}$$

$$\text{or} \quad \log \bar{M} = \sum_{i=1}^{i-n} \frac{(n_i \log M_i)}{\sum n_i}$$

$$\text{and} \quad \log \sigma = \sqrt{\frac{\sum_{i=1}^{i=n} n_i (\log M_i - \log \bar{M})^2}{\sum_{i=1}^{i=n} n_i}} \quad \text{Equ.3.9}$$

σ is dimensionless and has a minimum value of one which occurs when $M_i = M_j$, i.e. all particles have the same size. $\bar{M}$ is the value of M at which 50% of the material is greater than, and 50% smaller than, the stated size on a numbers basis. σ is the ratio of the size at 15.87% probability to that at 50%. or the ratio at 50% probability to that at 84.13%. If a particle size distribution is truly log normal, then it is necessary to report only $\bar{M}$ and σ and the whole distribution function can be defined.

Because of the nature of the log normal distribution law, it is evident that the geometric standard deviations on a numbers or count basis, weight basis, surface area basis, etc., are equal. The relationship between the average sizes, based on weight, surface area, volume and specific surface area, of non-uniform particulate substances obeying the log normal distribution may be calculated and have been summarised in Table 3.1.

3.2.4. Abnormal Log-normal Distributions.

In many cases the plot of the particle size distribution is not a straight line on log probability paper, so that the "simple" log-normal distribution does not fit the data. These cases may be due to limited growth or crushing, artificial separation of fines or coarse particles or artificial combinations of these. For example heterogeneous, multimodal, particle size distributions can arise from mixing or from the existence of different rates and boundary conditions during the formation of particles perhaps due to different-shape particles or crystal characteristics, Irani and Callis (1963). Thus if there is a n^{th} Modal distribution, then P, the percent greater than size M, can be shown to be:

$$p = 50 - 100 \sum_{i=1}^{i=n} \int_i \operatorname{erf} \left[\frac{\ln \dfrac{(M-Mo_i)\,(M\infty_i - Mo_i)}{\bar{M}_i\,(M\infty_i - M)}}{\ln \sigma_i} \right] \quad \ldots \text{Eqn.3.10}$$

Where the subscript i refers to a particular population. In most practical cases n = 2. In such cases if the two parent distribution curves do not intersect on a log probability plot, a curve similar to that shown in Fig. 3.2. is obtained. The characteristic of the plot is that it asymptotes at its upper and lower levels to two non-vertical lines, these lines being the parent distributions, Equation 3.10.

If the parent distribution curves intersect on a log probability plot, a curve similar to that shown in Fig. 3.3. is obtained. In this case the experimental points asymptote at both ends of the distribution towards the parent distribution with a higher σ. The asymptotes do not approach specific size values as was found in the previous condition. The point of inflection is, however, an important point as both parent populations must go through it.

3.2.5. Rosin and Rammler's Law.

The most widely applicable distribution law is the log-normal or distribution or one of its modifications, however, several other empirical relationships have also found favour. These empirical relationships are useful only when the "simple" log-normal law is not obeyed. Rosin and Rammler (1933) proposed such an empirically derived relationship based on the distribution law that :

$$p' = 100 \exp \left(- \frac{M}{c} \right)^b \quad \text{.................. Eqn.3.11}$$

where c and b are constants and P' is the percentage of particles having a size larger than M. From this equation then it is easily shown that :

$$\ln \ln \frac{100}{P'} = b \ln \frac{M}{c} \quad \text{.................... Eqn.3.12}$$

Therefore, the plot of log $\frac{100}{P'}$ against M on a log-log grid should give a straight line if the distribution law is obeyed. The Rosin and Rammler Law is, however, strictly empirical and relies heavily on curve fitting, Irani and Callis (1963), and has been found to be applicable only in the case of powdered coal having a small range in particle size. Even so, a modified log-normal distribution equation can also be shown to give a good fit in such cases. In addition, the Rosin and Rammler distribution cannot be conveniently used to obtain the various statistical measures of the particle size distribution.

3.3. GLACIAL COMMINUTION OF ROCKS.

3.3.1. Development of Terminal Grades in Tills.

When during glacial erosion and transport, the rock composing the basal debris and to a lesser extent, the englacial debris, is crushed, as discussed in Section 3.1., it is to be expected that it will fracture in a similar manner to that observed in industrial grinders. As indicated in Section 3.2.4., an abrupt transition in the comminution process is also to be expected. This change, as found in the comminution of rocks by other processes, will be associated with a change from polymineral rock fragments, which may break along joints or fabrication planes, to mono mineral fragments containing portions of single crystals, which will break in a way characteristic of the mineral concerned. Elson (1961) states that as a consequence of this phenomenon, at least two size modes or two groups of size modes develop for each lithic component of the till; one consisting predominantly of rock fragments which often act as discrete clasts in the till, and the other consisting of mineral fragments, which generally form the till matrix. Several mineral modes may in fact develop depending on the physical properties of the minerals present. Thus it is to be expected that till will have multi-modal size distributions.

According to Dreimanis and Vagner (1965, 1971), and Dreimanis (1969), close to the location where the glacier picked up the rock fragments initially, the polymineral fragments mode will be relatively larger than the mono-mineral mode or modes. With increasing distance of transport away from the source, the mono-mineral modes will increase, recording increasing comminution of the rock fragments, and their size mode therefore becomes relatively smaller. The frequency distribution of dolostone-dolomite in till samples from the Hamilton-Niagara areas of Western Ontario, Canada measured by Dreimanis and Vagner, clearly illustrate the diminution of the rock fragment mode, Fig. 3.4., and show that after

300 to 500 km transport, the dolostone mode had nearly disappeared. The similarity of the progressive development of the fine size mode and reduction and disappearance of the coarse mode in mechanically crushed materials described by Alling (1944), outlined in Section 3.2.1., and the process described by Dreimanis and Vagner for comminution of basal debris is thus very close indeed.

Dreimanis and Vagner (1969) also suggested that in glacial comminution, mono-mineral modes are restricted to particle size grades which are typical for each mineral. These size grades were called the "terminal modes" or "terminal grades" by these investigators. Later, Dreimanis and Vagner, (1971), suggested that the terminal grades of some of the minerals common in till were as shown in Fig. 3.5.

Dreimanis and Vagner also illustrated the gradual development and final restriction of these modes to relatively constant particle size ranges by reference to two examples: dolomite, Fig. 3.4., representing a medium-hard mineral with excellent cleavage, and garnet, Fig. 3.6., a much harder mineral with very poor cleavage.

Several minerals, as shown in Fig. 3.5., have bi- or tri-modal terminal grades, which Dreimanis and Vagner explained in several ways. But for chemically and mechanically very resistant, minerals such as quartz and garnet, they suggest the principal cause for the multi-modal terminal grades may be the different original sizes of the mineral grains in their source rocks. In less resistant rocks, besides the effect of crushing and abrasion, solution during or after glacial transport must also be considered. This latter factor would apply particularly to the more soluble minerals, as for example calcite, which is particularly vulnerable to solution when present in low concentrations in a till where the circulating water is not saturated with calcium bicarbonate.

Predominance of terminal grades over the rock fragment modes may be taken to indicate a higher degree of maturity of the till compared with those tills which consist mainly of rock fragments. The comminution process is also known to be more severe during basal transport than it is during englacial transport, therefore, tills of englacial derivation can be expected to be richer in rock fragments from the more distant rock types than a basal till, which is generally as it is found in such cases.

3.3.2. Suitability of Log-normal Distribution Law to Particle Size Distribution in Basal Tills.

Multi-modal distribution of rocks and their constituent mineral fragments has been recorded if not fully understood by Elson (1961) and Dreimanis and Vagner (1965, 1971) and by a number of other investigators in other geographical areas. Examples include Jarnefors (1952), Harrison (1960), Raukas (1961), Sarraitor (1962), Stinkule (1964), Wilding et al (1971) and Slatt (1972). Thus it appears that the development of multi-modal distributions is a widespread phenomenon. It also corresponds closely to the phenomenon of multi-modal particle size distributions in mechanically crushed rocks arising from mixing or from the existence of different rates and boundary conditions during the formation of particles, Irani and Callis (1963), as discussed in Section 3.2.4.

However, it is recognised that just as various different types of mechanical crushers attain different degrees of fineness of crushed product so any mechanical crushing process does not necessarily exactly replicate glacial comminution. The approach adopted to the analysis of the particle size distribution should nevertheless quite reasonably be the same. The log-normal distribution law as applied to multi-modal distributions should therefore be applicable.

Elson (1961) suggested that Rosin and Rammler's law of crushing should be applied to the granulometric composition of tills. He found that a straight line cumulative curve was developed on the Rosin and Rammler plot for the tills he studied, as described in Section 3.2.5. Such a phenomenon may, however, have developed because of the multi-lithologic composition of the tills he studied which caused several bi-modal distribution curves to be superimposed, with the resulting curve becoming more or less straight. In tills with much less complex lithologic compositions, the cumulative curve does not approach a straight line, Fig. 3.7. As stated in Section 3.2.5. even where Rosin and Rammler's law does hold, a modified log-normal distribution can also be shown to give a good fit, therefore the particle size distribution of tills should be compared to the log-normal distribution law or one of its modifications.

3.4. CLAST SHAPES IN BASAL TILLS.

The shapes of clasts in tills vary widely according to their lithology, whether they were reduced by crushing or abrasion, or whether they have been worn by meltwater before being incorporated in the till or during ice melting, Flint (1971). General agreement, however, exists that there are certain shape characteristics which are diagnostic of glacial transport. In their ideal form, clasts in till are roughly pentagonal or triangular in plan, broad at one end and narrow at the other and generally are slightly convex in the transverse and longitudinal directions. The longitudinal convexity increases strongly at their narrow end and their sides and "top" are smooth either rounded or faceted. The clasts may be striated on any part of its surface, most commonly on the "base" and in many cases parallel to their long axis, Flint (1971).

This idealised clast shape for glacial transport while generally agreed is not, however, fully identified as the final product of glacial transport. For example, Wentworth (1936) found that pentagonal forms predominated in the tills he studied, but Holmes (1960) concluded, for central New York tills, that with continued wear, the clasts tended to become rounded and that pentagons although conspicuous in most tills, really represented intermediate forms.

In New Hampshire basal tills, Drake (1972) studied the changes in roundness of clasts at increasing distance from source, as determined by Krumbein's (1941) visual comparison chart, and indicated two alternatives to explain his findings :

a) That clasts go through many cycles of change each mile of transport so that a similarity in form exists at successive distances from source, representing a dynamic equilibrium condition.

b) No change takes place in clast roundness during glacial transport.

Drake preferred the first alternative as the fresh rock fragments when incorporated into the glacier probably possessed a roundness of 0.1 on the Krumbein scale whereas the average roundness in the tills studied was 0.5. On this basis repeated crushing and abrasion occurred during transport. The second alternative could nevertheless possibly result in the circumstances where large quantities of pre-weathered material was incorporated in till. From a comparison of the shapes of clasts of artificially crushed bedrock with clasts from the basal till, Drake (1972) also concluded that crushing and abrasion appeared to be about equally effective in destroying clasts.

Emerging from the investigations of clast shape in tills there does, therefore, appear to be evidence to substantiate the hypothesis of continuous comminution during glacial transport which has developed from the granulometric studies in tills referred to in Sections 3.3.1. and 3.3.2.

CHAPTER 4. DESCRIPTION OF TILLS AND SITES STUDIED.

The drifts which form the subject of this study are from both Pleistocene and modern glaciers. They are known to be composed either of sub-glacial or englacial materials. They have been deposited by a melt out process either at the base of an active glacier or in the terminal zone of an active though shrinking glacier or by slow ablation on or adjacent to a stagnant glacier. These tills may, therefore, be classified as basal melt out tills or ablation melt out tills, where the latter are derived from englacial drift. Such a distinction cannot readily be made for the Pleistocene drifts and to avoid confusion with ablation melt out tills derived from supra glacial drift, all the materials studied have been classified as basal melt out tills.

4.1. LOCATIONS AND CHOICE OF PRINCIPAL STUDY SITES.

The principal sites studied were essentially local Scottish sites associated with roadworks within the Cowal district of the County of Argyll in the West Highlands of Scotland, roadworks for the Forestry Commission in their Northern, Western and Southern Scotland Conservancies and Backwater Dam in Angus, East Central Scotland, Fig. 4.1. These sites were chosen as major earthworks were in progress through tills during the period of study and because in many cases particular engineering difficulties were being experienced when excavating and recompacting the tills during wet weather.

As the investigation of the properties of the Scottish tills developed, it was found necessary to determine more detailed knowledge of the depositional processes associated with basal melt-out tills and two field trips were therefore undertaken to modern active glaciers. The first glacier visited was Breidamerkurjokull, an outlet glacier of Vatnajokull in S.E. Iceland and the second was Blaisen, an outlet glacier of Hardangerjokulen, in Southern Norway. Further data has, however, been contributed by Dr. E. Derbyshire, University of Keele, on the Lacroix Glacier in the Taylor Valley, Antarctica.

Detailed reports of the investigations by the Norwegian Geotechnical Institute at several dam sites in Norway have also been made available and these sites have therefore been included in the investigations. Much less detailed reports of several Canadian dams have also been reanalysed and used in the study together with data provided by a number of individual investigators in several countries.

4.2. DESCRIPTION OF SCOTTISH SITES STUDIED.

4.2.1. General Late Glacial History of Scotland.

During the last glaciation the Highland ice established a dominance over the other powerful ice centres which formed to the south, in the Southern Uplands and to the west in Ireland, Fig. 4.2., a fact which is established by the presence of Highland ice erratics and fossils found on the slopes of Welsh mountains, in Ireland and on the Ayrshire coast. The main off-shore islands, other than Mull and Skye which supported local ice caps, also show evidence of the passing of the main Scottish ice sheet in the drift deposited on them, Sissons (1967).

The ice advancing from the Highlands into Central Scotland found itself opposed by the advance of the Southern Uplands ice. It stopped the advance of this ice and split into two streams, one flowing southwards down the Firth of Clyde and the other heading due east along the Firth of Forth into the North Sea where it met the advancing Scandinavian ice sheet. This off-shoot then split into two sections, one half going northwards and merging with the other Scottish land ice and the Scandinavian flow to sweep north westwards over Caithness and Orkney into the Atlantic. The other half of this easterly stream turned southwards over the east coast of England.

The glacier which flowed down the Firth of Clyde impinged upon the coast of Antrim where it was opposed by the Irish ice and divided into two, one branch heading westwards between Donegal and Islay out into the Atlantic and the other half turning southwards through the North Channel into the Irish Sea and thus returning to the Scottish mainland on the Ayrshire coast.

The basin of the Irish Sea, being congested with ice from the Clyde, Ireland, Wales, Cumberland and Westmoreland, forced the ice advancing from Galloway to split into two streams, the westerly one of which swung up the coast of Ayrshire while the easterly one passed through the Vale of Eden and thence over the Pennines into the headwaters of the Tyne and Tees.

The ice sheet attained its maximum extent approximately 17,000 to 20,000 years ago and Fig. 4.2. indicates the directions of flow from the main ice centres of the British Isles, and the approximate lines of maximum advance. Having attained a maximum the ice sheet, entered a period of decay and readvance until the disappearance of the last of the main ice masses some 8,000 years ago.

Sissons (1967) suggests that there were three major readvances of the last ice-sheet known as:

i) The Aberdeen-Lammermuir Readvance

ii) The Perth Readvance

iii) The Loch Lomond Readvance.

The suggested extents of these readvances are shown in Fig. 4.3. and it is likely that the materials investigated in this study were variously deposited by one of these readvances.

4.2.2. Cowal Road Sites.

The sites studied were all located within the Cowal district of Argyll, which is a peninsula jutting out into the northern flank of the Firth of Clyde and bounded on one side by Loch Long and on the other by Loch Fyne.

4.2.2.1. Solid Geology.

The area investigated forms part of the Dalradian Series of rocks. This series has been dated as partly Cambrian in origin. The metamorphosed sediments have produced Mica Schists, Limestones, and Quartzites, intrusions of Granite and related igneous rocks have pierced them. They are much folded and inverted forming part of the Iltay Nappe series which has Quartoze Mica Schists, Quartzite, Slates, Phylites and Mica Schist with some Epidiorite near Loch Fyne. A large area of Epidiorite-Chlorite-Schist often Hornblendic is present, with sections of Limestone and outcrops of Basalt or Dolerite occurring frequently over the area. To the North-east there is an outcrop of Glen Fyne Granite which has been used to trace the path of the glacier southwards.

4.2.2.2. Glaciology.

The ice advancing from the reservoir of the Grampians was split into two by the Cowal Watershed, one leg passing to the east into the Firth of Clyde and the other passing down Loch Fyne.

The ice flowing into the Fyne Glacier was fed by the Awe, Shirra, Arry and Kinglass Glaciers while an offshoot from the Fyne Glacier reinforced the main flow of the Eck Glacier. Fig. 4.4. shows the trends of the glaciers in this area, as suggested by Charlesworth (1956).

4.2.2.3. Description of Samples.

The samples taken from the locations shown in Fig. 4.5. were found to be from unstratified basal melt-out tills and in one case possibly from a lodgement till. They consisted of angular to sub-angular flaky aggregates which showed slight evidence of rounding in some cases.

Two types of till were identified, (i) a brown sometimes oxidised, open textured melt out till which was found near the surface and (ii) a grey relatively compact till underlying and containing more fines than the brown till. The latter till was not encountered on a sufficiently large number of separate occasions to be critically examined and may either be a lodgement till or a melt-out till of a previous stage of glaciation.

4.2.3. Scotland North Forestry Conservancy - Corrour Forest.

The Corrour Forest covers the Ghuilbinn - Ossian, Ghuilbinn - Laggan and Spean - Laggan Valleys in the County of Inverness within the Central Highlands of Scotland.

4.2.3.1. Solid Geology.

This area is classified as Moinian. It is metamorphic in origin and consists of schists and granulities with granitic intrusions of Caledonian Orogeny. The Moine Schists have by recent dating been said to be some 740 million years old thus placing them in the Pre-Cambrian Period.

The Ghuilbinn - Ossian Valley is predominantly Granite with some intrusive rocks such as Porphyrite. The Ghuilbinn - Laggan valley is part of the Ballappel Foundation and is principally composed of the Appin Nappe series of rocks, giving Quartzose Felspathic Schistose Flags and some Mica Schists. A small outcrop of Granite lies to the west of Loch Ghuilbinn. The Spean - Laggan Valley is another part of the Appin Nappe series of rocks penetrated to the west by an intrusion of Porphyrite. Some Limestone occurs here also, while towards Spean Bridge there is Quartzite.

4.2.3.2. Glaciology.

The main glacier of the area was that of the Spean-Laggan Valley, this flowed westwards from Spean Bridge fed by corrie glaciers and ice from the west, eventually joining up with the Upper Spey Glacier to form the main Spey Glacier. At some point in its history a pause in the advance of the ice occurred in the west and glacial lakes were formed giving rise to large deposits of fluvio-glacial and glacio-lacustrine sediments and to the raised beaches or parallel roads of Glen Roy, Glen Loy and Glen Spean.

The later readvance and retiral of the main valley glacier, and glaciers such as the Ghuilbinn which fed it, caused the removal of many of the fluvioglacial deposits and their replacement by ground, fluted, hummocky and terminal moraines. The raised beach still remains intact, however, where no valley glacier has readvanced over it.

A sketch map of the advance of the glaciers in the area as suggested by Charlesworth (1956) is shown in Fig. 4.6.

4.2.3.3. Description of Samples.

The samples, taken from the positions shown in Fig. 4.7. were from ground, fluted and hummocky moraines, being unstratified basal melt out tills containing clasts of irregular appearance, that is angular and cubical with some slight evidence of abrasion being present.

The Ghuilbinn - Ossian Valley is overlaid by hummocky and fluted moraines containing Corrour Granulites and Pelitic Schists as well as the local Granite and Prophyrite intrusive rocks. The Ghuilbinn

Laggan Valley is covered by ground and fluted moraine containing Corrour Granulites as well as the local bedrocks described in section 4.2.3.1. The Laggan Valley is overlaid by both ground and hummocky moraines which contain Mica Schist, Granulites, Granite, Quartzose Felspathic Flagstone, and Limestone.

4.2.4. Scotland North Forestry Conservancy - Glengarry Forest.

That part of the Glengarry forest in which the investigations were undertaken occupies Glen Kingie, a tributary valley of Glen Garry lying to the west of the Great Glen in Inverness-shire.

4.2.4.1. Solid Geology.

This area is Moinian in origin with some granitic intrusions. The metamorphosed sediments ranged from originally sandy through mixed sandy and clayey types to originally clayey sediments. These are now respectively represented by psammitic metamorphic rocks, mainly Siliceous Granulites, semipelitic and pelitic rocks, mainly Mica Schist. Subsequently these sediments were intruded by igneous material mainly granitic in composition.

4.2.4.2. Glaciology.

The paths of the glaciers in this area, according to Charlesworth (1956) are as shown in Fig. 4.8., with ice advancing from the west fed by corrie glaciers.

During the confluent stage of glaciation the Quoich and Kingie Glaciers formed part of the Garry Glacier. It was not until the ice had retreated and exposed the 915 metre ridge to the north of Glen Kingie that the Quoich and Kingie Glaciers started to separate from the Garry Glacier. The Kingie Glacier separated later from the Quoich Glacier when Beinn Bheag (329 metres) emerged from the surface of the ice.

4.2.4.3. Description of Samples.

The morainic deposits of this area were found to be ground and hummocky moraines containing unstratified melt-out basal till. The clasts were mainly angular with some slight rounding evident in a few samples and were found to be mainly derived from the local bedrocks described in Section 4.2.4.1. The locations of the roadline and sampling points are shown in Fig. 4.9.

4.2.5. Scotland West Forestry Conservancy - Strathyre Forest.

The Strathyre Forest covers the area around the village of Strathyre at the head of Loch Lubnaig in Perthshire in the Southern Highlands.

4.2.5.1. Solid Geology.

This area is Dalradian in origin and the metamorphosed sediments have produced around Loch Lubnaig an area of Schistose Grit with a section of Epidiorite and Hornblende-Schist on the side of Ben Vane. An intrusion of Basalt lies just to the north, while the Loch Voil area has deposits of Quartzose Mica-Schist.

4.2.5.2. Glaciology.

The lines of advance of the principal glaciers of this area as suggested by Charlesworth (1956) are as shown in Fig. 4.10.

The Voil Glacier to the north of Loch Lubnaig sent offshoots down Lubnaig while proceeding to form part of the Earn Glacier. An offshoot of the Earn Glacier joined the Lubnaig Glacier by Glen Ample leaving excellent evidence of its passing in the hanging valley of present times. The Lubnaig Glacier then proceeded southwards to join the eastward flow of the Katrine Glacier finally entering the Callander Piedmont Glacier.

The retiral of the Lubnaig Glacier exposed the rock basin of Loch Lubnaig, and a covering of sheet moraines on the lower hillsides. Scarps and near vertical rock faces show where the glacier met more resistant rock and this is clearly shown by the bend at Ardandare Hill where scarps exist to the west and more gently sloping hillsides to the east.

4.2.5.3. Description of Samples.

The samples were taken on the line of the proposed road as shown in Fig. 4.11. The moraine was found to be of the ground moraine form with block erratics appearing on the surface. The till was not very thick with bedrock appearing at surface level on numerous occasions. Although a shallow layer of brown till was found to cover a much thicker grey till, the physical characteristics of the two layers were found to be identical. Thus the difference in colouring is in all probability due to oxidation by exposure to weathering.

From a visual inspection of the till it was found to be unstratified basal melt-out till in character. The clasts showed some slight evidence of rounding but were in the main both angular and flaky and derived from the local bedrocks described in Section 4.2.5.1.

4.2.6. Scotland West Forestry Conservancy - Glen Orchy Forest.

The Glen Orchy Forest occupies the valley of the same name which runs between the villages of Dalmally and Bridge of Orchy in the County of Argyll in the West Highlands.

4.2.6.1. Solid Geology.

This area is Dalradian in origin with its metamorphosed sediments forming part of the Ballappel Foundation with the Appin Nappe series of rocks predominating, although some outcrops of the Ballachulish Nappe occur in the upper and lower glen.

Intrusive sections of Diorite with some Felsite or Trachyte occur in the upper glen while the central portion has mainly Quartzites. Phylites, Mica Schists etc. with a few intrusions of Diorite. The lower glen has Graphitic Schists, Slates and Limestone with some intrusions of Felsite. A section of Epidiorite also occurs in this area.

4.2.6.2. Glaciology.

The Rannoch Moor ice Reservoir and the corrie glaciers of the mountains surrounding Glen Orchy fed a glaciar which moved down Glen Orchy in a south westerly direction to meet the Strae and

Lochy Glaciers. On merging these glaciers became the Awe Glacier as shown in Fig. 4.8. and proceeded in a south-westerly direction down Loch Awe.

4.2.6.3. Description of Samples.

The samples taken from the positions shown in Fig. 4.12. were mainly from hummocky moraines on the hillside and in the valley bottom. Several samples from the upper glen were taken from well formed mounds which could be fluvioglacial in origin or at least fluvially modified.

The samples on visual inspection were unstratified. The clasts were slightly waterworn but some angular material was also present. They were found to be derived from Granite and Central Highland Granulite from the North as well as of local bedrock, which latter formed a high proporation.

4.2.7. Scotland South Forestry Conservancy - Glen Trool Forest Park.

The Glen Trool Forest Park covers a very large area in the South West of Scotland in Kirkcudbrightshire. The particular parts of the Park investigated were the Bennan Section of the Cairn Edward Forest, The Garcrogo Forest and the Garraries Forest all in the area surrounding the towns of St. Johns Town of Dalry and New Galloway. The Cairn Edward Forest is located in the lowland between the Fell of Fleet, Airie Hill and Cairn Edward Hill to the South of New Galloway. The Garcrogo Forest lies to the east of these towns alongside the A712 between Garcrogo Hill and Mochrum Fell. The

Garraries Forest lies to the west of the towns north west of Clatteringshaws Loch, just south of the Rhinns of Kells.

4.2.7.1. Solid Geology.

The Cairn Edward Forest area is of the Older Palaeozoic Period and is mainly Silurian in character. These rocks were formed from the sediments which were deposited during a period of submergence that occurred at the end of the Pre-Cambrian period. The submergence lasted through Cambrian and Ordovician times into the Silurian period when the Caledonian Orogency which had started in late Ordovician times, became intense. The sediments which lay in the submerged area were pushed up into a folded mountain range known as the Caledonian chain, the remnants of which are the Southern Uplands of today. The Granite of the Cairnsmore of Fleet intrusion dominates locally, separated from the Silurian Greywacke by the aureal of contact metamorphism which exists between them.

The Garcrogo forest area is principally Silurian Greywacke with an intrusion to the north of Micro-Diorite.

The Garraries Forest lies on the slopes of the Rhinns of Kells which are predominantly Silurian Greywacke with some intrusions of Porphrite occurring throughout the area. The Granite mass of the Loch Doon intrusion lies slightly to the North West.

4.2.7.2. Glaciology.

The ice which covered this general area moved in a southerly direction bringing erratics from the Loch Doon Granite mass on to the Greywacke slopes of Merrick and adjacent hills. Granite erratics do not seem to appear on the northern section of the Rhinns of Kells and this may be explained by the fact that the ice from the Kells was flanked by powerful glaciers from the region of Carsphairn flowing on approximately the same line.

The Merrick Glaciers flowed down the valleys of the Doon and the Dee, the latter joining the ice from the Rhinns of Kells and flowing south to meet the ice from Carsphairn to the east. The combined flow then acted as a feeder to the Cree Glacier and thence flowed into the Solway breaking east and west when contact with the ice was made.

4.2.7.3. Description of Samples.

The Cairn Edward Forest samples were taken from the positions shown in Fig. 4.13. and were in general from existing borrow pits, the exceptions being 12A and 13, which were trial pits excavated below the peat to ascertain whether useful supplies of till could be obtained from these points for roadworks.

The samples, other than Nos. 5 and 6 were found to be unstratified in character with the aggregate showing slight rounding but tending to be cubical in form, with some angular material present and derived from Conglomerates, Greywacke and Granite, the latter being mainly decomposed.

The samples from the Garcrogo Forest were from ground moraine at the positions shown in Fig. 4.14. They were unstratified in character even when exposed, in the case of samples No. 15 and 17, in borrow pits with a considerable face (approximately 5 metres high). Sample No. 16 was taken from a trial pit in the forest at a depth of some only 1 metre Samples 15 and 17 had aggregate which showed evidence of water rounding while No. 16 was flaky in appearance and had a high stone content. The clasts were derived from Granite from the north as well as the local bedrocks described in Section 4.2.7.1.

The Garraries Forest samples were unstratified in character and were taken from the positions shown in Fig. 4.15. They contained aggregates which were generally cubical and angular in shape with some slight evidence of rounding being present. Granite was present, although no large erratics of this material have been found on the upper slopes of the Rhinns of Kells, along with Greywacke and Intrusive rock.

4.2.8. Backwater Dam.

The dam for Backwater Reservoir is situated in the foothills of the Grampian Mountains some 30 km N.W. of Dundee. The valley in which the dam lies is a tributary of the Isla Valley and is located only some 3 km north of a major geological fault which traverses Scotland from Stonehaven in the east to the Clyde Estuary in the West.

In order to provide the optimum storage of 24.3×10^6 m^3 (5,400 million gallons), an earth embankment type of dam was constructed

43 metres high above the valley bottom and 550 metres along its crest containing 1.23 million cubic metres of materials. The materials used in the dam were the local deposits of sand and gravel and glacial till. These materials were utilised in the various parts of the dam as shown in Fig. 4.16.

4.2.8.1. Solid Geology.

The bedrock of this area belongs to the Dalradian series of Pre-Cambrian Age, the most commonly occurring type being Schistose Grit which is hard and unweathered. Extensive faulting occurs in the area and adjacent to shear zones and other shattered areas the rock has been subjected to deep weathering which has softened it. A sub-ordinate fine grained highly Micaceous Schist with well developed foliation occurs in bands but is also generally soft due to weathering. Random but steeply inclined jointing is extensive, frequently being clay filled and iron stained, Geddes, Rocke and Scrimgeour (1972).

4.2.8.2. Glaciology.

Evidence of successive glacial advances and retreats are evidenced by the variety of drift deposits in this valley within which the bedrock is gouged out to form a deep steep-sided control section with gently sloping flaules. The depth to bedrock in the central section is some 50 metres. The rock at this point is covered by 6 metres of till. Sedimentation from glacial lakes has resulted in deposits of fine laminated silts and sands to a further depth of 6 metres over the till. Above this, 15.25 metres of lenticular beds of fluvioglacial sand and gravel were deposited in a rather confused manner. A major glacial readvance and retreat subsequently covered these deposits with a comparatively thick layer of homogeneous glacial till approximately 15 m deep in the centre of the valley.

The paths of glaciers during the last glaciation as suggested by Charlesworth (1956) are as shown in Fig. 4.17. The dominant local ice was the Isla Glacier which was fed by the snowfields of the Grampians. After parting from the Strathmore Ice, with the emergence of the Forest of Alyth, the Isla Glacier withdrew a lobe thrust into the Muckle Valley. It lost the equispaced Alrick, Balloch and Mor Lobes of the Shee Glacier and ponded the lateral drainage. It then dissolved into a series of cirque glaciers.

4.2.8.3. Description of Samples.

A very extensive site investigation was carried out at the dam site and in several upstream deposits of till, sand and gravel, in order to ascertain the quality and quantity of these materials both beneath and for use within the dam. The dominant rock types present in the tills were similar to those described in section 4.2.8.1.

4.3. DESCRIPTION OF MODERN GLACIER SITES.

4.3.1. Breidamerkurjokull South East Iceland.

Breidamerkurjokull is an active temperate maritime glacier located in south-east Iceland some 30 km west of Hofn. On the southern side of Vatnajokull several outlet glaciers descend from the plateau ice almost down to sea level and Breidamerkurjokull is one of these outlet glaciers. It can be regarded as a valley glacier some 20 km in length, 10 km wide at a distance of 1 km from the ice front (in 1965), but which broadens out into a lobe towards its terminus, Fig. 4.18. Plate 4.1.

The proglacial area of Breidamerkurjokull consists of two parts, the areas beyond and within the limit of last readvance of the glacier, i.e. beyond and within the 1890 moraine. The area within the 1890 moraine consists of till plains morain ridges, small sandar, eskers kames and kettle-hole topography, lake basins and meltwater channels (Price 1969). The study area in this investigation was confined to two small parts of this area, one at the extreme western corner of the glacier and the other somewhat further to the east close to the Mavabyggdarond moraine, as shown in Fig. 4.18.

4.3.1.1. Solid Geology.

The rocks in Iceland are volcanic in origin, and were formed during the Tertiary and Quaternary, Thorarinsson (1937). The original formation consisted of a horizontally bedded lava plateau composed of basalts. This was later divided into two by a "broad central zone of submergence", which began to develop in Pre-Pliocene times, Thorarinsson, (1937). Deposits of the "Palagonite Formation", now occupy the central zone, and extensive faults occur running north-south and northeast-southwest. The faulting is thought to have taken place in the Tertiary, but movements still occur Thorarinsson (1937). Volcanic activity at present is mainly limited to this area, and its submarine extensions.

Thoroddsen (1906) stated that on the south coast the Palogonite Formation extends from Reykjanes to Breidamerkurjokull, a distance of 300 kilometres. Others however, consider the boundary to be too far east at Breidamerkurjokull, and place it at Skeidararsandur, Jonsson (1954). Thoroddsen had stated that Breidamerkurfjall on the west side of the glacier is formed of Palagonite breccia, whilst Fellsfjall on the east side is composed of basalt. From his investigations in the proglacial area of Breidamerkurjokull, Thoroddsen found that stones of gabbro occurred on the eastern side of the glacier as far as the Breida river, but west of the Breida river they disappeared and stones of Palagonite breccia began to occur. Stone counts in the western half of the proglacial area, however, found gabbrowest of the former Breida river. This suggests that it is perhaps correct in placing the boundary of the Palagonite Formation at Skeidararsandur.

4.3.1.2. Glaciology.

It is believed, Price (1969), that for at least a century prior to 1890, this glacier was advancing, however, since that date there has been a rapid and continuous retreat. The average rate of retreat between 1890 and 1937 was 12-13 m/year, between 1937 and 1945 it was 94 m/year and from 1945 to 1965 it varied between 60-75 m/year. This frontal retreat was accompanied by a general thinning of the glacier, the rate of downwastage in the frontal zone for the period 1945-1965 ranging from 5.0 to 7.5 m/year, Welch (1967).

4.3.1.3. Description of Samples.

The samples were taken from within and beneath the ice in tunnels under the glacier, from fresh tills at the glacier margins and from tills at the immediate proglacial till plains which had been uncovered by the glacier for less than five years, all in the general locations shown in Fig. 4.18. and in the detailed locations shown in Fig. 4.19. and 4.20. referring to the western and central areas respectively.

All the tills are derived from rocks of the Basalt suite, clasts being predominantly of dense flow Basalt and Breccia with Vesicular Basalt being rare. The tills are found to be an admixture of glacio fluvial gravels, melt-out tills and lodgement tills. The till surface is characterised by widespread, often remarkably uniform flutings rarely standing more than 0.5 m above the general ground level, Plate 4.2.

4.3.2. Blaisen, Hardangerjokulen, Southern Norway.

Blaisen is an outlet glacier of the small plateau ice cap of Hardangerjokulen, Southern Norway, Fig. 4.21, Plate 4.3. It may be classed as an active temperate maritime glacier and lies some 5 km south of Finse, the highest point on the Bergen to Oslo railway. The glacier snout lies at an altitude of 1300 m and is only some 600 - 700 m wide.

4.3.2.1. Solid Geology.

The northeastern extension of Blaisen traverses coarse granitic gneiss, crystalline schist, phyllites and the granitic basement complex. The area of the ice front in which the glacial deposits were investigated in detail is underlain by basement complex and grey-black phyllites. In detail, the structure is complex, a shatter zone traversing the western end of the sampled area. The ice immediately above the glacier snout (1972) is underlain by an extension of the phyllite outcrop and, by analogy with the cliff to the west, may coincide with a fault within the basement.

4.3.2.2. Glaciology.

General retreat since at least the middle of the eighteenth century has left a sequence of small end moraine ridges which have been dated and mapped in some detail by photogrammetric methods, Andersen and Sollid (1971), Fig. 4.22. The ice front position at the time of the study in 1972, coincided with the base of an ice fall, Fig. 4.21. Plate 4.3, so that the till is discontinuous and thin and the currently forming moraines are very small and composed of melt out tills.

4.3.2.3. Description of Samples.

The area of study was located on the eastern part of Blaisen, as shown in Fig. 4.21. and samples were taken from fresh tills, 1972, and tills formed in 1970, 1965 and 1952, Fig. 4.23, using the dating system adopted by Andersen and Sollid (1971). The samples were taken from small moraine ridges 0.5 to 1 m high, resting directly onto bedrock which sloped away from the glacier at an average of 5°. The tills are composed predominantly of local granite-gniess and phyllites.

4.3.3. Lacroix Glacier, Taylor Valley Antarctica.

The Lacroix Glacier is a small remnant of a "wall-sided" glacier of polar type in the Taylor Valley, Antarctica, Fig. 4.24, Plates 4.4. and 4.5. Only one sample was available for study from this glacier which was taken from non-fluted hummocky till overlying lacustrine sediments a short distance in front of the glacier which is frozen to its bed. The lithology of the till is dominated by local granite gniess with minor components derived from dolerite and sandstone. Despite its freshness and proximity to the glacier, this till may be some thousands of years old. It shows a well developed macro-fissility, Plate 4.6, which dips downslope at 13° approximately in accord with the dip of the basal surface of the glacier.

4.4. NORWEGIAN DAM SITES.

The last ice sheet which covered Norway about 15,000 years ago, has been reduced today to a few isolated glaciers in the mountains, such as Hardangerjokulen, described in Section 4.3.4, which altogether now cover only slightly more than one per cent of the total area of the country. During the retreat of the ice sheet, moraines, characterised by a material deposited and reworked by glaciers, were exposed and today cover 60 per cent of the country.

The bedrock in Norway, 95 per cent covered by glacial, fluvial and marine sediments, lakes and peats, consists mainly of igneous and metamorphic rocks of Pre Eocambrian Age together with Eocambrian and Cambro-Silurian metamorphic sedimentary rocks represented in the first case by Gneiss and Granite and in the second by Mica Schist, Quartzite, Dolomite and Gneiss. The general distribution of these rocks is indicated in Fig. 4.25.

The oldest man-made dams existing today are thought to be 200 years old dams and have impervious cores of peat. In modern times numerous earth and rockfill dams have been built in the mountain areas for the purpose of raising and storing supplementary water in natural lakes and for creating hydraulic heads above the associated power stations in nearby valleys or fjords. The earth and rockfill dams are therefore situated in areas, Fig. 4.26, where morainic soils are available for use as impervious materials, sand and gravel deposited by mountain rivers, are available as filter material and rock, blasted from the mountain, is available as supporting fill, Kjaernsli (1968).

Due to the topography of the mountain areas, dams of medium height can create huge reservoirs and therefore, dams in Norway are not very high. The maximum height of existing earth and rock-fill dams is approximately 90 metres; however, heights up to 150 metres are planned for the near future.

The choice of the cross section of the dams is based on stability requirements, permissible seepage and unit price of the various fill materials to be used in the dam. In many cases the limited amount of moraine or gravel available is the decisive factor in the selection of the cross section. Quarry run rock may generally be produced at a competitive price in Norway, therefore, it is generally used for the supporting fill. Because of its low cost, available spoil from nearby tunnels is always placed in the dams as filter zones or as supporting fill. Data have been provided by the Norwegian Geotechnical Institute relating to the geotechnical investigations of the morainic sediments at the dam sites indicated in Table 4.1. The identity of the bedrocks which form the dominant clast lithologies are also given in Table 4.1.

4.5. CANADIAN SITES.

The geotechnical properties of impervious fill materials used in some Canadian dams have been reported by MacDonald et al (1961), Fig. 4.27. A number of the soils considered were tills and their reported properties are given in Table 4.2. These data were used in this study for comparison with the properties of tills from other areas in Canada reported by Dreimanis and Vagners (1965, 1969, 1971) Dreimanis (1969) and Audy (1970). The sites investigated by Dreimanis and Vagners were related to basic geological investigations in the Ontario region but those studied by Audy were associated with major motorway projects in the environs of Montreal. Detailed identification of the lithological content of the Ontario tills are therefore available but this is not the case for the Montreal tills.

In fact, during the latest glaciation, the Laurentide ice sheet covered the entire country east of the Cordilleran Region. It originated in, and moved outwards from several centres, the two main ones being in Central Quebec and in the North West Territories just west of Hudson Bay. Minor centres were located in Northern New Brunswick, Newfoundland and Baffin Island. The Laurentide ice sheet, during its period of maximum extent, abutted the Cordilleran ice sheet along a line approximately coinciding with the boundary between the Plains Region and the Cordilleran Region. The Cordilleran ice sheet originated in the mountainous area of British Columbia and spread outwards in easterly and westerly directions. Two areas of moderate size were not covered by ice, a part of the Yukon Territory, located along the Alaska boundary, and a number of the outermost islands of the Arctic Archipelago.

During the advance and retreat of the glaciers, the bedrock surface and most of the then existing overburden, were either eroded or reworked and subsequently deposited as unsorted glacial drift and water-sorted glacial outwash deposits. Much of the country is now covered with such materials. As the glaciers waned, fresh-water lakes such as the extinct Lake Agassiz in Manitoba, the extinct Lake Barlow-Ojibway in Northern Ontario-Quebec, and the immediate areas surrounding the larger present-day lakes, such as the Great Lakes, were formed. Marine incursions also occurred at this time, particularly in the Hudson Bay Lowlands, and along the St. Lawrence River Valley. Marine and estuarine conditions prevailed in these areas and sedimentation of fine grained soils produced the well known marine and estuarine clays.

CHAPTER 5. TEXTURAL VARIATIONS IN BASAL MELT-OUT TILLS.

5.1. PREVIOUS INVESTIGATIONS OF THE TEXTURAL VARIATIONS IN TILLS.

The textural and lithologic variations in tills have been used by many authors as a means of differentiating and correlating various till deposits. Krumbein (1953) carried out such an investigation on the Valparaiso moraine tills, but when considering the textural variations he did not recognise the multi-modal nature of these soils and analysed the statistical constants of the particle size distribution as one population. Krumbein did, however, recognise that till is not heterogeneous, as had previously been supposed, and that a given ice sheet tends to produce till having a fairly well defined frequency distribution. He also suggested that the homogeneous basic composition could be modified locally, by drainage conditions at the ice margin, and by incorporation of unconsolidated deposits beneath the edge of the ice. His method of investigation led him, however, to the conclusion, which he stated was strange, that the textural composition of the tills he investigated did not reflect the changes in pebble lithology which he noted were associated with the changes in bedrock over which the glaciers had passed.

Jarnefors (1952) did note a change of the slope, on a semi-log plot, of the cumulative grading curves of tills from Northern Sweden. This change occurred at 100-50 µm, Fig. 4.26, and Jarnefors associated this with a change from complex to monomineral particles, which he concluded was also indicative of a retardation of the rate of grinding of the soil during formation. Such a phenomenon related to industrial grinding has been previously discussed in Section 3.2.4, and was similarly reported by Beaumont (1971) in relation to tills from Durham, England.

The multi-modal nature of the till particle size distribution was not recognised in North American tills until some time after Jarnefors (1952) observations. For example, Shepps (1958) presented statistical data relating to the complete grain size analysis of till from the Allegheny Plateau, Northeastern Ohio. In so doing, he suggested that the large amount of data so generated could be simply and effectively presented on a diagram, Fig. 5.1, showing only the percentage sand and clay. These size ranges were, however, chosen as they exhibited the greatest variation and not that they represented a separate population. By accepting that sorting was similar within each till sheet, Shepps could ignore the spread due to this. Thus he narrowed the band of results to a line. By dividing the line into a series of numbered classes, called Size Factors, the texture of the soil he suggested could be described by a single number. Histograms of size factors for various till sheets could then be drawn up and used to distinguish one till from another.

Chryssafopoulos (1963) also employed statistical techniques on the full particle size distribution of a number of tills from morainic deposits surrounding Lake Michigan. He considered those sieve sizes at which 80, 60 and 40 percent, by weight, of the total soil was passing, together with the percentage of soil finer than No. 200 U.S. sieve, (opening size - 0.074 mm). The tills were all clayey soils and he found that the data from the percentage passing the No. 200 sieve size was sufficient to distinguish the various tills he was studying. His analysis again confirmed that tills do not randomly vary in particle size distribution, but conform to a reasonably predictable pattern for any given ice sheet, the same point made earlier by Krumbein (1953).

A better recognition of the basic composition of tills was made by Elson (1961) who, taking tills as products of simple crushing plotted their grain size distribution Rosin and Rammler's "Law of Crushing" paper. The deviations from the expected simple straight line plot, Fig. 5.2, a curve with two or more straight line portions being common, were taken as indicative of variations in the properties controlling the fragmentation of the particles within the different size ranges. As an example he quoted the retardation of the comminution of the finer particles by a water environment, Elson also suggested that, apart from the products of chemical weathering, tills were the only naturally derived soils whose grain size distribution obeyed the laws of probability and that this may be used to recognise tills as being directly formed by crushing.

Elson points out that superglacial tills may be subject to washing out of fines during or before deposition and so may not conform to the above pattern. Also a glacier may readvance over its proglacial area, overriding its previous fluvial deposits. On a subsequent retreat, such reworked materials may be deposited as tills but would not have the grain size distribution of a simple comminution product.

Elson, nevertheless, makes use of ternary diagrams to classify tills, Fig. 5.3. The problem is that it is necessary to divide the complete cumulative grading curve into three arbitrary fractions viz, sand and gravel, silt and clay. Tills may have a wide range of gradings over short distances. Samples in very close proximity to each other can thus, using this system, be given widely different classifications, so obscuring any basic relationships.

Later, Dreimanis and Vagner, (1965, 1969 and 1971) suggested that every lithological component of till has a bi-modal particle size distribution, if it is monomineralic or consists of minerals of similar physical properties. As discussed in Section 3.3, they suggest that one of these modes is to be found in the clast-size group and another in the till matrix, and that several such modes exist when the comminuted rock consists of minerals whose physical properties differ.

When a number of bi-modal curves are superimposed one upon the other, the resulting curve on Rosin and Rammler's "law of crushing" paper will they suggest be a more or less straight line. Thus the straight-line cumulative grading curves of tills mentioned by Elson, may develop because of the multilithologic composition of most tills.

Dreimanis and Vagner further point out that bi-modality requires that at least two particle size groups should be investigated for the description of the lithologic composition of a till:

a) clast size consisting predominantly of composite grains and rock fragments, formed mainly be frost action and crushing, effective in the breakdown of inter grain bonds.

b) matrix, consisting predominantly of single grains and minerals, formed mainly be attrition and chemical weathering effective in the breakdown of molecular bonds at mineral surfaces.

Dreimanis and Vagners found that where such sets of mineral modes have formed in a till sheet, the particle size distribution of the matrix, i.e. the fine soil fraction will, for uniform geological conditions, remain uniform.

The variability of gradings of tills over short distances influences the relevance of all the above approaches to textural analysis, with the exception of the investigations of Jarnefors (1952) Dreimanis and Vagner (1965, 1969, 1971). The principle of recognising and utilising the bi-modal nature of tills, as suggested by Dreimanis and Vagner is probably the one which can contribute most towards both the engineering and geological classification of tills. Also, as suggested in Section 3.3.2., the particle size distributions should be compared to the log-normal distribution in order that the parent populations in the tills be identified. The Geological Survey of Canada (Scott, and St. Onge, 1969) have in fact, adopted this approach.

5.2. SAMPLING AND TEST PROCEDURES.

5.2.1. General Approach.

Bulk samples of approximately 50 kg of soil were obtained from all

Scottish sites at depths ranging from 1 to 6 metres depending on the nature of the sampling point, i.e. borrow pit, road cutting or trial pit.

Where possible the samples were taken from a depth of approximately 1 m below exposed surface level at the time of sampling but as this depended to a great extent on the angle of repose of the till in the cuttings and borrow pits some samples had to be taken at a greater or a lesser depth.

The wet masses of the bulk samples were obtained on site and the samples were then transported to the University where dry masses, moisture contents and particle size distribution data were evaluated.

At Breidamerkurjokull and Blaisen, between 6 and 11 kg samples only, of less than 80 mm diameter materials were taken at each sample point. These were sealed in plastic, waterproof containers and shipped back to the University laboratories for further study.

Only one sample of Antarctic soil was available and of this, only 300 g could be used for particle size distribution. The maximum particle size present in this fraction was less than 10 mm therefore the sample tested may not be entirely representative of the till.

The Norwegian moraines investigated in connection with the construction of dams by the Norwegian Geotechnical Institute are sampled and tested in the same manner as was adopted for the

Scottish tills, Kjaernsli (1968).

5.2.2. Laboratory Test Procedures.

The bulk samples of material were separated on a B.S. $\frac{3}{4}$ inch diameter sieve into two fractions, (a) Retained $\frac{3}{4}$ inch and (b) Passing $\frac{3}{4}$ inch. These fractions were then analysed as below:-

a) Retained B.S. $\frac{3}{4}$ inch Sieve.
This material was washed and dried and a dry sieve analysis to B.S. 1377 (1967) Test No. 7B carried out over the range of B.S. Sieves 4", 3", $1\frac{1}{2}$", $\frac{3}{4}$". The respective "mass retained" for each sieve was recorded.

b) Passing B.S. $\frac{3}{4}$ inch Sieve.
A representative sample of approximately 3 kg was obtained from the material passing the B.S. $\frac{3}{4}$ inch sieve. This sample was oven dried and a 1 kg sample, obtained by quartering, was dry sieved to B.S. 1377 (1967) Test No. 7B through B.S. $\frac{3}{4}$ inch and 3/16 inch sieves. The weight of material retained on each sieve was recorded.

A 500 gm sample of the material passing the B.S. 3/16 inch sieve was then wet sieved according to B.S. 1377 (1967) Test No. 7A, the resulting mass of material retained on each sieve being recorded.

The cumulative percentage passing each sieve was obtained and the particle size distribution curves were drawn down to the silt fraction.

Critical examination of the curves enabled certain samples to be selected for further examination by Hydrometer Analysis (B.S. 1377 (1967) Test No. 7B) down to the clay size fraction.

On completion of the hydrometer analysis, the particle size distribution curves were completed down to the clay fraction and examined in detail.

Where samples showed sufficient clay content plasticity index tests were carried out.

The completion of the data from the particle size distribution tests allowed the moisture contents of both bulk samples and material less than B.S. $\frac{3}{4}$ inch sieve size to be calculated.

5.3. METHODS OF INTERPRETING TEXTURAL VARIATIONS IN THE TILLS STUDIED.

During the investigations in Cowal, Scotland, it was noted that the grain size distribution of the brown/yellow melt out tills of the area, although varying through a wide range, showed either a break or a gap in their particle size distribution in approximately the same size range, Fig. 5.4. The split or gap size range was found to be generally in the fine to medium sand size range (0.06 - 0.60 mm diameter) but a few gradings were found to split in the coarse sand size range (0.60 - 2.00 mm diameter).

As a first step in the investigation of this phenomenon, frequency curves of the percent by weight of various size classes were drawn as in Fig. 5.5. This indicated the existance of two size populations making up the overall grading of the till, as discussed in Section 3.3.2. Log-probability plots were then drawn, as in Fig. 5.6 using particle sizes described in mm and classified to B.S. 1377 (1967) but were also drawn, as in Fig. 5.7, using the more comprehensive Modified Wentworth Scale (Wentworth 1922) as in Fig. 5.7 and phi (ø) units to describe particle size. The ø units are found by conversion from the mm scale, where ø is $-\log_2$ of the diameter in mm. This conversion means that one division of the Wentworth scale is equivalent to one unit on the ø scale.

Two or more near straight lines, sometimes linked by a short transition curve were generally obtained. The form of these curves is, in fact, similar to Fig. 3.2, indicating a mixture of two parent size populations which do not intersect. It was also noted that the point of minimum frequency and the point of contraflexure of the log-probability plot occurred at or very close to the same particle size and that this remained fairly constant for all samples of the till. Investigations of the form of the particle size distribution of other Scottish and foreign tills, McGown (1971), revealed similar findings, as for example is shown in Figs. 5.8 to 5.11. The consistency of the split or gaps size range in these tills was also found to be very high, as for example for two of the Scottish tills shown in Fig. 5.12 and 5.13.

While the parent populations most certainly did not intersect, i.e. no curves of the type shown in Fig. 3.3. were found, they were sometimes estimated to overlap somewhat. This is evidenced in semi-log plots when a split and not a definite gap in the grading occurs. Frequency curves of such cases indicate a degree of overlap in the parent size distributions by never reducing to zero at any intermediate point although exhibiting a minimum value. In order to detail the parent populations fully, an analysis of the type described in Section 3.2.4, would be necessary. For the purposes of this general classification of the soil fractions for geological and engineering purposes, such an approach has been considered but judged to provide greater detail than was necessary. The errors in taking either the minimum frequency point or the point of centraflexure on the log probability plot, as the particle size separating the coarse and fine fractions of the composite soil were considered to be acceptable for split-graded tills. As many of the tills were gap graded, the point of separation of the coarse and fine fractions could be placed at any point within the gap size range. Thus for most tills a single separation size was chosen, being the average split or mid-gap size and the identity of the fractions taken with reference to this. Thus full investigation of the possible degree of overlap of the parent populations was not undertaken. From the engineering viewpoint particularly, this was quite acceptable as small variations in the upper size limit of the fine fraction or lower size limit of the coarse fraction would not significantly influence any predictions of engineering behaviour.

Having so identified the soil fractions, they may then be classified. For the purposes of quantitative assessment, three digit grain size indices have been adopted in this investigation in the manner described by Doeglas (1968). For qualitative assessments the soil fractions have been classified according to both British Standard 1377 (1967) and the Modified Wentworth Scale, Wentworth (1922).

The range and average percentage fine fractions have been noted in each case. Also comparisons of the identity of the fine fractions of tills from different geographical areas with the same dominant clast lithology have been prepared to establish if particular fine fractional gradings can be associated with particular rock types.

5.4. TEXTURAL VARIATIONS IN SCOTTISH TILLS.

5.4.1. Cowal Road Sites.

Two distinct tills were found lying one upon the other along the length of the roadworks in Cowal. The lower till when present was grey, while the upper and much more common till was brown or yellow. The grey till contained noticeably fewer stones and appeared finer than the brown till. The relative position and general character of these soils suggests that they are two separate types of till, the grey soil, a lodgement till and the brown soil a melt-out till. The grey till was not encountered on a sufficiently large number of separated locations to be critically examined, however, typical gradings from two sites are shown in Fig. 5.14 and 5.15. The break in the curves can be seen to be around 0.2 mm diameter but the grading of the fine fraction of the Dunans sample does not appear to conform to the log probability law. This may be a sampling error and with only two samples no further investigation of this type of soil was possible.

The brown/yellow tills from Cowal were found to be very uniform in nature. The range of gradings at the various sites were as shown in Figs. 5.16 to 5.20 and the average gradings have been plotted in Fig. 5.4 together with the largest range of gradings found. From frequency and log probability plots, the split point was taken as 0.6 mm and the coarse and fine fractions separated at this diameter. As the coarse fraction is greatly influenced by the maximum particle size included in the grading analysis, the uniformity of the coarse fraction was established for these materials on particles less than 20 mm diameter. The coarse and fine fractions deduced in this manner are given in Figs. 5.21 to 5.25. The spreads of the sizes in these fractions are given in Fig. 5.26 on the basis of median (Md), upper (Q_3) and lower (Q_1), quartile sizes. The three digit grain size indices and textural classifications are given with the range of percentage fines in Table 5.1.

5.4.2. Scotland North Forestry Conservancy - Corrour Forest.

The grading of the tills from the Fersit and Ghuilbinn roads and the Strathossian Way are as shown in Figs. 5.27 to 5.29. The frequency curve of sample 1 + 2600 Fersit Road is shown in Fig. 5.30 as a typical example of the tills in this area. The split point for the tills in Fersit Road was found to be 2.0 mm, Fig. 5.31, while the tills of the Ghuilbinn Road and Strathossian Way were split at 0.8 mm diameter, Figs. 5.32 and 5.33 respectively.

Textural classifications based on the median, upper and lower quartile size were determined as shown in Figs. 5.34 to 5.36. The coarse fractions in these tills were analysed on the basis of a maximum size of 100 mm. The three digit grain size indices and their classifications together with the range of percentage fines in the soils are given in Table 5.1.

5.4.3. Scotland North Forestry Conservancy - Glen Garry Forest.

The grading of the tills from the Glen Kingie Forest within the above forest area are shown in Figs. 5.37 to 5.39. The frequency of sample No. K12 is given as a typical example in Fig. 5.40. The split in the grading was taken as 0.4 mm diameter and the coarse and fine fractions so determined are given in Fig. 5.4. to 5.44.

Textural classification based on Q_1, Md and Q_3 is shown in Fig. 5.45. The three grain size indices of the fine fraction and coarse fraction, (maximum size 100 mm diameter), are given in Table 5.1, together with classifications, according to BS 1377 and the Modified Wentworth Scale and the range of the percentage fines.

5.4.4. Scotland West Forestry Conservancy - Strathyre Forest.

The gradings of the tills from the above area are shown in Fig. 5.46. A typical frequency curve, for sample No. 7 is given in Fig. 5.47. The split in the grading was taken as 0.4 mm diameter and the fine and coarse fractions so determined are shown in Figs. 5.48 and 5.49. The maximum grain size included in the analysis is again 100 mm diameter. The textural classification plot is given as Fig. 5.50. The grain size indices and other textural classification data are given in Table 5.1.

5.4.5. Scotland West Forestry Conservancy - Glen Orchy Forest.

The grain size distribution of the tills in the above area are given in Figs. 5.51 to 5.54. A typical frequency curve is given in Fig. 5.55 and the split point taken as 0.2 mm diameter. The coarse and fine fractions are given in Figs. 5.56 to 5.59 and the textural classifications based on Q_1, Md, Q_3 are given in Fig. 5.60. Data relating to the textural classification are given in Table 5.1.

5.4.6. Scotland South Forestry Conservancy - Glen Trool Forest Park.

The grain size distributions of the Cairn Edward Forest (Bennen Section), Garcroggo Forest and Garraries Forest are given in Figs. 5.61, 5.62 and 5.63 respectively. A typical frequency curve is given in Fig. 5.64. The split points for the Bennen tills was 0.6 mm diameter, for the Garcroggo till it was 0.3 mm diameter and for the Garraries till it was 0.9 mm diameter. The coarse and fine fraction so defined for a maximum size of 100 mm diameter are given in Figs. 5.65, 5.66 and 5.67. The textural classification plots of the three areas are given in Figs. 5.68 to 5.70. The textural classification data are given in Table 5.2.

5.4.7. Backwater Dam.

The gradings of the upper silty till at the dam site are shown in Fig. 5.71. The range of gradings on a log probability plot is given in Fig. 5.72 and the split point can be seen to be 0.2 mm. The fractions coarser and finer than the split point are given in Fig. 5.73 and the Q_1, Md and Q_3 plots are given in Fig. 5.74, both plots based on a maximum particle size of 40 mm.

The gradings of the till from the north borrow pit, the principle source of the dam materials, are given in Fig. 5.75. A typical frequency diagram is given in Fig. 5.76 and the sudden change in population characteristics at 0.2 mm can be seen. Log probability plots also give a split point around 0.2 mm, thus the coarse and fine fractions have been determined using this size as in Fig. 5.77, and their Q_1, Md, Q_3 sizes plotted in Fig. 5.78. In fact a very close similarity exists between the till grading from the dam site and the north borrow pit. Detailed data of these tills are also given in Table 5.2.

5.4.8. Discussion on Textural Variations in Scottish Tills.

The Scottish tills all showed a definite change in the slope of their grading curves when plotted on semi logarithimic paper. This split in the grading sometimes developed into a gap indicated by a near horizontal line. The split or gap occurred in the sand size fraction; Tables 5.1 and 5.2.

When the particle size distributions of the tills were plotted on log probability paper, two or more straight lines linked by short transition curves were obtained. The log-probability plots so determined are typical of hetergeneous, multi-modal particle size distributions and confirm the tills to be the direct products of comminution. In addition the point at which the split in the grading occurred could be more closely identified from these plots.

Further analyses also lead to the following conclusions:

a) The parent distributions do not generally overlap greatly and so the split point or mid-gap on the grading curves may be used as the separation point for two fractions to be utilised for identification and testing purposes.

b) The coarse soil fractions, range in grain size distribution from very large boulders down to the sizes at the splits, which are usually in the sand size range. The maximum size of particle included in the testing was, however, rarely more than 100 mm thus it is likely that the coarse soil fractions tested and presented in the plots are not representative. Maximum size limits of 20 and 40 mm diameter were thus frequently adopted in the plots to assist in establishing the variability of the coarse fraction in at least a limited manner. The variability of the coarse fraction is then not found to be any more significant than variations in the fine fractions as seen in the Q_1, M_d, Q_3 plots. Further analysis of the coarse fraction beyond this was not considered to be worthwhile and further analysis of the coarse fractions will not therefore be undertaken for the foreign tills investigated later.

c) The fine soil fractions range from the sand grain sizes of the split down to silt or clay sizes. The possible variations in engineering properties of these fine fractions are thus greater than those for the coarse fractions. Also it will be shown later that the fine fractions often dominate the structural and engineering properties of the tills, thus the identity of the fine soil fractions may be taken as a possible basis for a system of classification for geological and engineering purposes.

From all the data it may be seen that there is generally a very low clay content in these Scottish Tills. Backwater till is, in fact, exceptional in this respect with clay contents up to 30 per cent, the badly weathered and fractured nature of the bedrock may have influenced this. All the other tills could reasonably be grouped into one as shown in Fig. 5.83.

d) The percentage fines in the Scottish tills was very variable within and between tills, using a maximum particle size of 100 mm diameter. Glen Orchy and Garcrogo Forest tills had very low percentage fines content, 5-25 and 9-35 per cent respectively, while the others had never less than 20 per cent fines. The average for Glen Orchy till was 14 per cent and for the Garcrogo till 25 per cent, otherwise the average percentage fines was never less than 30 per cent and most frequently it was between 40 and 50 per cent.

Thus the Scottish melt out tills have been shown to be the direct products of comminution and may be described as split or gap graded soils with the break in their gradings occurring in the sand size range. They have an average percentage fines content generally in excess of 30 percent, with a maximum particle size of 100 mm in the composite soil, but exceptionally the percentage fines can reduce to very small proportions. The fines content is in any case very variable within and between tills. The nature of the fines is generally a mixture of fine sands and silts and within any particular deposit a remarkable degree of gradational uniformity in the fines is exhibited. In fact, only Backwater Dam till contained a significant but somewhat variable clay content.

5.5. TEXTURAL VARIATIONS IN MODERN TILLS STUDIED.

5.5.1. Breidamerkurjokull, South East Iceland.

The tills from the central and western study sites were found to be an admixture of glacio-fluvial gravels, melt out tills and lodgement tills. Fig. 5.84 shows the gradational variation in a number of the samples tested. All exhibit a very low clay content. The varying proportions of silt and sand together with the variations in shape of the grading curves are not consistent with the pattern established for the Scottish tills. Plots on log probability paper do not give straight line portions as was the case with these other tills and frequency plots are complicated and non-uniform. Therefore, these tills not being the direct products of comminution are not obeying the log-normal distribution, as might be expected. Since the proportions of till and fluvio glacial is likely to vary at any sample point the overall gradation is likely to vary in detailed composition. The finest fractions are also likely to be from the tills thus the low clay content is consistent with the findings from other melt out tills at least in this respect.

5.5.2. Blaisen, Hardangerjokulen, Southern Norway.

The gradings of the till samples taken at the above glacier are shown in Fig. 5.85. The samples were taken during the summer of 1972, thus samples B/72/C,D,E were fresh tills, in fact B/72/D was sampled while still frozen beneath the edge of the glacier. The maximum size of particle in the samples tested was normally 75 mm, however, the maximum size in B/72/D and B/65/C was only 40 mm. It thus appears that B/72/D in particular is finer than the other samples however, when the others are adjusted to 40 mm maximum particle size this is clearly not the case. The gradings of the 1972 till and those from 1970 and 1965 are very consistent which suggests that over that period no significant general wash out of fines occurred during or after placement of the tills. Local wash-out of fines may, of course, have occurred at any time.

A typical frequency distribution chart is given in Fig. 5.86 and the full range of gradings together with a typical curve are given on a log-probability plot, Fig. 5.87. Both these plots indicate a split point at 0.12 mm. Fig. 5.88 shows the variations in the coarse and fine fractions obtained from splitting on the 0.12 mm diameter and the high degree of uniformity in the grading of the soil fractions is apparent. Fig. 5.89 shows the Q_1, Md, Q_3, plot and the classification and grain size indices of the tills are given in Table 5.3.

5.5.3. Lacroix Glacier, Taylor Valley, Antarctica.

The one sample taken from the Lacroix Glacier possessed the grading presented in Fig. 5.90. The log-probability plot of the curve is given in Fig. 5.91 and the break point is seen to be 0.095 mm. On this basis, the coarse and fine fractions were derived as in

Fig. 90 and classified as in Table 5.3.

5.5.4. Discussion on Textural Variations in the Modern Tills.

The inclusion of glacio-fluvial deposits in the Icelandic tills greatly influenced their gradational variations and they did not, therefore, obey the log-normal distribution. The Norwegian tills were, however, found to be the direct products of comminution and a high degree of uniformity was evidenced in the coarse and fine fractions of these tills. The Antarctic sample also appeared to be the direct product of comminution. The triangular textural plot of the Norwegian and Antarctic tills are shown in Fig. 5.92.

Further consideration of the coarse and fine fractions of the Blaisen and Antarctica tills confirms their general nature to be very similar to the Scottish tills. The split sizes are again in the sand size range with the percentage fines content in both, within the range determined in the Scottish tills. The percentage clay fraction in both is, however, higher than in the Scottish tills other than Backwater Dam till.

5.6. TILLS IN NORWEGIAN DAMS.

5.6.1. Norwegian Till Gradation Data.

From the data in the internal reports obtained from the Norwegian Geotechnical Institute, Sande (1973), the ranges and typical gradings used for testing of tills used in fourteen dams are given in Fig. 5.93 to 5.103. The log probability plots for a maximum particle size of 20 mm are given in Figs. 5.104 to 5.106 and the average coarse and fine fractional gradings determined from these are given in Fig. 5.107 to 5.109. The classifications of the fine fractions and the grain size indices are given in Tables 5.3 and 5.4. The Q_1, M_d, Q_3 and ternary diagram plots of the fine fractions are given in Figs. 5.110 and 5.111 respectively.

5.6.2. Discussion on Textural Variations in Norwegian Dam Tills.

The gradings of the tills used in Norwegian Dams and analysed in this section all exhibited a split or gap, the basic characteristic of direct comminution products as discussed in Chapter 3. The split in the gradings always lay within the sand size fraction, just as has been found previously for Scottish and Modern tills. The range of percentage fines, with a maximum size of 20 mm diameter in the composite soils, lay between 14 and 83 percent and was variable within and between tills as before. The average percentage fines was found to lie between 35 and 62 percent which is similar to the general pattern of previously investigated tills. The coarse soil fractions were again composed of coarse sands and gravels and no detailed investigations were therefore conducted into their nature. The nature of the fine fractions was, however, analysed and although they were generally classified according to B.S. 1377 (1967) as sandy silts, some fines contained significant clay contents. From Figs. 5.110 and 5.111, two or perhaps three groups of till fines can be identified. Tills from Dams 2, 18, 21, 24, 51, 52, 55, 56 and EX1 form one grouping while, 7, 12, 13 and 17 form one or perhaps two other groupings, (7 and 13 as one group with 12 and 17 as another or 7, 12 and 17 as one group with 13 on its own). The first grouping marked Group A in Fig. 5.11

is very similar to the majority of Scottish till fines, shown in Fig. 5.8.3, but Groups B and C, indicated in Fig. 5.111, are somewhat finer than these or the Backwater tills but resemble the Blaisen till, Fig. 5.92, which is of course another Norwegian till.

Thus all the tills from the dam sites investigated obeyed the log normal distribution. As with the other tills so far studied, their clay contents were in the main rather low. A few had significant clay contents but no consistent geological nor geographical explanation is apparent for these. Within themselves and between each other these tills are again remarkably uniform in character when analysed as coarse and fine fractions. The estimated break points again all lay within the sand size fraction.

5.7. CANADIAN TILLS.

5.7.1. Canadian Dam Sites.

From the data given by McDonald et al (1961), for fills used in Canadian dams, the semi log plots of the particle size distributions of some Canadian tills are given in Figs. 5.112 and 5.113. Log probability plots of these data are also given in Figs. 5.114 and 5.115. Using the split points determined from these plots, the fine fractions have been established as in Fig. 5.116. The ternary textural classification and Q_1, Md, Q_3 plots of these fines are given in Figs. 5.117 and 5.118. The detailed classifications of the data are given in Table 5.5. No classification or detailed analysis of the coarse fractions has been carried out as the maximum size reported in each soil was different and comparisons may therefore be quite misleading. No data on the lithology was available either.

A detailed report of the till used in the construction of the Shand Dam, No. 18 in list given by McDonald et al (1961), has previously been given by Leggett (1942). With the exception of a small area to the south west of the dam-site, the rock of the surrounding area is known to be dolomite and it is to be expected that the tills will be predominantly derived from this. The range of particle size distributions of this till is given in Fig. 5.119 and the log-probability plots are shown in Fig. 5.120. Using the upper split point of 9.3 mm, the fine fractions are as shown in Fig. 5.121. The ternary and Q_1, Md, Q_3 plots are as shown in Figs. 5.117 and 5.118 respectively. The classifications of the fine fractions are as detailed in Table 5.5.

5.7.2. Other Canadian Tills.

Dreimanis and Vagner (1965, 1969, 1971) and Dreimanis (1969) have studied in detail the lithologic relationships of tills to bedrock in Ontario, including consideration of the granulometric compositions of these tills. Dreimanis (1969) plotted the granulometric composition of the tills from Southern and Central Ontario on Rosin and Rammler's plots, an example of which was shown in Fig. 3.7. Frequency distribution plots were also given, as is shown in Fig. 5.122, and the multi-modal particle size distribution of these tills can be clearly seen. These data have been replotted in Figs. 5.123 and 5.124 on log probability paper and they confirm the tills to be the direct products of comminution. Also the fine fractions have been plotted in Figs. 5.125 and 5.126 the coarse fractions not being vital to this investigation they have been ignored. The ternary and Q_1, Md, and Q_3 plots are given in Figs. 5.127 and 5.128. No detailed classification of the fine fractions of general plots have been made only the Dolomitic tills have been so classified and the data is given in Table 5.6.

In connection with the construction of the Montreal-Laurentian Autoroute, detailed investigations of the geotechnical properties of the tills forming the moraines through which the roadline passed, were carried out around Lachine, on the Southern outskirts of Montreal. Details of these investigations have been provided by Audy (1970). Figs. 5.129 and 5.130 show the granulometric variations of the moraine in the Ville la Salle and Ile Herons, River Nord Sections respectively. Fig. 5.131 and 5.132 show the log-probability plots and the variations in the split points around 0.03 and 0.04 mm respectively. Taking these as the average split points, the fine fractions have been replotted as in Fig. 5.133 and represented on the ternary and Q_1, Md, Q_3 plots in Figs. 5.134(a) and (b) respectively. Detailed classification of the fines are given in Table 5.6.

5.7.3. Discussion on Textural Variations in Canadian Tills.

Once again all the tills investigated were found to be the direct products of comminution in so far as they all produced two or three straight line plots on log-probability paper. The split points were, however, spread over both the sand and the silt size ranges. In particular, Dams 6, 7, 8 and 9, the Ville la Salle and Ile Heron tills all exhibited breaks in the coarse silt size range. Also the till from the Shand Dam exhibited two breaks, the lower of which was in the coarse silt size range. It may be that some of the other tills from the Canadian Dams also have tri-modal distributions, but the averaging and transferring of data from McDonald et al (1961) has possibly obscured this.

The range of percentage fines is, as stated previously, difficult to compare, because the upper size limit is not a constant for the data, however, in general the percentage fines noted from the gradings curves is quite high. If data with a maximum of 100mm diameter size were available it is most probable that the percentage fines would be in line with the data obtained for the Scottish tills.

The coarse soil fractions are again sandy gravels and no detailed analysis of their characteristics has been undertaken. The fine fractions from all the Canadian sites are in fact, more comparable with the Norwegian data than with the Scottish data, many tills having significant clay contents. For the dam tills, there are three groupings, the first, Group D, Fig. 5.117, falls into the same category as Group A, Norwegian Dams, 5.111, and the majority of the Scottish tills, Fig. 5.83. Group E of the Canadian Dams would include Norwegian Groups B and C and overlap somewhat the Scottish Backwater Dam tills, Group F of the Canadian Dams is finer than any of the previously investigated tills and compares only to the Sedimentary Rock Grouping of Dreimanis, indicated in Fig. 5.127. The Ville la Salle and Ile Heron tills are comparable with Group E Dam tills, with Ile Heron tills perhaps somewhat more silty. Dreimanis's dolomitic tills also have quite similar gradings to Group E dam tills but particularly the 77% Dolomite till has a very low clay content.

In the main then, the Canadian tills are comparable to each other and to the tills previously investigated. By virtue of the wide geographical and likely wide lithological range contained in the tills analyses, the spread of results is quite reasonable. Although some of the tills have break points outside the sand size range, the breaks are contained in the coarse silt sizes and this again seems reasonable and compatible with previous determinations.

5.8. KRUMBEIN'S VALPARAISO AND ILLINOIS TILLS, UNITED STATES.

Of the numerous reports of the textural and lithologic variations in the tills from Illinois, Indiana and Michigan, in United States, the most extensive and most fundamental work was carried out by Krumbein (1953). This study has therefore been used for re-analysis in the present investigation.

The sampling area of Krumbein's study, was as shown in Fig. 5.135. Those parts of the moraines directly involved in Krumbein's study are shown in solid lines; adjacent field relations are indicated for the purposes of orientation. The Valparaiso moraine trends at right angles to the direction of the ice sheet that deposited it, and was thus chosen by Krumbein to study variations in the till with lateral extent, (Samples 1 to 24). The north-south line of sampling lies in the direction of ice flow and was used to study variations in the tills along the ice flow direction, (Samples

A to W).

5.8.1. Reported Variations of the Valparaiso Tills.

Twenty four samples of till from localities near the margin of the Valparaiso moraine,Fig. 5.135, were collected and analysed. The samples were separated by intervals of from 6.5 to 16 km (4 to 10 miles), with an average interval of 11 km (7 miles). They were collected from the distal half of the moraine, and most of them were secured within a mile of the distal edge.

Krumbein observed that the till comprising the moraine underwent several striking changes as the moraine was followed along its extent. In its north-western part, near Elgin, the moraine was composed almost entirely of a limestone gravel, and no exposures of clayey till were noted. Nevertheless, the moraine preserved its hummocky topography, and the material appeared to be largely unbedded. South of this, the till became more clayey in its appearance, and this condition persisted without noticeable change until the Indiana state line was crossed. Near Valparaiso the moraine became quite sandy over large areas, with here and there a small area of typically clayey till. The sandy material was apparently unbedded, and preserved the form of hummocky moraine but it did not resemble typical till. East of Valparaiso the sandy nature of the material increased, and the morainic edge became more elusive, with wide flats extending for considerable distances into the moraine, giving the outer edge a peculiar finger like pattern. Drainage ditches disclose that the flats were composed of gravel, and the morainic fingers that separated them were often quite sandy but structureless. Even here, however, small areas of clayey till were found. Farther east, beyond La Porte, the morainic edge became more distinct again, and the till assumed a more clayey character, although lenses of sand and gravel were not uncommon. In Michigan, southeast of Benton Harbor, the sandy and gravelly phases again predominated but there were also found scattered areas of clayey till.

5.8.2. Textural Variations in the Valparaiso Till.

The semi-log plots of the till gradings are given in Figs. 5.136 to 139. The log probability plots are given in Figs. 5.140 to 143. The range of the fine fractions determined from these plots are shown in Fig. 5.144 and the detailed grain size indices are plotted in Fig. 5.145 and 5.146. The triangular plot, Fig. 5.147 shows the range of the till fines texture and Tables 5.7 to 5.9 give the detailed classification data for the soils.

All the tills except Sample 22 were found to be split-graded comminution products with the split size generally in the coarse silt size range. The clay content of the fines ranged from 18 to 38 per cent and all the split graded materials were found to be tri-modal, the lower split being in the fine silt range. The samples exhibited fairly uniform fine fractions with possible finer materials in the fine fractions of samples 11, 23 and 24 than the others and coarser than average in samples, 8, 13 and 14. The variations do not entirely correspond to lithologic variations, as detailed in Fig. 5.148. The nature of the fines fraction does not vary in step with the variations in physical appearance as described in Section 5.8.1. but as can be seen in Fig. 5.149 the percentage fines varies exactly in accordance with Krumbein's description i.e. clayey appearance of tills in area of Samples 5 to 11 and sandy appearance of Samples 15-16 etc. Thus it appears that minor variations in the fine fraction of the till occurred but that the changes in percentage fines were the dominating visual feature and overall gradational influence in Krumbein's analysis.

5.8.3. Reported Variations of the Illinois Tills.

Twenty three samples of till were taken by Krumbein in the approximate line of glacial movement, Fig. 5.131. The samples were taken from parts of the moraines not directly associated with outwash channels in order to avoid complexities arising from drainage factors affecting the composition of the tills.

Krumbein suggested that the overall gradings of the tills fell into three groups. The first group comprised Samples A to I which were the coarsest tills. The middle set of gradings comprised Samples J to O and the third group containing the finest soils, included Samples P to W. Thus he implied that there were three types of till included in this study, and referred to these by their relative geographical locations as "Southern", "Middle" and "Northern" tills. The boundary between the first and second groups was found to coincide with groups of moraines but overlap existed in this respect with the second and third groups.

Krumbein also suggested the very coarse nature of samples A and B as possibly being due to ice-margin drainage. Nevertheless he maintained the groupings of the various tills as before and correlated at least the division of the Southern and Middle tills with changes in pebble lithology. The division between Middle and Northern tills he did not find to be entirely compatible with changes in pebble lithology or bedrock. He therefore suggests that the tills may in fact be admixtures of glacial lake clays, other glacio fluvial materials and direct comminution products which therefore have influenced the textural characteristics of the tills.

5.8.4. Textural Variations in the Illinois Tills.

The semi log plots of the tills gradings are given in Figs. 5.150 to 5.154. The log probability plots are given in Figs. 5.155 to 5.159. The range of the fine fractions determined from these plots are as shown in Fig. 5.160 and the detailed grain size indices are plotted in Figs. 5.161 to 163. The triangular plot of the fine fractions grading is as shown in Fig. 5.147 and the detailed classification of the fines is given in Tables 5.10 to 5.12.

All the tills except Sample I were found to be split graded and so direct comminution products, with the split size varying from the fine sand to coarse silt sizes. The clay content ranged from 15 to 39 percent and all the split graded materials were shown to be trimodal, the lower split being in the fine silt size range as in the Valparaiso tills.

The samples exhibited gradually finer fractions from A to P in reasonable agreement with a gradually increasing siltstone/shale content, Figs. 5.164 and 5.165. Additionally the percentage fines changes dramatically between Samples H and J and again between O and P with quite large variations occurring from J to O. The groupings are identical to those of Krumbein's Southern, Middle and Northern tills. Thus once again the percentage fines rather than the nature of the fines appear to agree with Krumbein's interpretation of the variations in the tills.

5.8.5. Discussion on Textural Variations in Krumbein's Valparaiso and Illinois Tills.

For the Valparaiso tills, Krumbein suggested that, with the noted exceptions of Sample numbers 4, 15, 16, 22, 23 and 24, the tills appeared to deviate in a non systematic manner but within certain limits, from a mean composition. He also stated that they had very irregular distributions which with the additional presence of several secondary maxima rendered then polymodal. Such polymodal curves he considered, were due to a mixture of several distributions behaving under different laws and contributed to by the materials picked up by the ice in its forward movement.

In many respects these observations are absolutely in agreement with the observations made in Sections 5.8.2. and 5.8.4. on Krumbein's data following re-analysis. The samples excepted by Krumbein are, however, noteworthy. Sample numbers 4, 15, 16 and 23 he discriminated on the basis only of their larger percentage coarse fraction. The present analysis shows them to be split graded tills similar to the others, but with significantly greater coarse fractions. Sample 22 he considers to have lost some fines by washing out and the present analysis confirms that the till does not plot as straight lines on the log probability paper and is therefore not the direct product of comminution. Thus Krumbein's deductions could be correct. Sample 24, he noted had an unusual silt content and this is clearly shown in Fig. 5.143, where a distinctly different split size and grading is exhibited by this till. Consideration of Fig. 5.148 which lists the percentage pebble lithology, shows a uniquely large amount, 23.3 percent, of miscellaneous rock types. It is likely that the particular lithological character of the sample has evidenced itself in a characteristically different grading which would indeed explain the unusual silt content noted by Krumbein.

The relationship between the bedrock and the lithological and textural composition of the Valparaiso tills was rather complex in Krumbein's view and the present analysis does not simplify it in any way. One factor which must be considered, however, is that the full depth of till was not always the result of a single glaciation, therefore the bedrock would not have been exposed at all points beneath the glacier. The dynamic equilibrium of ice erosion and deposition might therefore have been interrupted at several points. This is confirmed by the fact that the position of the intersection of the Limestone and Shale curves indicated in Fig. 5.148, takes place some sixty kilometres west of the contact of the two bedrocks, i.e. the bedrock is limestone under some sixty kilometres of till which has predominantly shale and silt stone pebbles. The possible interruption of dynamic equilibrium in the glacier could therefore have caused a more or less uniform till fines composition to be deposited except where there was a significant crystalline rock content where the split size, Q_1, M_d, Q_3 values all showed an increase in phi values. Whilst the composition of the fines was consistent, the percentage fines varied greatly, indicating that the factor controlling the split size Q_1, M_d and Q_3 are different from these controlling the percentagesfines in the tills.

For the Illinois tills, Krumbein suggested that three groups were clearly distinguishable the Southern, Middle and Northern Groups. He considered the distinction between the Southern and Middle Groups was very clear but that between the Middle and Northern Groups, the difference was much less marked. The bases of Krumbein's differentiations are the changes in lithological content and the overall gradation characteristics. As can be seen in Fig. 5.165, it is the percentage fines which changes most dramatically, and in sympathy with Krumbein's observations. As stated previously, the percentage fines may be associated with visual coarseness and overall grading, on which factors Krumbein's assessments were made. These alone would not, if the basic premise of the study is correct, substantiate his case, however, Krumbein's assertions are also borne out by the nature of the fine fraction as evidenced by the variations in split size, Q_1, M_d and Q_3, values indicated in Fig. 5.165. The three groups show more or less different grain size indices with the Northern Group the finest and the Southern Group the coarsest. The distinctly different trend of the variation in the grain size indices from the percentage fines variations are, however, once again evidenced and the possibility of different factors controlling them is further indicated.

The relationship between bedrock, lithological and textural variations is complex in this till series when taken in the direction of glaciation, as in the Valparaiso tills, or taken transverse to the direction of glaciation, Illinois till, and no clear correlations are evidenced. This, as most of the other observations have been, is in agreement with Krumbein's assessment. The present approach differs nevertheless in the assumptions made towards the final conclusions, in particular Krumbein's assumptions that local wash out of fines and inclusion of old sediments were the principal causes of variation in the till gradings is not made. The present study asserts that the variations in the tills are directly associated with their glacial mode of formation and that the data from these tills is generally compatible with that obtained from the various other tills analysed. In fact, these tills are very similar to those previously analysed from Canadian Dam Numbers 6, 7, 8 and 9.

5.9. DISCUSSION AND CONCLUSIONS.

a) The present analysis has shown that Scottish, Norwegian and North American Pleistocene tills have with few exceptions all showed a definite change in the slope of their grading curves when plotted on semi-logarithmic paper. A similar characteristic has been noted for a modern till from Hardangerjokulen in Norway and for the small sample of Antarctic till investigated. The modern Icelandic till from Breidamerjokull did not conform to the pattern but it was known to be an admixture of fluvio glacial materials and tills and not the direct product of ice comminution.

b) On plotting the size distributions on log probability paper two and sometimes three straight line portions of the curves were obtained perhaps linked by short transition curves with the plots always curving asymptotically to the upper size cut off in the sample. These plots have been shown to be typical of heterogeneous, multi-modal particle size distributions obtained from materials which are the direct product of comminution. By comparison of the nature of the grading curves obtained for the tills to those obtained by industrial crushing of various materials, as outlined in Chapter 3, it is suggested that the parent distributions in the composite soil gradings do not overlap greatly therefore the split point or points in their gradings may be used as the separation point for the various parent populations.

c) Consideration of the various particle sizes at which the separation of the parent populations occurs has shown that a high proportion are to be found in the sand size range, 0.06 to 2.0 mm. Indeed if only the upper break point in trimodal distributions are considered, all break points occur in the coarse silt to coarse sand size range, 0.02 to 2.0 mm. Fig. 5.166 shows the variation of the upper split or break sizes for all the sites considered. A feature of this plot is the fact that no pattern emerges of particular rock bed types influencing the split size. The lithological data is by no means detailed but this finding coincides with Krumbein's (1953) comments on the lack of influence of lithological variations in the Valparaiso till.

The factors controlling the split sizes in tills cannot be investigated in detail without an in depth study of the englacial regime of the till and such factors as the particle shapes, mineralogical character and perhaps surface energy in the various size ranges. Only by such a study could it be determined if, as Jarnefors (1952) suggests, the change in grading is due to a change from complex, poly mineral, to monomineral particles. It seems on the basis of the uniformity of the split sizes, however, that the hypothesis of Elson (1961) is more probable. He suggests that rock from the outcrop, can either become englacial or be subjected to further comminution at the base and that in either event the debris produced should have the particle size distribution of a crushed rock. He then states that sands and finer particles created in the initial crushing will not be further reduced as they will collect in globules of water within and between ice crystals and as wet coatings on pebbles and larger stones, the fines maintaining their environment of water by virtue of their surface energy. The lithological nature of the particles could very well influence surface energy to some extent but no absolutely critical influence would be operating, therefore as is found, the split size would remain essentially in the sand size grade. Most probably both Jarnefors and Elson are to some extent correct and that both phenomena are operating in glacial comminution. Accepting that these factors apply to the upper break point, then the development of a lower break point in trimodal distributions can be attributed to similar differences in particle crushability occurring at a lower size range.

d) The percentage of the fine fraction in the various tills is shown in Fig. 5.167. It must be recognised that the maximum size included in composite soils was not always the same and that these data are not all directly comparable, nevertheless, the very large variations in percentage fines in the tills are clearly seen.

From the detailed study of Krumbein's Valparaiso and Illinois tills it is known that the percentage fines are not associated with local variations in lithological content. From the investigations in Cowal it is known that very large changes in percentage fines can be found very locally. It is in fact suggested that the percentage fines in the composite till is controlled by very local variations in the crushing activity of the glacier. If as Drake (1972) suggested on the basis of his studies of particle shapes in tills, that the crushing in the glacier is a continuous process and that rock fragments are successive crushed, then the local variations in percentage fines may be due to variations in the continuity of crushing at different points within the glacier or due to differences in the bed load and so the ability of the glacier to crush down varying amounts of rock fragments in the time, or better the transport distance, available to it.

A further point that should be noted in Fig. 5.167 is that apart from two sites, Glen Trool (Garcrogo) and Glen Orchy, all tills have average percentage fines of 30 or more per cent. The majority of the tills in fact have average percentage fines in excess of 45 percent. The data are important in later chapters when the relative dominance of the coarse and fine fraction in the tills are considered.

e) The coarse soil fractions in the soils ranged from boulders down to the split size in the gradings or at least from the maximum size included in the testing down to the split size. Investigations of the nature of these fractions showed them to be no more variable than the fine fractions in the soils.

f) The nature of the fine fractions has been described in detail in Tables5.1 to5.12 but for ease of comparison Figs. 5.168 and 5.169 have been constructed to show respectively the median grain size indices of all the tills and their distribution in the triangular diagram. Firstly the previous analysis in this chapter has shown that a high degree of uniformity of the fine fraction for both modern and Pleistocene tills exists at any one site. Yet between sites fairly large variations in the nature of the till fines has been found. This is evidenced both by their median sizes in Fig. 5.168 and by their spread in the triangular diagram in Fig. 5.169. However, particularly, Fig. 5.169, shows that the fines are essentially sandy silty materials with some clay sizes sometimes to be found.

Comparison of the limited data on the lithological content of tills with the nature of the fines suggests little correlation exists between them. The influence exerted by lithology may be strong, indeed if the terminal grade hypothesis of Dreimanis and Vagners (1965) is accepted then it must be, but when the nature of the fines are considered as a whole, other factors must be considered. From the analogy with industrial crushing it is obvious that a sufficient amount of crushing must be applied if a load of stone is to be broken down fully in the crusher. The glacier, is not a fixed crusher but a crushing system in dynamic equilibrium such that material is continuous being added to the system, processed and possibly recycled. The fines produced may then either be separated out into globules of water or they may alter their grindability, with the result that they are maintained within a fairly restricted range of sizes and size frequencies.

For any particular glacial circumstance the materials melted out to form the till must be an intermediate product and not the fully broken down ultimate product. They will contain some terminal grades and some materials in process of being broken down to these. As many of the terminal grades suggested by Dreimanis and Vagners (1969) are in similar size ranges then the tills produced by different rock types may appear similar to each other depending on the details of the glacial comminution process to which each was subjected. Another lithological or mineralogical property influencing the nature of the fines may however be the surface energy characteristics of particles in the various size ranges. The electrical state of the water surrounding these particles would also be important. The picture is thus complex and leads therefore to the confused pattern of till fines formed from the various rock types.

g) Thus the variability of the gradings in basal melt out tills although large is systematic and directly related to their mode of formation. As previously discussed in relation to Krumbein's (1953) observations the variation in the percentage fines in these multi-modal tills is the most significant factor in the variation of overall grading, and is also the factor which gives a visual appreciation of in situ variability. But by considering the material as two size fractions, all be they mixed in widely varying proportions the inherent uniformity of the size fractions present may be detected. Application of the log normal laws to these tills in fact permits the easy identification of the size fractions.

The use of grain size indices to characterise their gradings proves to be very useful for the purposes of comparing them. No direct correlations have, however, emerged between the nature of the fines, split sizes or percentage fines and the lithological variations in tills but this has been explained by the nature of the formation process.

CHAPTER 6. PARTICLE ORGANISATION IN BASAL MELT OUT TILLS.

6.1. THE PHYSICAL PROPERTIES OF TILLS COMPOSED OF TWO SIZE FRACTIONS.

It has been shown that the particle size distribution of basal melt out tills produced by primary comminution is frequently multimodal, the number and character of these modes being indicative of the properties controlling the fragmentation of the various rocks present in the different size ranges. The development of the several modes may vary from place to place within and beneath the same glacier so that the overall grading of the till produced is subject to variations in the component rock and fines contents. Essentially two size fractions may be distinguished, the multimineral rock fragments, the coarse modes, and the monomineral fine fractions, the fine modes. A range of conditions may therefore be envisaged, but three cases are of particular relevance to consideration of the physical and structural properties of tills. First, the finer mode, or modes may predominate so that it may be regarded as a matrix and the coarser mode or modes, as discrete particles within it. Second, the coarser mode, or modes may predominate, in which case the till may be regarded as a granular mass with a coating of fines or aggregations of fines occurring within the mass. In the third case, neither coarse nor fine modes, predominate and there is, therefore, a complex interaction of all sizes of particles. Owing to the textural variations that exist between and within tills, the nature and function of the fines varies. Moreover, with variation in the clay mineralogy, the bond between matrix and aggregate varies so that the physical properties of the size components also vary.

To assist in predicting the behaviour of these tills a soil model, comprising a coarse soil fraction and a fine soil fraction, with water and air filling the voids, has been postulated, Fig. 6.1. In establishing the soil model it has been assumed that the fine fraction of the soil at its maximum stable void ratio can exist within the voids of the coarse fraction when the latter is at its minimum possible void ratio and that the fractions are completely mixed one with the other. To satisfy the first assumption, the mean sizes of the fractions of a soil must be sufficiently different. The actual mean size difference required will not be a constant but will depend on a number of variable such as grain sizes, shape and gradation.

6.1.1. The Concept of Composite Soils.

A soil may be described as a composite soil if in a plot of the soil grading, for example in the standard semi-logarithmic plot, two size fractions are readily distinguishable one from the other. The mean grain sizes of the fractions must also be sufficiently different to allow the finer fraction to exist at its maximum stable void ratio, in the voids of the coarse fraction at its minimum possible void ratio, without increase in volume over that of the coarse fraction alone.

Composite soils will thus be split graded or gap graded soils which have sufficient difference in the mean particle sizes of the soil fractions finer than and coarser than the split or gap in the grading.

6.1.2. Physical Parameters for Composite Soils.

Now void ratio of coarse fraction alone $e_c = \frac{V_{vc}}{V_c}$

$$\therefore \; e_c V_c = V_F + V_v \; \text{.......... Eqn. 6.1}$$

Also void ratio of fine fraction alone $e_F = \frac{V_{vF}}{V_F} = \frac{V_v}{V_F}$

$$\therefore \; V_v = e_F \, V_F$$

$\therefore$ In Equation 6.1

$$e_c V_c = V_F \, (1 + e_F)$$

$$\therefore \; V_F = V_c \, \frac{e_c}{(1 + e_F)}$$

hence

$$\frac{M_F}{G_F \rho_W} = \frac{M_c}{G_c \rho_W} \, \frac{e_c}{(1 + e_F)}$$

Note:
ρ_W = Density of water

$$\therefore \; M_F = M_c \, \frac{e_c}{(1 + e_F)} \, \frac{G_F}{G_c} \; \text{..........Eq.6.2}$$

$\therefore$ Percentage by mass of the fine fraction relative to the total dry mass of the soil (%F) is :-

$$\%F = \frac{M_F}{M_F + M_c} \cdot 100$$

$$\%F = \frac{\frac{G_F}{G_c} \cdot \frac{e_c}{(1 + e_F)}}{1 + \frac{G_F}{G_c} \cdot \frac{e_c}{(1 + e_f)}} \cdot 100$$

$$\%F = \frac{e_c}{\frac{G_c}{G_F} \cdot (1 + e_F) + e_c} \cdot 100 \; \text{........Eq.6.3}$$

Also Void Ratio of the composite soil

$$e_s = \frac{V_v}{V_F + V_c}$$

$$= \frac{1}{\frac{V_F}{V_v} + \frac{V_c}{V_v}}$$

$$= \frac{1}{\frac{1}{e_F} + \frac{V_{vc}}{e_c V_v}}$$

$$= \frac{1}{\frac{1}{e_F} + \frac{1}{e_c} \frac{(V_v + V_F)}{V_v}}$$

$$\therefore e_s = \frac{1}{\frac{1}{e_F} + \frac{1}{e_c}\left(1 + \frac{1}{8_F}\right)}$$

$$\therefore e_s = \frac{e_c \cdot e_F}{(1 + e_f + e_c)} \qquad \text{........Eq.6.4}$$

From Equations 6.3 and 6.4 it can be seen that

if $\frac{G_c}{G_F}$ is unity then $e_s = \frac{e_F \%F}{100}$ Eq.6.5

Also dry density of the composite soil will be

$$\rho d = \frac{G_s}{1 + e_s} \times \rho w \qquad \text{........Eq.6.6}$$

and dry density of the coarse fraction only

$$\rho d_c = \frac{G_c}{1 + e_c} \times \rho w \qquad \text{........Eq.6.7}$$

and dry density of the fine fraction only

$$\rho d_F = \frac{G_F}{1 + e_F} \times \rho w \qquad \text{........Eq.6.8}$$

6.1.3. The limiting grain size difference.

The dependence of pore size and porosity upon the diversity of particle size in naturally occurring materials does not permit the simplifying assumptions of particles of mono-sized spheres and of their packing being an orderly arrangement. As yet, however, no completely general relationship has been formulated which includes the influence of particle shape, size and gradation. Of the many attempts made to include these factors one of the methods with the greatest degree of generality is that developed by Furnas (1931).

Furnas considered the optimum packing condition of mixtures of different particle sizes, in which the interstices between the larger particles were occupied by the smaller particles and consequently the voids in the soil mixture were less than the voids in the packings of the separate components.

To show how in a binary system of particles the voids change with the ratio of the particle sizes and with their percentage contribution, he considered a coarse aggregate of particle size, d_1, and a fine component of particle size d_2. The fractional void volumes in a unit of total volume of the bed for the coarse component was taken as V_1 and as V_2 for the fine component. The respective specific gravities were taken as G_1 and G_2.

It was also assumed that all the smaller particles pack into the interstices of the bigger particles without any increase of the bulk volume of the packing.

For the mass, M_1 of the larger component in unit of total volume of bed, then

$$M_1 = (1 - V_1)\, G_1 . \rho_w \qquad \text{........Eq.6.9}$$

Similarly, for the smaller size component, taken by itself we have

$$M_2 = (1 - V_2)\ G_2 . \rho_w \qquad \text{........Eq. 6.10}$$

Considering that the only space available for both the smaller particles and their voids is that part of the unit volume of the mixed packing which is not occupied by the larger particles then for the mixed packing:

$$M_2 = V_1\ (1 - V_2)\ G_2 . \rho_w \qquad \text{........Eq. 6.11}$$

Using these relations between the mass and voids of the two components, the composition of the binary system which will produce the closest packing may be given as:

$$Z_1 = \frac{M_1}{M_1 + M_2} = \frac{(1 - V_1)\ G_1}{(1-V_1)G_1 + V_1\ (1-V_2)G_2} \qquad \text{..Eq.6.12}$$

Furnas, by considering the actual values of voids, computed curves for the minimum voids in mixtures of two soils, of the same fractional voids volume, at specified ratios of the smallest to the largest particle size in the mixture, Fig. 6.2. It can be seen from the diagram that the voids decrease and the density increases the smaller the ratio of particle sizes, however, beyond a size ratio of 0.01 the decrease in the voids is small. Thus for a binary system of uniformly sized materials of equal voids volume, the critical size ratio below which little or no decrease in voids occurs, may be taken as 0.01.

This critical ratio may not of course be directly applied to naturally occurring gap-graded or split graded soils which have neither uniformly sized fine and coarse components nor equal voids volume. Nevertheless, Furnas's analysis does give some indication of the order of mean particle size difference of the fractions, required to allow the fines to occupy the voids in the coarse fraction without increase of bulk volume. From the data on Q_1, Md, Q_3 plots in Chapter 5 and coarse fraction gradings on other plots, it is possible to deduce the D_{50} sizes of the fine and coarse fractions in the tills and hence their ratios, as shown in Table 6.1. It is apparent that not all tills have mean particle size differences of 0.01 or less but they are all of this order and many are less. Therefore these tills are likely to act in a manner similar to that of the ideal composite soil.

The determination of whether a naturally occurring soil complies with the composite soil concept, the fractional dry densities of the components, at maximum density conditions, must be made experimentally for the range of percentage fines by mass in the mixture. If the fine fraction can exist at, or at less than, its maximum stable voids content within the voids of the coarse fraction at its minimum possible voids content without increase in the bulk volume, then the soil can be described as an ideal composite soil.

6.1.4. The Application of the Principle of Composite Soils.

To facilitate the determination of the fractional void ratios, the variation in these ratios with the percentage of fines by weight, for any void ratio of the soil mixture, may be plotted using Equations 6.1 and 6.2, as in Fig. 6.3. The fractional void ratio of any composite soil may then be determined as indicated on the diagram. Similarly, but with the additional use of Equations 6.3, 6.4 and 6.5, the variation of the fractional dry unit weights may be plotted. Fig. 6.3 has been so constructed for the condition that the specific gravities of the soil fractions are the same and equal to 2.68. The determination of fractional dry densities using the curves is as shown in Fig. 6.4.

From the equations derived in Section 6.12 or plots of the type described above, the fractional voids ratios of the fractions may be determined. If the fractional void ratio of the coarse particles is in excess of the maximum stable void ratio obtainable for these by themselves then it is postulated that the grains are not in contact but separated by a matrix of fines. Similarly when the fines fractional void ratio is in excess of the maximum stable void ratio, the fines are considered to act as separate particles in the voids of the coarse grains. Thus for any composite soil, the dominant fraction may be determined.

The assumption is made that the fines only exist within the interstices of the compacted coarse fraction until a critical fines content, when they separate the coarse particles and act as a matrix. This will not, however, apply to actual systems since at less than the critical fines content, fines will be caught between coarse particles and the shape and size distributions of the pores within a graded coarse fraction will be considerable. With a graded fines fraction also, interference will take place and the theoretical reduction in voids due to mixing of the two fractions will not be attained although the difference in their mean particle sizes is theoretically sufficient. With a fines content in excess of the critical, for the same system, the structure of the matrix will inevitably be subject to interference from the coarse fraction. In both cases this interference will increase towards the critical fines content and may be small enough to be ignored at high and low fines content.

6.2. TESTING THE CONFORMITY OF SPLIT GRADED TILLS TO THE COMPOSITE SOIL PRINCIPLE.

If split graded tills are ideal composite soils, then the fines may exist at their minimum stable dry density within the voids of the coarse fraction at its maximum dry density. Thus at maximum compaction conditions, over the range of percentage by mass of fine fraction, no change in the fractional dry density of the coarse fraction should occur until the fractional dry density of the fine fraction at least equals its minimum stable dry density. To establish to conformity or otherwise of split graded tills to this principle, the dry density of a Cowal till sample was determined in the loose and compacted states over the range of percentage coarse and fine fractions.

6.2.1. Test Soil and Test Procedures.

The soil gradings used in the tests are as shown in Fig. 6.5. The minimum dry densities of the soil mixtures were obtained by slowly pouring the mixture through air into a 150 mm diameter by 165 mm high container. As vibratory compaction methods were found to cause segregation of the size fractions, British standard compaction tests were carried out over the range of percentage fine fraction.

These tests were carried out in accordance with the procedures laid down in British Standard 1377 (1967), Test 11.

6.2.2. Test Results.

The test data are plotted on Fig. 6.6 in the form of optimum dry density for the compacted state and minimum dry density for the loose state against percentage fines. The data relating to the compacted state have been reduced for the fractional soils using the relationships derived in Section 6.1.2.

The fractional dry density of the fines in the compacted test is shown in Fig. 6.6 to be the same as the theoretical value from 100 down to 80 per cent fines. Below this down to 21 per cent fines, the composition at which the coarse particles theoretically come into contact, (termed the Critical Fines Content), the fractional density of the fines steadily reduces. This reduction continues at lower fines contents with the minimum stable dry density obtaining at 15 per cent fines. At lower fines content these particles can only partly fill voids in the coarse. The coarse fraction dry density is also shown in Fig. 6.6 to be the same as the theoretical over the range 0 - 10 per cent fines. It quickly reduces however, at higher fines content and at 37 per cent fines, the coarse particles reach their minimum stable density that density which the coarse particles are theoretically only just in contact.

The shape of the minimum dry densities curve for the composite soil is seen to be similar to the compacted density curve but is also seen to diverge much more widely from the theoretical density curve for the loose conditions.

6.2.3. Discussion of Test Data.

Deviations from the theoretical densities of compacted composits soils therefore exist and the till tested is not acting as an ideal composite soil. This form of behaviour has, however, previously been noted for other soil mixtures containing more than the critical fines content by Holtz and Lowitz (1957). They noted this when investigating the effect of gravel content on the compaction characteristics of silty and clayey soils and attributed the discrepancies, to coarse particle interference reducing the compactive effort applied to the fine fraction. It is reasonable to assume that this is occurring in the tills also. Further, it is reasonable to suggest that the fines similarly interfere with the compaction of the coarse particles at mixtures less than the critical fines content. Thus in natural, non-ideal soils, there will not be a dramatic separation between fine fraction controlled mixtures and coarse fraction controlled as predicted, and it is best therefore to define three principal states in the composite tills and two transition stages between these as follows:-

Principal States -

a) Coarse grains, so called clasts, in contact, with the fines partly filling the voids. The fines neither interfere with the stress transference nor with the geometrical arrangements of the coarse grains. This is described as the Clast Controlled State.

b) Total interaction of coarse and fine particles with neither size fraction dominant. Both fractions interact in stress transferrance and geometrical arrangements. This may be described as the Well Graded State.

c) Coarse grains acting as separate particles in a matrix of the fine fraction. In this state stress is transmitted through the matrix and it may be described as the Matrix Controlled State.

Transition Stages.

i) Between (a) and (b) the coarse grains are generally in contact, the fines while not completely filling the voids, are interfering in various degrees with the stress transmission and geometrical arrangement of the clasts. This stage is, therefore, described as the Clast Dominated Stage.

ii) Between (b) and (c) the coarse grains are generally separated but are interfering in varying extents with the stress transmission function and geometrical arrangement of the fine matrix. This stage is thus described as the Matrix Dominated Stage.

For the Cowal till, it may be suggested that the particle organisation varies with fines content as shown in Table 6.2.

It is not to be expected that every till will have the same fines content limits for the various particle organisation states, since the nature, size, shape and gradation of particles together with size difference between the coarse and fine fractions will also influence these limits. In Chapter 7 the compaction characteristics of other tills do, however, show similar trends with fines content limits of the same order as for the Cowal till. Consideration of the percentage fines in the tills investigated in Chapter 5, Fig. 5.167, suggests that in general melt out tills will fall into the categories of matrix controlled, matrix dominated or well graded tills, with the majority being matrix dominated.

6.3. IN-SITU AND REMOULDED DENSITIES OF THE COWAL TILL AND IN-SITU DENSITIES OF TILLS FROM MODERN GLACIERS.

6.3.1. Cowal Till Densities.

A number of determinations of the natural water content and in-situ bulk densities have been made in the tills in Cowal, Scotland. The density measurements were carried by the Replacement Method Test, 14(B) British Standard 1377: (1967)using a 216 mm diameter sand pouring cylinder. Also 150 mm diameter by 300 mm long tubes were carefully driven into the soils and the density of the soil in the tube determined. In each case, the particle size distribution of the extracted soil sample; whether from the in situ replacement technique or the tube sample, was carefully determined in accordance with British Standard 1377: (1967) Tests. 7 (A), (B) and (D).

As an indication of the relative density of the in-situ till, the in-situ dry densities have been plotted against percentage fines in Fig. 6.7 and the laboratory determined loose and B.S. compacted states are super-imposed for comparison. The in-situ densities can be seen to generally increase with reduction in percentage fines however a large spread of densities is apparent at any particular percentage fines content. Indeed some of the in-situ densities are apparently less than the laboratory determined loose condition although none are denser than the B.S. Optimum compaction densities.

Either the methods used to determine the in-situ densities are sometimes under estimating the density of the soil or the in-situ soils have a geometrical arrangement which is more open than that produced by the laboratory minimum density test methods. It is most probable that a combination of both these factors is contributing to this phenomenon. Nevertheless the in-situ density data appear to follow a very reasonable pattern lying generally within or just below the laboratory determined limits, varying with fines content generally in accordance with the theoretical and laboratory experimental data.

6.3.2. Density Variations at Breidamerkurjokull and Blaisen Glacier.

The in-situ densities of the tills at the Breidamerkurjokull and Blaisen glaciers were determined by carefully driving 150 mm diameter by 300 mm long tubes into the soils and weighing wet and dry the known volume of soils so extracted. At both sites, Figs. 6.8 and 6.9 the in-situ densities can be seen to be very variable. The Icelandic till is of course not a direct comminution product and cannot therefore be split into coarse and fine fractions, but the Blaisen till can. In fact, the percentage fines in the Blaisen samples varied between 45 and 51 per cent, which is not a very large variation. The measured differences in the till are therefore due to variations in the deposition process and not to gradational changes. The Breidamerjokull tills sampled were also relatively uniform in overall grading and a similar conclusion may be applied to them. Thus the measurements in these modern tills confirm the variability measured in the Scottish Pleistocene tills.

6.3.3. Implications of Density Data.

The measured in-situ densities in Cowal, Iceland and Norway, all show that the depositional process associated with the formation of melt-out tills, is rather variable. The very low measured dry densities of the Cowal tills further suggests that some very loose arrangements of particles may exist in the tills, products of slow melt-out of ice under low imposed stresses. It is to be expected, however, that much more compact arrangements will also exist in close proximity to the loosely arranged till, products of poor drainage conditions and higher imposed stresses. This combined with the variations in gradation discussed in Chapter 5, which also greatly influence density, gives much to the explanation of the observed highly variable nature of engineering properties of the in-situ tills.

6.4. TECHNIQUES EMPLOYED TO STUDY PARTICULATE MATTER ORGANISATION IN TILLS.

Traditionally, the term "till fabric" has been applied to measurements of the longest axis of those till stones, predominantly of pebble grade, which have relatively low dips and no apparent contact with other clasts. As such, the technique has been used much more as a descriptive tool than an analytical one. Wadell's (1936) pioneer instrumental and analytical design for the measurement of the orientation of particles in sediment has been developed by Karlstrom (1952) and more recently by Harrison (1957) who applied it to the measurement of the a - b planes or maximum projection area of particles. In these studies a normal rectilinear co-ordinate system is used with the a-axis in the direction of the longest axis of the stone, the c-axis along the shortest axis of the stone with the b-axis being the intermediate axis. As Harrison's technique is time consuming, it has not replaced the measurement of the long axis of pebbles in descriptive work. However, it has served to increase the systematic study of till fabric from a genetic point of view. Other techniques, notably those of field sampling, assessment of sample variability, and the statistical representation of the fabric data, have been developed since the work of Kauranne (1960), particularly by Andrews, Andrews and Shimizu (1966), Andrews and Smithson (1966), Andrews and King (1968) and Andrews and Smith (1970).

It is a fair generalisation to state that all techniques of till fabric analysis are at least moderately selective and some are highly so. For example, the results of selective clast sampling on statistical representation and interpretation have been pointed out by Andrews and Smith (1970), including the fallacy implied in the exclusion of pebbles with dips greater than 45^{o}. It should be added that, despite the widespread recognition that little specific is known about the mechanism which produces a till fabric, the use of the long axis measurement and the selection of stones according to some minimum ratio between longitudinal and intermediate axes, commonly 2:1, remains the general rule.

In view of the growing strength of the opinion that the fabric of subglacial tills are the product of a stress field of hydrostatic type in which the matrix of the till is subject to the laws of fluid mechanics, Hoppe (1952), Andrews and Smith (1970), cf. Carey and Ahmad (1961), it seems prudent to include disk shaped particles as well as those with a clearly defined long axis, as they are better indicators than rod shaped particles, their well developed planar feature being a more sensitive indicator of force distributions, Harrison (1957).

While varying degrees of selectivity have characterised most sedimentological studies in the past, the understanding of genetic relationships in a heterogeneous material such as glacial till demands that selectivity of measurement within a sample be kept to a minimum. This is certainly so with respect to the size, shape, and dip of particles making up the deposit and their apparent degree of contact. The dangers of a selective method are particularly great in respect of particle size, because of the split or gap that has been shown to occur in the grading curves. Yet, as previously suggested, the matrix is the dominant stress transference medium and the study of the organisation of the matrix clearly essential. In general, fabric work on glacial tills has not included an extension of the investigation into the size ranges of the matrix. Notable exceptions to this statement are the papers by Ostry and Deane (1963) and Korina and Faustova (1964) in which they studied the organisation of the fines using light microscopes. The relatively recent application of the scanning electron microscope to the study of the fabric of engineering soils, Barden and Sides (1971), Barden (1972), Collins and McGown (1974), has pioneered a new approach to the study of matrix of sediments.

6.4.1. Field Techniques.

The vast majority of the published work on the orientation and dip of till stones is based on measurements taken in the field using pebble and cobble sized clasts. The techniques, here classified as macrofabric methods, have been summarised recently by Andrews (1971) and will not be further discussed.

In the series of investigations during which the techniques described here were developed, the laboratory method pioneered by Harrison (1957) was slightly modified by Dr. E. Derbyshire, Univ. of Keele and then used in the field, McGown and Derbyshire (1974). In this work, mesofabric is defined as the measurement of the amount and direction of the true dip of the a-b planes of granular size particles of 64-2 mm. The orientation and dip of the longest axes and the short c axes of the clasts are also measured as a matter of routine. This allows comparison both with previous work and with the planar dip data within the same specimen as well as allowing multivariate analysis of the particles, using size, shape, packing and lithology as well as orientation, and to further reduce selectivity by the use of appropriate mathematical techniques, Griffiths (1966, 1967), Griffiths and Ondrick (1969) and Andrews (1971).

Small blocks of till some 100-150 mm square have been taken from several sites, including tills from freshly formed moraine ridges and subglacial deposits. The measurements made on fresh materials in which diagenesis is absent permits the true depositional fabric to be studied and allows assessment of the influence of diagenesis in the Pleistocene till. The top surface of the sample is levelled and a magnetic north arrow inscribed upon it so that the block may be reorientated and relevelled immediately and measurements taken using a lightweight contact goniometer Plate 6.1. Ideally, this method should be used in conjunction with field measurements of macrofabric. It possesses one great practical advantage; as both the sample and the goniometer are portable, it may be used in covered accommodation under expedition conditions without any appreciable loss of accuracy. In the field, the mesofabric method is usually more rapid than macrofabric analysis when in the hands of a practised operator. Another advantage of mesofabric analysis as a field method is that it provides a practical technique for the investigation of frozen subglacial and englacial tills, and so offers a means of investigating directly the genesis of till fabrics. Ice and debris, mixed in a variety of proportions, have been studied in this way, a block being cut and reorientated in the manner described above. Working either in a glacier tunnel or right at the ice front, the upper surface of the block is allowed to melt slowly and clasts are measured as they emerge, Plate 6.2.

6.4.2. Laboratory Techniques.

Mesofabrics may also be studied in the laboratory where the field methods may be elaborated in a variety of ways. Samples are first coated with plaster of paris in the field, this having been found to provide adequate protection even for fragile specimens of loose silty and sandy tills transported great distances over rough ground. On arrival at the laboratory, the sample is levelled and oriented on the contact goniometer and the plaster removed from the upper surface and one side, Plate 6.3. It is then brushed to remove the fines. The brushing apparatus developed by Dr. E. Derbyshire, Univ. of Keele, and described by McGown and Derbyshire (1974), consists of a rolled lawn brush with flagged hair as used in the pottery industry. It is mounted on a metal spindle and rotated by a small electrical stirrer. The sample is adjusted using a laboratory jack and the whole apparatus placed on a plastic tray and enclosed in a transparent polythene tent Plate 6.4.

Samples show some variation in response to the brushing technique. For example, two samples of silty tills from adjacent locations at Breidamerkurjokull, southeast Iceland responded differently, compactness of the matrix being the controlling factor. In samples with more open microfabric, for example Icelandic sample BR/C17, Plate 6.3, fines were removed cleanly and quickly. All silty and sandy melt-out tills examined have been successfully etched by dry brushing, the more compact matrices merely taking longer to remove. The use of the mechanical brushing technique greatly reduces laboratory time as the clasts are left standing in bold relief and are quickly measured and catalogued. Given this and the low percentage rejection attributable to the use of the a-b plane for dip measurements of particles of all shapes, sizes, and lithologies, the method is essentially unselective within the granular size ranges. Moreover, fabric may be investigated in tiered fashion, working down through a sample block at regular intervals of 10 or 20 mm. A transparent overlay graticule may be used to give each clast a unique reference location which may also be recorded in mono, or better stereo, scale photographs before the surface is destroyed.

The readings provide a description of the three dimensional particle arrangement in the till and a semi quantitative indication of the degree of particle interception, Figs. 6.10 and 6.11. In silty tills studied, sample numbers from each layer have varied in size up to 50 clasts, but 25 has been found to be the minimum acceptable size on statistical grounds. By providing up to 50 values from each brushed level within the sample, the method is capable of yielding several hundred values for each small block studied. This, in turn, increases the confidence with which three dimensional orientation data may be used to establish the genesis of tills. Thus the method provides a more thorough documentation of clast fabric at the cost of very little more time than is required to complete a macrofabric analysis in the field.

6.4.2.2. Microfabric.

Microfabric or geometrical arrangement of the matrix of tills may be investigated using the light microscope or the scanning or transmission electron microscopes. Recent advances in the application of scanning electron microscopy to the study of the microstructure of sediments have emphasized the usefulness of this particular tool, Barden (1972). Whereas specimen preparation techniques employed for transmission microscopy are very sophisticated and time consuming Smart (1969), Silva et al (1965), Pusch (1968) the preparation technique developed for specimens to be viewed in the scanning electron microscope is very simple, Barden and Sides (1971). First a sample of the soil should be dried and in this study this is achieved by slow air drying over a period of 2 or 3 weeks in an ambient temperature of 20°C or so. In very clayey soils, air drying from well above the shrinkage limit can cause considerable shrinkage but few tills have been found to be sufficiently wet or clay rich to be troublesome. In cases where this may be a problem, properly controlled freeze-drying, Tovey (1971), can be used. After drying, the oriented block is subjected to mesofabric analysis as described in the preceding section and from the remains, small samples are detached and trimmed to a cross section 10 mm or 25 mm square, depending on the size of the viewing stage of the particular instrument being used. This sample is then grooved on the outside and mechanically fractured to expose a surface for viewing.

To remove loose debris which may be left on the fractured surface, peeling is recommended using adhesive (cellophane) tape for 50 or more applications. In sandy and silty tills, such peeling has been found to create as many loose particles as it removes from the viewing surface. Thus little peeling (5-10 peels) or, in some cases, no peeling has been found to be best.

The specimens used in these studies were oriented. This is easily accomplished by carefully taking oriented pieces of till from the brushed block of till used for mesofabric analysis. This is important methodologically, for it is important that all the measures described here be performed on the same oriented sample. By taking care during trimming and fracturing, a surface oriented in any particular plane may thus be viewed and preferred orientations of the matrix diognosed. As yet, no reliable and simple method of quantification of scanning electron microscopy observations of till fabric is available. The qualitative approach taken to the description of microfabric is, based on the system developed by Collins and McGown (1974).

This new system of classification of microfabric features was developed as previous attempts at modelling microfabric had been undertaken by a series of different investigations each describing isolated observations or depicting simple electro-chemical hypothesis. Also the multi-level nature of particle arrangement in natural soils previously reported by Barden et al (1973), Collins et al (1973) and McGown (1973), had not been fully appreciated nor portrayed in previous fabric models. The new system is designed, therefore, to take account of the multi-level interaction of the clay and other particles but it also incorporates a large number of previously accepted terms and definitions and whenever possible it seeks to avoid duplication or introduction of new terms.

Basically three types of microfabric in nature soils were suggested by Collins and McGown (1974); Elementary Particle Arrangements, Particle Assemblages and Pore Spaces.

a) Elementary Particle Arrangements - which consist of single forms of particle interaction at the level of individual clay, silt or sand particles or interaction between small groups of clay platelets or silt or sand particles clothed in clay.

b) Particle Assemblages - which are units of particle organisation having definable physical boundaries and a specific mechanical function. At their basic level they consist of one or more forms of elementary particle arrangements or smaller particle assemblages are are derived in an uninterrupted sequence.

Higher Order Assemblages resulting from interruptions in the formation sequence are also distinguished. These features have definable physical boundaries and include features such as layers laminations, varves, kink bands, shear zones etc.

c) The pore spaces within, between and across the features described above must also be considered. These include Interparticle, Intra-assemblage, Interassemblage and Transassemblage Pores. The latter may include such features as cracks, joints, fissures and hydraulic channels.

Figure 6.12 shows the general models for the seven elementary arrangements suggested from observations on a wide range of natural soils. a) individual clay platelet interaction. b) individual silt or sand interaction. c) clay platelet group interaction. d) clothed silt or sand particle interaction. e) partly discernible particle interaction, i.e. the nature of the particle interaction was not fully discernible by the observation techniques employed.

The basic level of particle assemblages, which is possibly the level of fabric which is most accurately records stress history has been represented in a number of ways, as shown in Fig. 6.13. This classification is based principally on the form and function of the arrangements, i.e. whether they act effectively as individual units, connectors, matrices etc. The suggested forms included in Fig. 6.13 are a), b), c) connectors which may vary in their size and external physical form; d) irregular aggregations linked by connectors, e) irregular aggregations forming a honeycomb arrangement; f) regular aggregations interacting with silt or sand grains, g) regular aggregations interacting with particle matrix h) interweaving bunches of clay, j) interweaving bunches of clay with silt inclusions, k) clay particle matrix; l) granular particle matrix. The physical nature of the higher order particle assemblages are self evident and do not therefore require further elucidation.

The approach taken to the classification of pore space is in fact similar to that of Brewer (1964) and Bochko (1973). The schematic representation of the various pore space types are given in Fig. 6.14. Four broad groups are suggested as follows: a) Intra-elemental pores b) Intra-assemblage pores; c) Inter-assemblage pores; and d) Trans-assemblage pores. This pore space classification does not specifically account for the size and shape of the pores in the soil microfabric. However, the nature of the classifications adopted implies both shape and increase in absolute size from intraelemental to transassemblage pore spaces.

Collins and McGown (1974) concluded from their observations of a variety of recent transported soils that a number of different types of microfabric features could exist side by side in any one natural soil microfabric but that there may be a dominant feature or set of features present in any one soil. In order to assess this dominance or otherwise of particular microfabric features an attempt has been made to establish a scale of the relative apparent abundance of the features at various levels. The scales for the elementary, basic level of assemblages and pore spaces are common and are as shown in Table 6.3. Higher order assemblages are simply noted as being present or not. To date this crude assessment of fabric features abundance is the only available means of "quantifying" scanning electron micrographs.

6.4.3. The Relevance of the Multi Level Investigations of Till Fabric.

The methods described above allow observation of the particle organisation in tills both in the coarser fraction (sand particles and larger) and in the matrix range (silt particles and finer). The critical size range in which particle orientation becomes dominated by particles greater in size rather than by the inherited stress pattern will vary from one till to another depending on the grain size distribution. However, as has been shown, the break in the size distribution curve between matrix and clast tends always to fall in the coarse silt or sand grades. This serves to justify the fabric study of glacial tills in terms of both clast and matrix populations. Given that the organisation of both clasts and matrix may be examined in some detail, the possibility arises of distinguishing within any one proglacial debris suite englacially stress-induced organisations and post-depositionally induced modifications of them.

It is recognised, of course, that the organisation of the matrix cannot be accounted for solely by the depositional process. For example, the mineralogy and the quantity of clay in the matrix may significantly influence the matrix organisation, as has been shown by Barden (1972) Collins and McGown (1974) for a range of engineering soils formed by a variety of depositional and weathering processes. Many geotechnical properties of the till matrix may, in fact, influence its ability to retain clasts in their primary depositional position.

Extending the study of the organisation of particulate matter in glacial tills to include matrix fabric thus demands the inclusion of a wide range of factors which, in the past, have tended to be considered separately. One such factor is lithology which affects clast shape and the development of primary and secondary clay minerals. Glacial regimen is also important in that it influences the glacial and subglacial stress fields, the availability of free water in the tills, and the presence or absence of free drainage.

6.5. OBSERVATIONS OF PARTICLE ORGANISATION IN SOME MELT OUT TILLS.

6.5.1. Tills Studied at all Fabric Levels.

Tills from two sites were studied at all fabric levels and these were taken from within, beneath and in front of the two active maritime glaciers studied in Iceland and Norway, Breidamerkurjokull and Blaisen respectively.

The Breidamerjokull tills were derived from rocks of the basalt suite, clasts being predominantly dense flow and breccia with tuff and vesicular basalt being rare. The study sites are situated in the central and western till plains which lie close to the sea, Fig. 4.18, and the tills were taken from sites which had been uncovered by the glacier for a period of less than five years. Two samples BR/C10 and C17, were selected from a group of samples derived from a partly-fluted drift plain showing only slight slope towards the glacier while a third sample was taken from a finely-fluted till only 50 m from the ice front on the western periphery of the proglacial plain of Breidamerkurjokull, Sample BR/W3B. No fissility was noted in these tills, although undisturbed dry samples display an orthogonal system of joints along which the material tends to break down into cuboidal peds. This characteristic is marked only near the till surface and may be ascribed to frost action since deposition.

Two Norwegian samples from Blaisen, B/65/A and B/72/D, composed predominantly of local granite gniess and phyllites will be discussed, the first dating from 1965 and the second having formed within the month in which the sampling was completed. The positions of these samples are shown in Fig. 4.23. Both samples are from small till ridges (1-0.5 m high) resting on bedrock which slopes away from the glacier at an average of 5°.

6.5.1.1. Physical Properties of Norwegian and Icelandic Tills.

The grading curves of the Norwegian tills have been shown to conform to the bimodal pattern, indicating that they are the direct product of comminution. As has been indicated in Section 5, the Icelandic tills display quite different grading characteristics.

This arises from the fact the tills are a mixture of varying amounts of glaciofluvial material, incorporated and transported by re-advances of the glacier, and comminution till. The resulting curves are thus of compound type.

The split graded, particle size distribution curves for the Norwegian tills can be regarded as an expression of the existence of two distinct populations within a sample, namely clast and matrix. This distinction is important in that the two populations can be shown to possess different behavioural properties during and immediately following the process of melting out of the glacier ice. While the grading curve for the Icelandic tills does not conform closely to this pattern, due to the incorporation of fluvially transported debris, it is assumed that both populations are sufficiently distinct for the meltout process to have had very similar behavioural expression. These populations appear to exist englacially, the clasts acting as units, often in contact, and the matrix occurring either in dispersed patches and layers or as clusters or groups, Elson (1961).

From the data in Table 6.4 it can be seen that the tills are of low plasticity. Data for the tills from both glaciers, Tables 6.4 and 6.5 indicates that the plasticity of the exposed tills in front of the glacier, although variable, is generally less than the plasticity of the tills sampled while in the frozen state within or beneath the ice. These variations in plasticity do not entirely correspond with variations in the particle size distribution of the tills outwith and within the ice, which suggests that washing out of clay sizes, not readily detected in particle size analysis, may occur. Silt and sand size particles can also be washed out in some cases. The water contents given in Table 6.4 are the average values for tills at a distance from the ice front where the moisture content has stabilised, apart from seasonal variations. At the ice margin, water contents of up to 40 per-cent were recorded in recently formed tills while samples from sub-glacial tunnels contained 60 per cent moisture content. Reduction in moisture content down to the average given for each soil occurr-ed over distances which varied depending on local drainage condi-tions.

6.5.1.2. Clast Shape in Norwegian and Icelandic Tills.

The characteristic mode of fracture of the basaltic rocks contained within the Icelandic tills favours the production of predominantly equidimensional clasts. The largest single shape class in sample BR/C/17, Table 6.6, is made up of wedges (40 per cent). This class occupies a somewhat equivocal position in terms of the clast fabric in that acute wedge forms are a special case of the tabular shape and behave very similarly to this group. Thick wedges, how-ever, show a response to a stress applied to the surrounding matrix which varies greatly according to the degree to which the outline of their a-c planes approaches the form of an equilateral triangle. For this reason wedge-shape clasts are classified as thick or thin. The granulometry of sample BR/C/10, Table 6.5 is broadly similar to BR/C/17, although the mean index of flatness is distinctly higher and wedge-shaped clasts are fewer. Sample BR/W/38 differs from the previous two tills, with 28 per cent of clasts being classified as thick wedges and only 8 per cent as tabular.

The mixed granite-gneiss and phyllite clast population of the Norwegian sample BR/65/A results in a rather higher mean index of flatness than those of the Icelandic tills. Over half the clast population (56 per cent) is made up of tabular and mainly thin wedge forms, ovoids/rhombohedroids making up only 24 per cent. The second Blaisen sample, B/72/D, was taken from till overlying a small outcrop of phyllite so that, while granite-gneiss and some dike rocks remain a significant element, phyllites are more notable than in the 1965 end moraine. This local lithological change influences the granulometry. Thirty-six per cent of clasts were classified as tabular or discoid and 28 per cent as of wedge form, over half of these being thin wedges. The mean index of flatness (225 with a standard deviation of 81) is considered high for small till fragments.

6.5.1.3. Organisation of Clasts.

Analysis of the long axis orientation of the two Icelandic samples BR/C/17 and BR/C/10 was not considered appropriate in view of the high proportion (70 per cent) of clasts with an a/b axis ratio of less than 1.5.

Sample BR/C/17 was taken from a non fluted area of the proglacial plain, the planar surface of deposition sloping towards the glacier at only 1-2°. It displays a meso-fabric, Fig. 6.15(A) which is very similar to but more diffuse than englacial clast fabrics measured within the adjacent glacier Fig. 6.15(B). The differences are minor, the large proportion of high dips expressing the response of the large proportion of thick wedges, ovoid and roller-type clasts, Table 6.6, to the englacial pressure field prior to stress release. The mutual interference of certain shapes of particle, notably thick wedges, due to the close packing of the clasts also serves to induce high dips. These clast fabric display gently dipping, up-glacier modes elongated within the known flow vector of the glacier. Their reflection of the glacier flow direction suggests that measurements of the a-b plane, as well as providing data on the formative englacial pressure field, may be of value in deducing mean ice movement directions in non-fluted tills with few elongate clasts.

Sample BR/C/10, taken from beneath the north-west facing slope of a small flute 0.30 m in height, is similar to the first sample although clast packing is closer. Distinctly higher flatness of particles in this sample appears to compensate for the closer packing and hence greater mutual interference of the clasts for the fabric plot, while not narrowly clustered, has a clearly defined mode, Fig. 6.15(C).

This fabric is interpreted in terms similar to the first sample. The mode accurately reflects the mean dip of the lateral slope of the flute from which this sample was taken. The slope, in turn, is the product of the overburden pressure of a glacier grooved by plastic deformation around obstacles, mainly boulders 1-2 m diameter which have been observed in slide at a rate several orders of magnitude smaller than the overriding ice, Plate 6.5. Rotation of the data with respect to the planesrepresenting the east-facing slope of this flute confirms the resemblance of this result to the non-fluted till. It may reasonably be inferred that a complementary fabric is to be expected on opposing slopes of moraine flutes, Boulton (1971). This is some measure of the sensitivity of the a-b plane to minor variations in the pressure field near the glacier sole and its relatively late development in the deposition process.

Icelandic sample BR/W/38 was taken from 0.2 m beneath the crest of a small but continuous flute which had been exposed for only one year. The plot of the long axis orientation Fig. 6.15(E) reveals two modes corresponding to an up-glacier dip of 10° for the principal mode and a downglacier dip of 20-22° for the secondary mode. The vector mode (10-20°) is very close to the mean observed ice movement and the bearing of the flute axis (020°). The plot of the a-b planes, Fig. 6.15(D), is complementary in form, exhibiting a symmetry about the known ice-movement direction. Diffuse maxima are notable corresponding with high dips of between 40-50° with azimuths of 80° and 305°. These results conform with the theoretical prediction that the principal maximum derived from plotting the long axes of elongate clasts will coincide with ice flow direction and dip gently upglacier. In the poor development of either a transverse maximum or a girdle this fabric exhibits the characteristics regarded as englacial rather than depositional by Lindsay (1970). The short-axis fabric, with its two maxima disposed transversely to the ice-flow direction, however, does not accord with representative englacial fabrics from the adjacent glacier, Fig. 6.15(B). This might be taken to be a reflection of the pressure field in subglacial melt-out till across the axis of a flute, in accordance with an existing hypothesis of fluted till formation, Hoppe and Schytt (1953) and would be consistent with the interpretation of the fabric of the previous sample, BR/C/10. The bimodality of the fabric, however, may be explained in terms of the combined effect of the shape of particles and their degree of contact.

Most clasts in the Norwegian sample B/65/A exhibit a well developed planar feature. This is expressed as three maxima in the stereographic projection of the a-b planes, Fig. 6.16(A). Two of these maxima show broadly downglacier dips of 18°-32° and 62°-72° in directions between 285° and 310° corresponding only roughly to the assumed ice movement direction. The third maximum corresponds to a dip of 15°-28° towards the east (80°-100°). The long-axis plot Fig. 6.16(B) is asymmetrical. It reveals a primary maximum representing a dip of 0-12° towards 240° and 055° and a secondary maximum with dips of 4°-26° towards 015°. The primary maximum coincides with the orientation of the axis of the moraine ridge. The diffuse pattern, notably the lack of any girdle, may be in part the result of the shape properties of the clasts in this till in which 12 per cent of clasts had no long axis and in which rods made up only 12 per cent and rhombohedroids a further 12 per cent of the sample.

The second till from Blaisen (B/72/D)was taken from beneath the axial crest of a small, freshly formed end moraine ridge with a radius of curvature of only 2 m. When sampled this silt-rich till was in a very wet though stable condition. Figure 6.16(C) shows a principal maximum with two modes representing a dip of the a-b planes of about 25° and 50° respectively toward the azimuth range 010°-015° and subsidiary maxima showing dips of 30°-45° and 68°-70° towards 325° and of 55°-62° towards 220°. In generalised terms, this pattern can be interpreted as a broad composite mode dipping downglacier about the mean observed direction of ice movement.

With only 5 per cent of clasts lacking a definite long axis and rods and rhombohedroids making up almost 30 per cent, the plot of the long axis data shows two clear maxima Fig. 6.16(D). The first contains clasts dipping at between 5 and 42° downglacier and along the direction of observed ice movement (342°) while the second is a clear transverse orientation along 065° with dips of 4-26°, and essentially normal to the direction of ice movement.

The fabric plots of the two Norwegian samples show essentially the same pattern. Modes of dip of a-b planes are downglacier and downslope in an arc about the known ice-movement direction, while the long-axis orientation is complementary in form, its primary mode lying transverse to ice flow. This pattern conflicts with that to be expected from hypotheses which explain end moraine genesis in terms of glacial lodgement in sub-frontal situations, Chamberlin (1894) or by the "squeezing" process as the ice terminus deforms wet till by simple loading, Price (1970). While not questioning the validity of either of these hypotheses at this time, the latter is not appropriate in this case, as the small end moraine ridges rest directly on a bedrock surface, often polished and moutonnee. The glacier producing these ridges in 1972 was observed to move once or twice a day by episodic basal sliding, producing regular regelation ice clusters on the glacier sole, Plate 6.6. Total daily movements ranged from 0.08 to 0.04 m and averaged 0.05 m. Currently forming arcuate ridges of till were observed to respond to the shock of glacier slip by developing radial fractures in their crests Plate 6.7. There was no evidence of liquefaction and flow of till down the distal slope of the small ridges. Evidently, the ridges form by a series of mechanical thrusts each of 0.03 to 0.04 m, acting on melt-out till at a moisture content around the plastic limit in the manner tentatively suggested for this area by Anderson and Sollid (1971) and for Austre Okstindbreen by Worsley (1974). The clast fabric, with its radially outward dips of planar clasts and the primary transverse mode of the long axes of clasts, is an expression of this process. The greater compaction of the matrix, in comparison with the other tills studied, may be another. The preservation of these small ridges depends on the local balance between rate of basal slip and rate of downwasting of the lobate ice front of which they form casts. Where the ridges are preserved, the clast fabric properties are also preserved although mean dips of tabular clasts may be less due to post-depositional water loss.

6.5.1.4. Organisation of the Matrices.

Under microscopic examination samples of both tills appeared fairly uniform in texture at low magnifications, 25 to 125 x, with no layering apparent. The medium to fine sand particles in Norwegian sample B/72/D were seen to be predominantly tabular, discoid or wedge shaped with the silt particles becoming more discoid. The other Norwegian sample, B/65/A had similar characteristics at this level of fabric but, as will be discussed, at greater magnification differences in the fabrics of tills were observed. The Icelandic tills studied did, however, all appear to exhibit the same fabric characteristics and are thus treated as one for the purposes of this study. In these soils, the incidence of wedge shaped particles was high in both the sand and silt size ranges.

(i) Elementary Particle Arrangements

The distribution of fine silt and clay size particles in the tills was not uniform, particularly in the Blaisen tills, where predominantly granular areas and areas rich in fines were found. Clean grain to grain contacts were to be seen, but generally the sand and coarse silt particles were coated in clay size materials, the so-called clothed grain - grain interaction. The clay and fine silt particles were also found arranged in groups. Many of these groups consisted of particles in very open individual particle arrangements of the cardhouse type Goldschmidt, (1926). This is very rare in other natural deposits, Collins and McGown (1974), and is possibly due in this case to the clay sizes being predominantly rock flour with relatively low surface energy, rather than "active" clay minerals. The fines were also seen aligned around and between the coarser particles in a sub-parallel arrangement suggesting a "sympathetic" organisation of these sizes to the larger particles rather than an "independent" organisation. This might result from depositional processes where free-water was present or consolidation due to loading or dessication. Obviously in viewing only the final result it is not possible to distinguish the particular process involved and each is quite likely to have occurred in the complex highly variable ice-margin environment. The predominance of the clay size and granular arrangements and the various elementary particle arrangements in the tills within these groups are set out in Table 6.7. It should be emphasised that these estimates of dominance are very crudely obtained by visual assessment but are still worthwhile as they do permit a rough comparison to be made between the various soils. It should also be noted that in Table 6.7 the abundances given for the particular elementary arrangement refer to the abundance within the relative overall presence figures as indicated.

ii) Particle Assemblages.

It was observed in the Icelandic tills and in the areas rich in fines in the Norwegian tills, that many of the particles combine to form higher order features with specific functions and definite physical boundaries - the particle assemblages. In particular, it was found that the sand and coarser silt particles were occasionally separated by groups of finer particles termed connectors by Collins and McGown (1974). Also at various levels of magnification the separation of coarser particles by fines grouped as connectors was to be seen. These connectors were variable in size and form and many were very loosely packed and appeared rather unstable, while some of the more compact aggregations gave the impression of being collapsed or partly collapsed forms of previously more loosely packed arrangements. In many other areas the fine particles formed "aggregations" which appeared to act as individual units within the microfabric. These aggregations were found to be variable in size, shape and internal organisation. Both of these assemblage arrangements were very often found to combine to form more complex and widespread matrices of both the clay and granular types with clay-granular matrices being quite common in clay rich areas. The relative abundances of the various assemblages have been estimated as before and are given in Table 6.8. No higher order assemblages were observed.

(iii) Pore Space Arrangements.

The pore space in the tills was very uniformly distributed in so far as few large trans-assemblage pores were observed, i.e. few pores were seen traversing the soil without specific relationship to the occurrence of individual microfabric features. Much of the pore space consisted of either inter-elemental pores occurring between the various elementary particle arrangements or intra-assemblage pore space occurring between individual particle assemblages. The remainder was inter-assemblage pore space occurring between individual particle assemblages at all levels of assemblage complexity. As there was less evidence of aggregations in the 1965 Blaisen till than in the others, it appeared more compact with voids generally much smaller. The relative abundance of the pore space arrangements are given in Table 6.9.

(iv) Overall Fabric in Blaisen 1972 Till.

To exemplify the detailed analysis of the fabric of the 1972 till, a series of typical micrographs of the till are presented. These represent a sample of the fifty two micrographs taken of this till.

Micrograph 1 shows a granular matrices of silt with a number of fine sand particles included and a medium sand particle located in the centre of the micrograph. Micrograph 2 is a detail of Micrograph 1 and shows the make up of the granular matrix and a regular aggregation. The clean and clothed grain to grain elementary arrangements are also clearly shown. Micrograph 3 shows another granular area with a number of fine sand and silt particles in a rather open arrangement. A few connectors are apparent in this area and Micrograph 4 is a detail of one of these. It is seen that the connector is composed of silt sizes ($< 2\ \mu m$) with no evidence of clay size particles. Micrograph 5 is a view of another granular but somewhat more compact area and Micrograph 6 shows this in detail. Comparison of these latter two micrographs with micrographs 1-4 suggest that the pore spaces in this area are intra elemental or intra-assemblage with few of the inter-assemblage pores seen in the other areas.

Micrograph 7 shows an area which is much richer in very fine particles than average although it is still generally granular in nature with a granular matrix fabric dominating. Detailed examination of the finer area reveals in Micrograph 8 to 11 fine particle aggregations and connector assemblages. Micrograph 8 shows the fines coating medium and fine silt particles and forming a regular aggregation which is shown in detail in Micrograph 9. Micrograph 10 another area of Micrograph 7 which exhibits fine connectors between medium to coarse silt particles and a detail of this is shown in Micrograph 11. All the fines in these micrographs were discernable and appeared to be very coarse clay sizes acting very often as single particles and not as groups. Also in Micrographs 7 to 11 the pore spaces are predominantly inter-elemental and intra assemblage with some interassemblage pores. No trans-assemblage pores are to be seen in these micrographs.

(v) Overall Fabric in Blaisen 1965 Till.

The detailed analysis of the 1965 till was based on forty-three micrographs of which the following are a representative sample. Micrograph 12 is a view of an essentially granular matrix, typical of large areas in this sample. The fabric appears quite compact but examination of detailed stereo pairs such as Micrograph 13 indicates that the surface is extremely rough and that the fabric is more open than when viewed in the overlap Micrograph 12. Micrographs 13 and 14 are successive details and show the nature of the matrix to be granular with few clay-size particles present. Many very flakey silt size particles are to be seen which was in fact a common characteristic. The pore spaces may also be seen to be inter elemental, intra or inter assemblage pores. Micrograph 15 is a stereo pair of another matrix area which has some clay-size particles in it. The area viewed is much more even than the previous micrographs and appears therefore more open. The individual granular particles are seen to be both clean and clothed in fines. At a higher magnification of a similar area, Micrograph 16, the clean and clothed granular particles are better viewed and the arrangement of the clearly discernible clay-size particles around and between the coarser grains is apparent with few other definite assemblage characteristics to be seen, perhaps a few aggregations only.

(vi) Overall Fabric of Breidamerkurjokull Till.

Three samples of this till were viewed but no differences could be detected between the fifty or so micrographs taken of each. From all of these, typical micrographs have been chosen. Micrograph 17 is a general view to the side of a gravel particle and shows the typical aggregated and clay-granular matrix of the tills. A more detailed view is given in Micrograph 18 and stereo viewing the large transassemblage pore around the gravel particle can be appreciated. The clothing of the gravel particle by fines is also apparent. Another area away from the large particle is shown in Micrograph 19 and is seen to be similar to the previous area in character. The granular particles, are apparent often clothed in fines. A detail of this area is seen in Micrograph 20. A few connector assemblages may be seen in the general clay granular matrix. Micrographs 21 to 23 show areas rich in discernible fine particles and the general very open, often unstable appearance of these often single particle arrangements in both random and parallel oriented fabrics. Pore space is evenly distributed in all of micrographs shown with a fairly high abundance of inter-assemblage pores. Micrographs 24 to 26 show details of an area with few fines and the separation action of successively finer sand and silt can be clearly appreciated. The coarser particles are generally clothed in fines but the silt particles often appear clean.

In general the data obtained from these microfabric studies together with data from other tills, McGown (1973) shows that the fine particles of the matrix in these tills were arranged in systems previously recognised in a variety of other natural soils, Collins and McGown (1974). Although some areas in the tills were found to have very open particle arrangements which suggests that the formation of the small frontal moraine ridges or flutes was not a flow phenomenon but rather a deformation process. In fact, the fines were generally found to act as separators for the coarser particles or as surface coating to these with some areas richer in fines than others. Where clay sizes were present they were found in particularly open arrangements often acting as single particles, a phenomenon rare in other natural soils. The distribution of fines in the Blaisen tills was generally more uniform than in the Breidamerkurjokull till but both tills exhibited many common elementary, assemblage and pore space fabric features and the basic clast separation function of the matrix was common to all the samples viewed with no recognisable preferred orientation of the particles with respect to ice flow direction or other stress direction.

6.5.1.5. Discussion on Organisation of Particles in the Norwegian and Icelandic Tills.

It has frequently been argued that certain fabric characteristics of glacial tills, notably their long axis orientation, may be derived with little modification from englacial structures, e.g. Slater (1926) and Harrison (1957). Moreover, long axis orientation of elongate particles may represent the response of particles to the effect of an overriding glacier sole on debris at the depositional surface, Holmes (1941) and Glen et al (1957). More recently, Lindsay (1970) has explained englacial fabrics in terms of shear domains and their preservation in tills as a result of low basal sliding velocities, small controlling obstacle size (Weertman, 1964) and abundant basal melting. Thus, it can be argued that fabric analysis may provide information not only on directions of movement of former glaciers but also on the englacial and subglacial conditions of the depositing ice.

It has been shown by Harrison (1957) that planar clasts in glacier ice respond to the overburden stress provided by the glacier such that they assume a gentle to moderate upglacier dip. This shear domain and a secondary domain dipping steeply down glacier are very consistent and both lie in the plane containing the flow vector, Lindsay (1970). Stereograms showing the attitude of the a-b planes of englacial particles sampled in the course of this study generally confirm this conclusion.

In view of the consistency of the englacial fabrics and those from non-fluted melt-out tills, the proposition that the attitude of the a-b planes of clasts constitutes the primary fabric characteristics, with the long axis fabric for all clasts other than rods being the product of it, is worthy of further testing. It has previously been suggested by McGown and Derbyshire (1974) that the clast fabric, organised englacially, may change in response to variations in the englacial stress field up to the moment when debris is released. The released till which is commonly frozen and may contain up to 60 percent by volume of water equivalent, eventually melts out. The melting out process appears to control the organisation of the matrix, i.e. microfabric. As the overburden stress is transferred from the ice to the particles, some collapse appears to occur within the matrix notably in the connectors of silt and clay between granular particles. Hydraulic pressures may also activate such collapse. Associated minor adjustments may be expected in the clast fabrics.

In this process, the consistently higher dips of the a-b plane fabrics are partly modified, weakening the mode and perhaps rendering it multiple, while the long axis fabric, being less vulnerable, persists essentially unchanged. Late stage processes such as ice-loading and simple thrusting produce a variety of responses in the disposition of the clasts. Notable amongst these is an a-axis parallel to ice-flow in flutes but transverse to ice-flow in small annual push moraines which also exhibit predominantly downglacier-dipping planar clasts.

Under the commonly occurring condition of free, unloaded drainage with only very small stresses, perhaps associated with limited subglacial refreezing of melt water within the till (Hoppe and Schytt, 1953) modification of the clast fabric is limited to minor readjustments. The tendancy for mean dips of planar clasts to decline very soon after deposition is one expression of this process.

With stabilisation of the moisture content, the final depositional fabric is achieved and will remain unless modified by post-depositional processes. The amount of modification from frozen to deposited (draining) state, as expressed in both matrix and clast organisation, depends on several factors each susceptible to local variation. The asymmetry of the fabrics of planar clasts beneath the side slopes of small flutes provides one example. A second is the imposition of a planar clast fabric by limited (thin ice) overburden pressure on saturated till. In such a situation, high pore water pressures and thinness of the marginal ice minimise compaction, so that planar clasts align themselves within a plane parallel to the depositional surface while the matrix retains abundant pore spaces. With drainage, the clast fabric remains and localised collapse occurs in the matrix.

Such a sequence, consisting of release of frozen till followed by slow meltout in submarginal cavities and finally, the imposition of low overburden pressures as the glacier sole in the lee of the cavity impresses itself on the saturated till, has been observed beneath several temperate glaciers. In the case of fluted glacier soles, it appears to offer the best explanation of the planar clast fabrics found in till flutes. In the case of non-fluted surfaces made up of meltout till, however, the expected planar-clast fabric would be characterised by a well-developed mode dipping gently up glacier. Such a fabric may be indistinguishable from a fabric of englacial origin. Apparent similarity between planar-clast fabrics from within ice and those from proglacial sites cannot necessarily be used, therefore as grounds for describing such fabrics as of essentially unmodified englacial origin.

As the matrix, with its interstitial ice and water, is the stress transfer medium, the microfabric is indicative of processes occurring during and following deposition. Thus the microfabric of a melt out till will differ from that of a lodgement till in both compaction and the degree to which it is orientated about the clasts. All the examples of microfabrics so far illustrated are from silty melt out tills but distinctly different microfabrics have been observed in normally and overconsolidated tills, McGown and Derbyshire (1974). It has been properly pointed out by Boulton (1971) that analysis of clast fabrics alone is unlikely to provide an adequate basis for the understanding of till genesis. In this context, the study of particle organisation by means of analysis of a - b plane data for stones, gravels and coarse sands together with observation of the organisation of the silt and clay matrix would appear to go some way toward providing the fuller genesis and the processes of till deposition.

6.5.2. Microfabric Observations in Other Tills.

The extension of the clast fabric study into the sand grades detailed for the Norwegian and Icelandic tills in the previous section served to reinforce the conclusions drawn by other investigators from observations of the stones and gravels in numerous other tills. The microfabric studies were, however, only reported previously by McGown (1973) and then, prior to the introduction of the new microfabric classification system suggested by Collins and McGown (1974). Thus it was decided to extend and confirm this part of the investigation by viewing the microfabric of a few of the other tills included in this study. The tills chosen for microfabric study were the Antarctica till, a polar till, Cowal till, from Laglingarten, and Glen Orchy till. These two Scottish

Pleistocene tills were chosen to represent an average till, Cowal, and the till with the lowest proportion of fines of all the tills studied, Glen Orchy.

6.5.2.1. The Microfabric of Antarctica Till.

The sample from which the electron microscope specimens were obtained was itself taken from non-fluted till overlying lacustrine sediments a short distance in front of the Lacroix glacier which is frozen to its bed, the glacier being a small remnant of a wall sided glacier of polar type. The lithology of the till is dominated by granite gniess with minor components derived from dolerite and sandstone. The tills basic soil properties are as listed in Table 6.10 and the grading curve has been shown in Section 5, Fig. 5.90, to conform to the bi-modal pattern indicating the till to be the direct product of comminution. Despite its freshness and proximity to the glaciers, this till may be some thousands of years old and the well developed macro-fissility it exhibits, dipping 13^{o} down-slope approximately parallel to the dip of the basal surface of the glacier, may well be due to long term deep frost action.

The Antarctica till was somewhat finer than the Norwegian or Icelandic tills so far viewed thus the clay size elementary particle arrangements were more abundant in this till than the others, although the granular arrangements were still the more common with clothed granular arrangements a little more abundant than clean granular arrangements. Aggregation and matrices were again the most abundant basic assemblages in the till with a few connector assemblages to be seen. The pore space was predominantly intra-elemental and intra-assemblage with some inter-assemblage pores to be seen, much as for the other tills. In this case, however, large transassemblage pores, mainly in the form of fissures, transsected the till. The relative abundance of the various features are given in Tables 6.7 to 6.9.

Approximately fifty micrographs of this till were taken and the following are typical examples of these. Micrographs 27 illustrates at relatively low magnification, the general nature of the tills microfabric. A number of sand particles can be seen distributed through and separated by the general clay-granular matrix of particles. This is shown clearly in Micrograph 28 and in even more detail in Micrograph 29. Also to be seen in Micrograph 29 are aggregations, general matrix and a few fine connectors. Micrograph 30 shows in stereo an essentially granular area which is rather open with a few aggregations and assemblages including clay size particles. Micrographs 31 and 33 show fines rich areas in the till, for as with the other tills the texture of the soil is by no means uniform. In these finer areas the elongated medium to fine silt particles are sometimes interacting with clay size particles but mainly embedded in partly discernible finer particle arrangements. The intergrowth tendancy of these partly discernible features are illustrated in Micrographs 32 and 34. Many of the finer particles were like these, arranged in very open arrangements.

There is growing evidence that more maritime conditions than at present existed in Antarctica, Dort et al (1969) and Denton et al (1971), thus it may be that the Antarctica till specimen viewed may not be typical of polar ice deposition conditions. In fact overall the fabrics viewed in this till bear a striking resemblance to these viewed in the Norwegian and Icelandic tills.

6.5.2.2. Microfabric Observations in Laglingarten, Cowal Till.

As previously discussed in Chapter 4, the brown Cowal soils are in general Pleistocene melt out tills and from the data analysed in Chapter 5, they are the direct product of comminution. Basic engineering properties of the soils from the Laglingarten site are given in Table 5.10 and the range of particle size gradings is given in Fig. 5.16. In general no macrofabric features were observed in this soil.

Once again this till was predominantly granular in nature and the most abundant elementary particle arrangement was clean grain to grain arrangement with many clothed grains also in evidence. The high proportion of micaceous particles is evidenced by the high proportion of extremely thin flaky particles which in the finer size range are almost translucent. These clay size arrangements present were as both single and group arrangements of generally parallel stratified particles. Some clay size particles appeared to be full of flaws and holes and perhaps were badly weathered mica rock flour. These particles were almost totally arranged in granular matrices thus giving a rather compact appearance, with pore spaces being predominantly intra-elemental and intra-assemblage pore space. The relative abundances of these arrangements are detailed in Tables 6.7 to 6.9.

Over fifty micrographs of specimens from three bulk samples were taken for this soil. The variations between the specimens were not in the form of the particle arrangements present but in the compactness of those arrangements. The following micrographs are typical examples of the fabrics viewed. Micrograph 35 shows at relatively low magnification the general arrangement of particles. A particular feature of this is the presence of a transverse feature of parallel orientated particles which is most likely to be a shear feature. Micrographs 36 and 37 show areas outwith the "shear" zone at higher levels of magnification and the confused arrangement of particles in the general matrix arrangement can be clearly seen. The clothed grains and clean grains are also apparent. Micrograph 38 shows in stereo the open arrangement of particles with many very thin flaky particles, probably mica, trapped between more bulky grains or occasionally forming very open perhaps unstable arrangements. Micrographs 39 and 40 show at two levels of magnification an area relatively rich in fines and the crinkled and perhaps rather badly weathered clay-size particles shown in detail in Micrograph 40.

The arrangement of the particles in the "shear" zone indicated in Micrograph 35 is shown in Micrographs 41 and 42. The flaky nature of the particles is a particularly good indicator of the shear feature. Such shear zones may exist in the other tills with more bulky grains but they have not been detected.

6.5.2.3. Microfabric Observations in Glen Orchy Till.

This Pleistocene till was coarser than those previously viewed and as has been discussed in detail in Chapter 5, the gradings shown in Figs. 5.51 to 5.54 are split graded and the till is the direct product of comminution. The basic soil properties are as indicated in Table 6.10. The particles composing the till are predominantly bulky grains with only a few flaky particles in contrast to the Laglingarten till. No macrofabric features were observed in this till.

The very granular nature of this particular till has produced a very open easily observed fabric with some very good examples of the basic assemblages suggested by Collins and McGown (1974). Although granular in nature, the fabric was not entirely uniform with many areas finer than others. The grains were, however, predominantly clean and the very few clay size particles present were generally in parallel oriented groups. The pore spaces were again predominantly intra-elemental and intra-assemblage with a few inter-assemblage pores. The size of pores was in this case noticeably larger than in previous cases due to the coarseness of this till. The detailed apparent relative abundances of the various fabric arrangements are detailed in Tables 6.7 to 6.9.

Once again some fifty micrographs were taken and the following are typical examples of the fabrics observed. Micrograph 43 shows the areal variation in coarse and fine particles in the till. The profusion of clean bulky grains in the general granular matrix can be seen with the lack of any ordered orientation once again apparent. Micrographs 44 and 45 show two connector assemblages in detail one composed of relatively coarse grains and the other composed of relatively fine grains. A detailed view of the latter connector is given in Micrograph 46 and the parallel orientation of the fine grains may be seen. Micrograph 47 shows an aggregation assemblage of granular particles from the coarser area of Micrograph 43, which is likely to act as an individual unit. Micrographs 48 and 49 show at two levels of magnification, detailed arrangement of particles in the finer areas of Micrograph 43. In fact very few clay particles are to be seen and the fines are dominantly fine silt.

The fabric of this till is the coarsest viewed and the particles are generally bulky in nature which leads to the very open appearance of the fabric. There does not appear to be any preferred orientation of particles with granular matrices being the most abundant fabric arrangements present.

6.5.2.4. Discussion on Observed Microfabrics.

The micro-fabrics of the Antarctica, Cowal and Glen Orchy tills confirm the observations made of the microfabric of the Blaisen and Breidamerkurjokull tills. All these tills exhibited a similar range of fabric features although they represent tills derived from different lithologies, both modern and Pleistocene age soils and some much coarser gradings than others. In all of them, however, the distribution of coarse and fine particles was patchy. The clasts were also unevenly distributed in the clayey silt mass of the till.

The micro-fabric features viewed were similar to those recognised by Collins and McGown (1974) in a variety of other natural soils. The most abundant elementary particle arrangements were granular with both clothed and clean grains in evidence. Where clay size particles were present they were arranged just as often in groups as in single particle arrangements. The presence of this latter arrangement is in fact rare in most natural soils, Barden (1972), Collins and McGown (1974). Granular matrices were the most abundant basic assemblages with few higher order assemblages noted. Some aggregations, generally regular, and some connectors were observed in most of the tills and the pore space was dominantly intra-elemental and intra-assemblage pores with a few inter assemblage pores.

No definite spatial distribution of the matrix of clayey silt was detected in the tills, in contrast to the observations of Korina and Faustova (1964). The matrices in fact appeared to act as a separaters and supports for the clasts as previously discussed by McGown (1973). The very open nature of these matrices and the apparently unstable nature of many of the connectors observed may be shown to compare quite closely to the microfabrics observed in collapsing soils by Barden, McGown and Collins (1973). As discussed previously the distribution of fines was patchy and this was to some extent associated with an uneven distribution of openness in the soils which would influence greatly the instability or otherwise of the till microfabrics.

6.6. CONCLUSIONS ON ORGANISATION OF PARTICULATE MATTER IN MELT-OUT TILLS.

Considerations of the present observations together with comparisons to previously reported observations on similar melt out tills suggest that the following conclusions may be drawn:-

a) Predictions of particle organisation made on the basis of the composite soil model for split graded till produced by direct comminution, are in general borne out by the trend of variations in in-situ dry densities and by fabric studies in the tills. As suggested from the composite soil model, the percentage of fines in the tills were such that they were either well graded, matrix dominated or matrix controlled, Glen Orchy till being a very notable exception to this.

b) The clasts in the tills from Blaisen and Breidamerkurjokull Glaciers clearly exhibited spatial orientations inherited from the active ice stress field. It has however, been found that the englacially organised clast fabric may change in response to variations in the englacial stress field up to the moment the debris is released. Only minor adjustments to clast fabric occur thereafter under the commonly occurring condition of free, unloaded drainage with only small stresses set up by limited subglacial refreezing of meltwater in the till.

c) Organisation of particles making up the matrix of the till takes place during melt-out of dormant ice. As the till is released from this dormant ice, the overburden stress is transferred from the ice to the particles and some collapse of the englacial fabric of the matrix occurs. Hydraulic pressures may also activate such collapse where these pressures are built up in conditions of poor drainage. Such readjustments of the matrix no doubt cause some readjustments of the clast fabric, however, these will not always be sufficient to completely destroy the englacially imposed orientations. The amount and nature of the matrix reorganisation from the englacial state will depend on numerous factors, particularly rate of melt out, local drainage conditions, grain sizes and shapes and particle size distributions.

In a matrix controlled or matrix dominated till, the matrix will act as the stress transference media during and after deposition. Thus any glacial tectonic or locally imposed overburden stress will be recorded in this matrix, perhaps as shear planes or local zones of compaction. It is therefore suggested that the study of the organisation of particulate matter in tills should be carried out at all levels in order to provide a fuller and better understanding of the depositional process associated with tills.

d) In the particular tills studied the sand grade was found, from both fabric and granulometric observations, to be the size grade at which change from clast to matrix behaviour occurred. Sometimes the sand size particles acted as clasts, sometimes they acted within the matrix. Considerable variations in the degree of contact of clast-size particles in these melt-out tills were also noted and the consistency of the clast fabric was found to vary accordingly. Diffuse modes in fabric diagrams, of both a-axis and a-b plane type, appeared to be due primarily to the degree of clast interference and, secondarily, to the range of clast shapes in the till. Thus the strength of the a-b plane fabric mode varied directly with the clast flatness index and, as might be expected, variation in the fabric mode for tills with equidimensional clasts, including thick wedge forms, tended to be less in matrix-dominant tills with similarly-shaped clasts. Clast shape also determined the degree to which a-axis and a-b plane fabrics were complementary in any till sample.

e) The nature of the microfabric for all the tills studied was distinctive and fairly consistent from one till to another. When analysed according to system suggested by Collins and McGown (1974) the elementary particle arrangements, particle assemblages and pore space features were all recognised as being similar to those viewed in many other natural soils from a wide variety of depositional processes. A characteristic of the till microfabric was the patchy distribution of the coarser and finer particles comprising it. It is probable that this uneven distribution is inherited from the englacial state which would confirm Elson's (1961) suggestion for englacially water entrapped fines, but as suggested previously, the detailed geometrical arrangement has been reorganised during the melt-out process and the final fabric viewed need not be the same as the englacial fabric.

The microfabric was also found to vary in degree of openness and these variations existed within specimens and between samples of the same till. Thus the degree of openness appeared to be a locally variable property of the microfabric. In matrix controlled or matrix dominated tills, the overall dry density may then be expected to vary greatly and locally. The reported variations of the in-situ dry densities in the Cowal, Icelandic and Norwegian tills confirm this, always taking account of the variations in dry density due to gradation. Some of the very open microfabric arrangements observed would also explain the very low dry densities measured in the Cowal till, although as discussed previously these low results may be due, to some extent at least, to sampling errors. The trend towards low dry densities is nevertheless evident and may reasonably be associated with the open microfabrics observed.

f) Investigations of the organisation of particulate matter in undisturbed basal melt out tills, at all levels of fabric has thus been shown to be necessary if the depositional process is to be better identified. The present series of observations have therefore included field and laboratory macrofabric observations together with scanning electron microscope microfabric studies. These studies have confirmed the applicability of the composite soil model postúlated for split graded tills and demonstrated the action of the matrix as the separator and support of the clasts in the tills. The Icelandic till, which is an admixture of glacial fluvials and till has been found to act in a similar manner, although the break between clast and matrix, identified as in the sand-size grade in other tills, is not easily identifiable in this till.

CHAPTER 7. ENGINEERING PROPERTIES OF BASAL MELT OUT TILLS.

7.1. THE FACTORS USED TO DISTINGUISH AND CLASSIFY TILLS FOR ENGINEERING PURPOSES.

Many attempts at classifying tills have been made on the basis of the principal components of their particle size distribution, and some were described previously in Chapter 5, but the engineering properties of tills, as Beskow (1951) reports, depend in a rather complex manner on the different size fractions present. The method of classification of tills suggested by the Swedish Statens Vaginstitut is based on size fractions in the tills and is a rather involved system as shown in Fig. 7.1. As an aid to classification another Swedish investigator, Bernell (1957), suggested the use of the Linear Shrinkage Difference, i.e. the difference between the shrinkage limit of the soil and the tangent value of liquid limit taken from the plot of liquid limit against maximum grain size included in the liquid limit test, Fig. 7.2. This factor cannot be considered as consistent in relation to the properties of till and it also makes use of rather laborious testing techniques. It is therefore of limited use.

The "composite soil" concept outlined in the previous Chapters, permits the identification of the fractions composing the tills and thereby utilises the fundamental nature of such comminution tills. The possibility of identification of the constituent soil fractions therefore permits a new system of classification to be suggested based on the identity of fines in these soils, the coarse fraction generally being a sandy gravel or a gravelly sand mixed with the fines in various proportions. It is of course recognised that it is insufficient to describe tills by their fractional composition alone, a number of other factors must be described. The data which are required for classification of unstratified basal melt out tills might be as follows:

a) Topographic form
b) Mode of deposition
c) Lithologic composition
d) Particle size distribution
e) Classification of soil fractions
f) Range of composition of coarse and fine fractions.

Having suggested the data required to classify melt-out tills, it is necessary to exemplify the influence of each item on the properties of these soils and thus confirm the need for its inclusion in the system.

a) Topographic Form - As yet no correlation between properties of tills and topographic form has been established but the study is not so far advanced as to allow this to be conclusive.

b) Mode of Deposition - The distinction between supraglacial and upper basal tills is important with regard to the in-situ behaviour of the soils. The generally greater average density of the latter is likely to increase its strength and decrease its permeability and compressibility relative to the former.

c) Rock Composition - The constituent rock types will, as described in Chapter 5, influence to some extent the grain size distributions derived during comminution, will indicate the influence of weathering on the aggregate and determine the mineralogical content of the fines. The identification of the rock types is therefore important.

d) Particle Size Distributions - The particle size distributions of unstratified ablation tills considered as a complete grading has been shown to vary greatly even in the same deposit. However, when the tills were considered as a mixture of two or more soils in varying proportions then a high degree of conformity is found within tills with the same parent rock types and glacial history. The grading can, therefore, be used together with the rock composition as a means of classifying these soils.

e) Classification of Soil Fractions - The coarse soil fractions may generally be described as sandy gravel or gravelly sand and since most of the tills studied are matrix dominated, its influence on the properties of the till will be to modify the properties of the fine fraction to some degree, depending on the amount of coarse fraction present. The fine soil fraction is, therefore, the indicator for the properties of the till. For this reason the tills should be classified according to the identity of the fine soil fraction.

f) Range of Composition of Till - The range of the mixture of the coarse and fine soil fractions of the tills will dictate the degree to which the properties of the fine soil fractions are modified to be the properties of the tills. Generally in a deposit, the range of the mixture will vary within determinable limits, e.g. 50 to 70 per cent fine soil fraction, when considering say less than 100 mm diameter particles, although there will be exceptions to this. The

degree to which the fine soil fractions properties will be modified are, therefore, generally determinable.

Adopting this approach, the variations in the engineering properties of the tills may be reconsidered and the influence of the mode of formation and deposition of the tills may be identified. By virtue of the characteristic rapid changes in gradation and density of in-situ tills, detailed investigations of the in-situ properties have not been undertaken. Nevertheless, in-situ engineering properties have been used when available as comparisons to the measured variations in properties. In reconstituted tills, it is possible to vary both gradation and density in a controlled manner and thereby study the relative influence of these. In many prototype situations anyway, the tills are excavated and recompacted such as in roads or dams hence the data from reconstituted tills have direct application.

The properties which have been examined are the compactibility of the tills, the permeability and shear strength. In each case the influence of grading has been established and in the latter two, the influence of density has also been considered. The implications of these measured variations have also been assessed in terms of the variations likely in in-situ tills.

7.2. IN-SITU AND LABORATORY DETERMINED DENSITIES OF SOME TILLS.

7.2.1. In-Situ Dry Densities of Basal Melt out Tills.

In Section 6.3 the in-situ dry densities of Cowal and Hardangerjokulen "composite" tills were considered and density determinations at Breidamerkurjokull Iceland were also analysed. These indicated that a great deal of fluctuation in the dry density is characteristic of the mode of formation of basal melt out tills. A particular feature is the occurrence of extremely low dry densities sometimes lower than obtainable by pouring dry till through air in a laboratory. The in-situ dry densities of the composite tills, however, conform in general to the trend of density range determined by laboratory techniques, as described in Section 6.2. Thus in-situ tills will have dry densities determined principally by their mode of deposition, the proportion of fines and local variations in these factors. Other factors will of course influence the densities achieved such as the shape of particles and nature of fines, in particular whether clay minerals are present or not. The inherent variability of in-situ dry densities of basal melt out till is therefore a feature to be recognised and is one that will greatly influence the values of other in-situ engineering properties such as permeability and strength.

7.2.2. Laboratory Investigation Programme.

7.2.2.1. The Influence of Mixing in Gravel in the Field.

While soil sampling in various Forestry Commission areas, a careful note was taken of the methods used in construction of the forestry service roads. In-situ density measurements were taken, McArthur (1969) from roads where different blends of aggregate had been used in base construction in order to compare the constructional qualities of each mix. The results showed that low densities were being achieved when the tills were used without blending with a coarser aggregate. The addition of river gravel or crushed rock, the quantity of which was determined purely by field experience, gave immediate improvement in the density and stability although it was noticed that there was still a lack of binder in the material.

The marked improvement measured in field densities due to alteration in the gradation of the till together with the preliminary investigation of variations in dry density with percentage fines carried out to validate the composite soil model, Section 6.2, led to a fuller investigation of the relationship between dry density, moisture content, percentage fines and compactive effort. The investigation was, however, limited to the relationships determined for a single standard dynamic compaction technique using a standard compaction mould, thus the limitations imposed by other factors which influence achievable density but are not investigated here are detailed and reviewed in Section 7.2.3.

7.2.2.2. Test Apparatus, Procedures and Materials Tested.

Samples from the Argyll County roadworks in Laglingarten, Cowal and Forestry Commission roadworks in the Corrour and Strathyre Forests were used for the investigation. The samples were first oven dried then dry sieved to remove the materials retained on the B.S. $\frac{3}{4}$ inch Sieve. Additionally, the samples were separated into their coarse and fine fractions on their split sizes determined in Chapter 5. As dry sieving had been used, the coarse fraction was then washed, dried and resieved to remove all traces of fines from their surfaces. The average and range of gradings obtained by separate wet sieving for the in-situ materials from the three sites are shown in Fig. 7.3.

Specific gravities of the fines and coarse materials were determined for each sample using the Pycnometer bottle method, Test 6 (B), B.S. 1377: (1967). The average values of the specific gravity measured are detailed in Table 7.1. Although the pycnometer method is not the most accurate method of determining specific gravity it was considered sufficiently accurate for the purpose of this particular study.

The laboratory compaction tests were carried out using the automatic compaction apparatus shown in Plate 7.1, so that a reasonable degree of accuracy and reproducibility of compactive effort could be applied to the soils. The soils were compacted into the standard C.B.R. mould, 152 mm (6 inches) diameter and 127 mm (5 inches) high, to reduce the effect of the container to a reasonable level as discussed in Section 7.2.4. For each of the three soils, test specimens were compacted in five layers, using a free falling 4.5 kg (10 lb) hammer moving through a height of 45.7 cm (18 in). The number of blows per layer was, however, varied from 5 to 55 blows and the moisture contents and proportion of fines and coarse materials varied between tests, in order to study the influence of these factors.

Moisture content dry density plots were constructed for each fines content in order that the maximum dry densities and optimum moisture contents could be determined. Also for each percentage fines content test programme, the percentage crushing of particles was determined for each compactive effort by resieving. Plots of percentage fines against maximum dry densities were constructed for each compactive effort used so that the relationship between these factors could be further assessed. In addition, plots were constructed of maximum dry density against total number of standard compaction blows applied to the test specimen. Since energy input equals total number of blows, times weight of hammer, times height of fall, times number of layers, then for samples compacted in the adopted manner, the energy input equals a constant times total number of blows.

7.2.3. Some Factors Influencing Laboratory Compaction.

7.2.3.1. Mode of Compaction.

In laboratory compaction tests, every effort should be made to simulate field conditions and at present three modes of compaction are widely used, namely impact, kneading and vibratory compaction techniques. A fourth method, static compaction is also used when it is desired to study the effect of a number of variables but maintain a constant dry density, however, it is not normally considered analogous to field compaction.

During compaction by impact or kneading high overall shear strains are imposed on the surface of the soil which induce soil particles to take up their most economical spatial arrangement. In vibratory compaction, the particles are set in motion and allowed to find their most economical spatial arrangement by a "trial and error" placement procedure. The various techniques have limitations in terms of their applicability to the various soil types, however, where they can be used on the same soil it is found that the greater the interaction of the particles during compaction, the greater is the amount of energy required to attain maximum dry density, Road Research Laboratory (1964), Highway Research Board (1962). If the soil is cohesive, the confining action of the compaction mould may in the laboratory tests induce the build up of significant pore pressures within the soil which have the effect of lowering the achieved dry density. Thus the type of compactive effort applied and the type of soil to which it is applied influence achievable dry density in compaction tests and these factors are not measured in the present programme of testing.

7.2.3.2. Effect of Compaction Mould Size.

The early compaction experimentation of Proctor (1933) was restricted to tests on material with a maximum size of 5 mm in a mould 1.1 x 10^{-3} m^3. MacLean and Williams (1948) showed that using the standard 0.994 x 10^{-3} m^3 (1/30 cu.ft.) mould, no significant changes occurred in maximum dry density and optimum moisture content until a maximum of 38 mm ($1\frac{1}{2}$ inch) aggregate was introduced.

This led to the British Standard's adoption of the use of material passing B.S. $\frac{3}{4}$ inch sieve in the standard compaction tests, Test 11, B.S. 1377 (1967). The present investigation uses the larger C.B.R. mould but retains the size limit of less than B.S. $\frac{3}{4}$ inch sieve size material only tested and container size errors are therefore reduced to a minimum.

7.2.3.3. Influence of Particle Shape.

Particle shape also influences dry density achieved and optimum moisture content and Holtz and Lowitz (1957) have reported for angular and rounded gravels of the same grading that the fines in the angular gravel produced the higher maximum densities and lower optimum moisture contents in impact tests. A particular study of particle shape was not made in the work reported herein but due to the difference in lithology of the tills tested particle shape differences existed and probably were a contributory factor to the differences in achievable densities measured.

7.2.3.4. Influence of Coarse Aggregate Content.

Due to the restrictions placed on the maximum size of the aggregate by the size of the compaction mould it became important to investigate the effect of the percentage of coarse aggregate in the soil fraction under test. It is reported by the Highway Research Board (1962) that when working with a sand-silt-clay mixture of 58, 18 and 24% respectively, it is found that the admixture of up to 25 per cent single size aggregate of either 9.5 - 13 mm ($\frac{3}{8}$" - $\frac{1}{2}$"), 13 - 19 mm ($\frac{1}{2}$" - $\frac{3}{4}$"), 19 - 25.4 mm ($\frac{3}{4}$" - 1"), grading had little effect on the compaction of the soil mortar but merely acted as a displacer. At higher coarse aggregate contents the dry density of the soil mortar fraction decreased rapidly, but the combined soil continued to increase in dry density up to a coarse aggregate content of some 50%. At 70% coarse aggregate content the contact between the coarse aggregate prevented compaction of the soil mortar and the dry density of the combined soil fell. Further experiments with a graded coarse aggregate produced similar results, but the dry density of the soil mortar decreased on the addition of even small quantities of coarse aggregate. This decrease as shown in Fig. 7.4 was not serious until about 45% coarse aggregate.

Mainfort and Lawton (1952, 1953) suggested when investigating highway fill material of continuous grading passing 38 mm (1½"), that the amount of coarse aggregate (plus No. 4 U.S. sieve size) which could be added to a soil mixture before decrease in dry density occurred was approximately 60 per cent. Fig. 7.5 shows the curve produced for a gravelly soil which had been crushed to provide the required grading. The optimum point occurred at approximately the same point in both 102 mm (4") and 152 mm diameter (6") moulds showing that the decrease in dry density is a function of the gradation of the soil and not of arching or restriction in the mould.

Holtz and Lowitz (1957) in their investigations into the compactive characteristics of gravelly soils found that the percentage gravel which could be added depended on the fineness of the soil mortar, a higher percentage gravel being permitted in silty and clayey soils. In this case compaction was undertaken in large mould 487 mm diameter x 229 mm deep (19.2" diameter x 9" deep) compaction effort, 12.06 x 10^6 m KN/m^3 (12,135 ft. lb/cu.ft.) on material passing the 76mm (3") sieve and in a 1.4 x 10^{-3} m^3 (1/20 cu.ft.) mould using a compactive effort of 12.28 x 10^6 m KN/m^3 (12,375 ft. lb/cu.ft.) on material passing the 19 mm (¾") sieve. Fig. 7.6 shows the percentage gravel maximum dry density plot and the grading curves for a sandy gravel.

The conclusion drawn from Fig. 7.6 is that the dry density of the total soil starts to drop at a gravel content of some 70 per cent for the 76 mm (3") maximum size soil and 60 percent for the 19 mm ($\frac{3}{4}$") maximum size soil. It would appear then that the permissible gravel content for maximum dry density, would be somewhere between 45 and 80 percent, depending on the type and gradation of the soil and that the compactive effort and mould size have little effect on these values.

7.2.3.5. Consequences of Particle Degradation.

Mainfort and Lawton (1953) studying the éffects of degradation of a sandy gravel found that the breakage of coarse aggregate (plus No.4 U.S. sieve) increased with the increasing percentage of coarse aggregate, but did not become significant in a 102 mm (4") diameter mould until 30% coarse aggregate had been added to the soil mortar.

The effect of the size of mould was found to be slight. The most significant feature of degration was that it not only influenced dry density directly, by producing a particle size distribution that would yield a higher dry density (should the existing percentage fines permit) but that it also results in a change in the specific gravity of the total soil. A correction factor of the ratio $\frac{\text{apparent specific gravity before compaction}}{\text{apparent specific gravity after compaction}}$ is applied to any maximum dry density where crushing is not expected to occur in the field.

7.2.3.6. Effect of Moulding Water Content.

This is by far the most important factor that effects the compaction of soils. The increase in dry density of a soil produced by compaction depends mainly on the moulding water content. With a given amount of compaction there exists, for each soil, an optimum water content at which a maximum dry density is obtained.

When the water content is low, the soil tends to be stiff and is difficult to compress. This condition gives low dry densities and high air contents are obtained. As the water content increases the water acts as a lubricant, causing the soil to soften and become more workable. This results in higher dry densities and lower air contents. When the air content reaches a minimum value, the water and air combination tend to keep the particles apart and prevent any further decrease in air content. The total voids, however, continue to increase with water content and hence the dry density of the soil falls.

7.2.3.7. Influence of Gradation.

It has been noted in the chapter on compaction that the increase in the maximum size of aggregate led to an increase in maximum dry density. This was attributed to the attainment of a better distribution of particle size and the more efficient transmission of compactive effort to the fine fraction of the matrix by the coarse fraction.

It has been found that the control of the gradation of a material in such a manner as to produce the minimum voids will, if no excessive pore pressures are built up, produce material of high dry density and thus stability.

The mathematical expression developed by Talbot, Fukuoka (1957), to produce a soil model in which the voids in any size fraction are filled by the next smaller fraction is:-

$$p = (\frac{d}{D})^n \times 100 \text{ ...... Eqn. 7.3}$$

p = percentage passing a sieve

D = maximum size of material

d = opening size of sieve

n = a variable parameter called the gradation index

Fuller and Thompson (1907) working on the proportioning of concrete aggregate showed that a granular mass has a relatively high density when its particle size distribution followed Talbot. Gradation Law with a gradation index of 0.50. This falls within the specifications laid down by the Ministry of Transport for various road sub-bases, bases, etc. thus giving an indication of the gradings which would be required for the use of the material for these various purposes. In practice it has been found that it is usually necessary to have a greater proportion passing the B.S. 200 sieve size than is given by this gradation index in order to obtain sufficient cohesion. It should be noted that Fuller was working on concrete aggregate and in this case cement would be used as binder. Table 7.2 shows the proposed limits laid down by the Ministry of Transport and Fig. 7.7 some of the more relevant particle size distribution curves with Fullers curve plotted on.

Later work by Fukuoka (1957) on granular soils found that maximum dry density increased with an increase in the value of "n" and that the value of unconfined compressive strength decreased with increasing values of "n". Having tested a series of soils with "n" values from 0.15 - 0.55 Fukuoka deduced, on the basis of his unconfined compression tests, that the ideal material for earth fills was one with a gradation index lying between 0.25 - 0.35.

Having a clear indication of the shape of the particle size distribution curve required for stability one can compare it with the soil which is to be compacted. It may be necessary to remove from or add to the natural soil a specific fraction, the blending of which may be carried out by use of such procedures shown in Road Note No. 4 (1962).

7.2.4. Dry Density, Moulding Water Content and Compactive Effort Relationships.

To determine their relationships, compaction tests were conducted at various compactive efforts with different soil gradations. During the tests, the standard C.B.R. mould was found to leak at high water content, therefore, rubber seals were fitted to reduce leakage to a minimum. Considerable difficulty was also found in trimming the samples with low fines content, the disturbance of the coarse gravel being high. The samples were therefore trimmed and carefully flushed off with extra material left over from the test.

It was found from the tests that all but one of the reconstituted tills tested exhibited a normal dry density - moulding water content relationship Figs. 7.8 to 7.10. The coarser gradings from Corrour Forest were free draining sandy gravels and showed increasing optimum moulding water content with increasing compactive effort.

Also the lower values of moulding water content tended to give higher dry densities than the intermediate ones, thus confirming the work of the U.S. Bureau of Reclamation (1965) and Pellegrino (1965) that free draining sandy gravel compact best either dry or saturated.

7.2.5. Gradation - Compaction Characteristics.

The effect of varying the percentage fines content has been studied for the three tills. Fig. 7.11 to 7.13 show the plots of maximum dry density against percentage fines content and the trend exhibited by the plots has been checked at values of water content ± 5% of optimum water content, Figs. 7.14 to 7.18.

It can clearly be seen in Figs. 7.11 to 7.18 that the tills follow the same dry density-percentage fines relationship exhibited by similar soils tested by the Highway Research Board (1962) Mainfort and Lawton (1952, 1953) and Holtz and Lowitz (1957). The results show that there is an optimum grading for maximum dry density. This occurred at the 25, 20 and 40 per cent fines values for Strathyre, Laglingarten and Corrour respectively. It is considered that the range of 15-45 per cent fines content will probably include the optimum values of percentage fines with respect to dry density for most of the Scottish tills.

It should be noted that small compactive effort produces a significant increase in dry density for all gradings but at, or near, the optimum percentage fines content, further increase in compactive effort produces little increase in dry density. The conclusion drawn from this is, that soils which exist or are reconstituted to the optimum percentage fines content will give higher relative values of dry density for lower, moderate, energy input.

It is of interest to note the relationship between the optimum gradation curves for the Laglingarten, Corrour and Strathyre tills and those given by Talbot, Fukuoka (1957), for varying values of gradation index "n" as shown in Figs. 7.19. This plot shows that the optimum values of "n" quoted by Fukuoka, i.e. 0.25 - 0.35 are in the main substantiated by the experimental curves. The lack of binder in the tills tested is however clearly shown in this figure.

7.2.6. Crushing of Aggregate During Compaction.

Acknowledging that crushing of the aggregate will take place during compaction, with subsequent changes in gradation of the material, checks were taken of the increase in percentage fines for varying levels of compaction in the Laglingarten and Corrour tills which exhibited the limiting conditions of compaction behaviour. Crushing data are presented in Fig. 7.20 and 7.21 for the particle size distributions of Laglingarten and Corrour tills before and after 55 blows, on five layers in the C.B.R. mould, from a 4.53 Kg. (10 lb) hammer falling through 457 mm (18 inches). From these it is apparent that the crushing effect is inversely proportional to the percentage fines content of the material and that the greatest degree of crushing is experienced under the initial compactive effort.
The different responses of the Laglingarten and Corrour tills, 26 percent and 19 percent increase in fines respectively, clearly indicates the influence of the differences in lithologies of the two tills.

7.2.7. Consideration of Data From Other Tills.

Data relating to water content - dry density relationships of numerous other Scottish and foreign tills are available and confirm that generally tills have a normal response. No other complete dry density-percentage fines investigation has, however, been found, therefore no further confirmation of the relationships determined is possible. However, there is no reason to believe that the relationships established for the Scottish tills tested are unique as they are similar to those previously described for other soil gravel mixtures by the Highway Research Board (1962) Mainfort and Lawton (1952, 1953) and Holtz and Lowitz (1957).

7.2.8. Discussion of Till Compactibility.

The field evidence collected by McArthur (1969) of the improvement of till compactibility in roadworks when mixed with gravels to give much coarser gradings has in fact been borne out by the laboratory investigations. While it is recognised that the mode of compaction in the laboratory is not necessarily the same as in the field, the trends established are most probably the same. Thus it may be stated that the tills behave in a conventional manner and exhibit normal dry density, moulding water content relationships. They also follow dry density - percentage fines relationships similar to those previously established for other soils.

However, when these relationships are compared to the variations of grading in the tills, detailed in Chapter 5, and to their natural moisture contents as detailed in Table 7.3 an understanding of the problems of compacting and compaction control becomes evident. Only the very sandy Corrour Till has an average natural water content approaching the optimum while the other two are very much wetter in their natural condition. Incidentally, the very high natural water contents also confirm the very open particle arrangements of some of the in-situ soils, as noted in Chapter 6, as extremely large void space is necessary to contain such large water contents. Also from Figs. 7.11 to 7.18, it is evident that grading has a greater overall influence on achievable density than has applied compactive effort. For the natural range of gradings determined for most of the tills the part of the dry density-percentage fines plot applicable in most cases is that for percentage fines content greater than 25 or so percent which represents the matrix dominated and matrix controlled regions and perhaps the well graded region. In these regions, the dry density percentage fines plot varies almost linearly and the influence of compactive effort increases somewhat with increasing fines. Therefore in the construction situation in roadworks or dams, the achieved dry density for any compactive effort is by no means a constant and the sensitivity of the soil to variations in compactive effort is also a variable.

Taking the data relating to in-situ densities discussed in Chapter 6 together with the investigations discussed in the previous sections, it is apparent that basal melt out tills in their in-situ condition may well have a very variable dry density due not only to variations in their mode of deposition but also to their gradings at the time of deposition, which from Chapter 5 is known to be highly variable.

In summary, problems which may arise when recompacting the till to a specification in roadworks and dams may be associated with the variation in grading and with the wide range of natural moisture contents sometimes exhibited by these soils. In particular compaction problems may result from the very high water contents of the tills attained by virtue of their very loose in-situ particle arrangements. The mode of formation and deposition of basal melt out tills thus greatly influences their compactibility.

7.3. VARIATIONS IN PERMEABILITY OF MELT OUT TILLS.

In the design of earth fill dams, a knowledge of the permeability of the material used is very important, not only in relation to the stability of the dam slopes but to the rate of construction possible and the rate of consolidation of the fill. Melt out tills have been used in construction of many dams, therefore the permeability of the tills is one of their most fundamental and important properties.

7.3.1. General Considerations Relating to Measured Permeability.

The law of flow of water through soil was first studied by Darcy (1856) who demonstrated experimentally that for laminar flow conditions in a saturated soil, the rate of flow or discharge per unit time is proportional to the hydraulic gradient.

$$q = kiA \qquad \text{Eqn. 7.4}$$

or $$v = \frac{q}{A} = ki \qquad \text{Eqn. 7.5}$$

where q = discharge per unit time.

A = total cross sectional area of soil mass, perpendicular to the direction of flow.

i = hydraulic gradient.

k = Darcy's coefficient of permeability.

v = velocity of flow, or average discharge velocity.

Since Darcy's law was proposed, many permeability investigations have been carried out over a wide range of soil types. Depending on the soil type and other important factors, confirmation and disagreement with the law have both been expressed. Where disagreement has been met the deviations have been found to be either one of two main types.

i) increasing hydraulic gradient causes either an increase or a decrease in flow rate.

ii) a threshold gradient exists that must be exceeded before flow occurs.

Generally, where the soil involved has been largely sand then reasonable agreement with linear flow behaviour has been found. On the other hand, where the soil has contained fine grained particles, many deviations from Darcy's law have been recorded. Causes of the invalidity of the law have been expressed variously in terms of electroviscous drag, Kemper (1960), plugging and unplugging of voids, Martin (1962), Mitchell and Younger (1966) and Younger and Lim (1969), quasi - crystalline water structure, Low (1960), and experimental error particularly from contamination of the measuring tubes, Olsen (1965).

In fact, the investigations of Younger and Lim (1969) were conducted on till from Backwater Dam which has previously been considered in Chapter 5. The data presented by them will thus be discussed later in this chapter with respect to the influences of percentage fines content and applied hydraulic gradient on measured permeability.

Now Darcy's coefficient of permeability is the average discharge velocity of the pore fluid for flow through soil of unit area under a unit gradient. The permeability value thus depends on the characteristics of both pore fluid and the soil. An equation reflecting the influence of the pore fluid and the soil characteristics on permeability was developed by Taylor (1948) using Poisuille's law. This equation is based on considering flow through porous media to be similar to flow through a bundle of capillary tubes.

$$k = D_s^2 \cdot \frac{\gamma}{\mu} \cdot \frac{e^3}{1+e} \cdot C \quad \text{.................... Eqn. 7.6.}$$

where k = the Darcy coefficient of permeability

D_S = some effective particle diameter

γ = unit weight of pore fluid

μ = viscosity of pore fluid

e = void ratio

C = shape factor.

In fact Eqn. 7.6 is a simplification of the Kozeny - Carmen equation, Carment (1956).

$$k = \frac{1}{k_o S^2} \cdot \frac{\gamma}{\mu} \cdot \frac{e^3}{1+e} \quad \text{.................. Eqn. 7.7.}$$

where k_o = factor depending on pore shape and ratio of length of actual flow path to soil bed thickness.

S = specific surface area

From Eqns. 7.6 and 7.7 the factors affecting permeability may be identified to be as follows:-

i) Properties of the pore fluid

ii) Grain size

iii) Void ratio of the soil

iv) Geometrical arrangement of the particles

v) Entrapped air and foreign matter

vi) Absorbed water in clayey soils.

i) Properties of Pore Fluid.

The permeability of a soil specimen is directly proportional to the unit weight of water and inversely proportional to its viscosity. Though the unit weight of water does not change much with the change in temperature, there is a great variation in viscosity with temperature. Hence when other factors remain constant, the effect of the property of water on the values of permeability can be expressed as

$$\frac{k_1}{k_2} = \frac{\mu_2}{\mu_1} \qquad \text{.............................. Eqn. 7.8.}$$

It is usual to convert the permeability to a standard temperature of $20^{o}C$ for comparison purposes but the influence of μ and γ may be eliminated as variables by defining the specific or Absolute Permeability (K) as :-

$$K = \frac{k\mu}{\gamma} \qquad \text{.............................. Eqn. 7.9.}$$

(Muskat 1937)

Viscosity and density are not the only characteristics of the pore fluid that influence the permeability of fine grained soils. Electro - osmotic backflow, i.e. the movement of pore fluid in the opposite direction to net fluid flow because of electrical potential generated by the fluid flow, and the mobility of the fluid immediately adjacent to the soil particles have both been shown by Michaels and Lin (1954) to depend on the polarity of the pore fluid.

ii) Grain Size.

Permeability varies approximately as the square of the grain size. Since soils consist of many different sized grains, some specific grain size has to be used for comparison. Hazen (1892), based on his experimental work on filter sands of particle size between 0.1 and 3 mm, found that the permeability could be expressed as

$$k = 100\ D_{10}^{2} \quad \ldots\ldots\ldots\ldots\ldots \text{Eqn. 7.10}$$

where k = coefficient of permeability (μm/sec)

D_{10} = effective diameter (m)

The degree of uniformity of particle sizes also has an important bearing on the water transporting capacity of the soil.

A uniformly graded material has a higher porosity than a less uniform mixture of fine and coarse material with the same average size, thus it will also have a higher permeability, Johnson (1966). A method of estimating uniformity has been provided by Hazen (1892) who defined the uniformity coefficient as

$$Cu = D_{60}/D_{10} \quad \ldots\ldots\ldots\ldots\ldots \text{Eqn. 7.11}$$

where Cu = uniformity coefficient

D_{60} and D_{10} = 60% and 10% soil particle size respectively.

An alternative definition which is often adopted is

$$Cu = D_{75}/D_{25} \quad \ldots\ldots\ldots\ldots\ldots \text{Eqn. 7.12}$$

where D_{75} and D_{25} = 75% and 25% particle sizes respectively.

iii) Void Ratio of the Soil.

The effects of void ratio can be expressed, from Eqn. 7.6 as

$$\frac{k_1}{k_2} = \frac{C_1 . e_1^3}{1 + e_1} \Bigg/ \frac{C_2 . e_2^3}{1 + e_2} \quad \text{.................... Eqn. 7.13}$$

Experimental evidence has shown that the dimensionless factors C_1 and C_2 change very little with the change in void ratio of unstratified granular soils, however, for clays they vary appreciably. But for granular soils, Eqn. 7.13 may be reduced to,

$$\frac{k_1}{k_2} = \frac{e_1^3}{1 + e_1} \cdot \frac{1 + e_2}{e_2^3} \quad \text{.................... Eqn. 7.14}$$

Based on quite an other concept, the hydraulic mean radius, the following relationship is obtained

$$\frac{k_1}{k_2} = \frac{e_1^2}{e_2^2} \quad \text{.................... Eqn. 7.15}$$

Test data from various soils shows that plots of k versus $\frac{e^3}{1 + e}$, $\frac{e^2}{1 + e}$ and e^2 all approach a straight line. In general a plot of e and log k is close to a straight line for nearly all soils.

iv) Geometrical Arrangement of Particles.

Permeability depends to a considerable extent on the geometrical arrangement of soil particles, soil fabric, Rowe (1971, 1972). Often the reduction in permeability that occurs with time is caused by a change in the arrangement of soil particles. As flow through a soil occurs particles tend to move to positions of greater stability to seepage forces. This particle movement always results in lower permeability if the particles are not washed out of the soil, Lambe (1955).

v) Entrapped Air and Foreign Matter.

The permeability of a soil is greatly reduced if air is entrapped in the void spaces. Should dissolved air in the pore fluid moving through these voids by liberated, the permeability will be further reduced. For this reason very often air-free distilled water is used in tests to measure permeability. This may, however, cause severe washing out of colloidal material as the test liquid used may not be in electro-chemical equilibrium with the soil sample. Generally de-aired water is nevertheless chosen.

Organic foreign matter has the tendency to move towards critical flow channels and plug them, which has the effect of reducing permeability. The use of de-aired water in tests may mask the tendancy for this to occur in in-situ soils. The possibility of it arising in reconstituted inorganic soils is most unlikely, however.

vi) The Effect of Absorbed Water.

Absorbed water is not free to move under normal seepage forces but it occupies part of the void space. The net effect is therefore by reducing void space to reduce permeability. The existence and amount of absorbed water is greatly influenced by soil compaction.

In silts, sands and gravels, with mica and organic matters being two exceptions, it is of little importance but in clay it is of major importance. In general the higher the ion exchange capacity of a soil, the higher the effect on permeability.

7.3.2. Test Materials and Procedures.

Test performed as part of this study were confined to constant head permeability tests carried out on Cowal till from Laglingarten. However, test data from the Backwater Dam carried out by Younger and Lim (1969) has been used together with the data relating to Norwegian Dams, from the Norwegian Geotechnical Institute (Sande, 1973). Further permeability results relating to Canadian Dam tills (McDonald et al, 1961) and the Montreal tills (Audy, 1970) have been utilised also. The test methods are known only for the Scottish and Norwegian tills and these were varied, thus it is best to consider each of the tills separately.

7.3.2.1. Laglingarten, Cowal Till Permeability Tests.

The constant head permeameter shown in Plate 7.2 was used in the tests and its main dimensions are given in Fig. 7.22. A balancing tank was suitably placed above the cylinder and connected to the test cylinder, a constant water supply and to an overflow. A set of six glass manometer tubes, 6 mm bore were set on a scaled board and connected to the nipples on the test cylinder.

A 25 mm layer of filter material was placed in the bottom of the cylinder and a weighed sample of test material was compacted in 50 mm layers to its required density at its selected moisture content, as determined in Section 7.2. Another 25 mm layer of filter was placed on top of the cylinder and like the layer at the bottom, it was separated from the test specimen by a piece of wire mesh. The lid was then securely screwed down and the sample carefully de-aired. This was achieved by applying a small vacuum to the test cylinder inlet and permitting the entry of de-aired water into the specimen through the outlet. The manometer tubes and balancing tank connectors were then opened to the specimen and left for 24 hours for the system to balance.

Each test lasted seven days and the discharge from the bottom of the cylinder was recorded at regular intervals together with the temperature of the water and the manometer readings. The coefficient of permeability was then calculated using Darcy's law and corrected to a standard 20°C. The applied hydraulic gradient in the tests varied between 4.5 and 5.3.

Although it would have been preferred to use a supply of de-aired water, the supply available was very limited and was only used for the de-airing of the test specimens and to fill the manometer tubes. During the test, settled tap water was used.

The six particle size distributions used in the tests are shown in Fig. 7.23. As can be seen the maximum particle size used was 20 mm and the gradings were reconstituted mixtures of the coarse and fine fractions of the Laglingarten till in the proportions 0, 25, 45, 65, 70 and 100 per cent fines.

7.3.2.2. Backwater Dam Permeability Tests by Younger and Lim (1969).

The constant head permeability apparatus used to determine the permeability of the Backwater till samples was as shown in Fig. 7.24 and Plate 7.3. The apparatus was designed to permit any hydraulic gradient to be applied from 0.2 to 12. Two test units were provided to allow two test specimens to be run at the same time.

The test cells were chrome lined steel cylinders 38 mm diameter by 90 mm high, covered by two aluminium end plates held together by three screwed rods. Both the melt and outlet passages were protected initially by porous discs and connected to flexible nylon tubing which passed through refilling reservoir along the horizontal scales into the saturating reservoirs. The horizontal scales were 1 metre long and could be read to 0.5 mm. By inserting a bubble into the nylon tubes, a change in volume of 1.43×10^{-3} cc could be measured by direct observation of the menisci. The hydraulic gradients were achieved by displacing vertically the outlet and inlet menisci.

Prior to testing, the whole tubing system was thoroughly cleaned out with a dilute acid solution and then flushed through and set with de-aired water. The porous discs in the test cells were boiled before each test. Saturation of the sample was ensured by using a back pressure of 70 kN/m^2 and the tests carried at constant temperature of 24° C $\pm$ 0.5° C.

Test runs were commenced by opening both cell valves simultaneously and taking periodic readings of inflow and outflow always taking care to maintain the menisci within the horizontal tubing. In most cases tests were carried out at gradients of 1 and then increased gradually in steps to 12. Thereafter the gradients were decreased in similar stages. In addition some samples were also tested at gradients less than unity.

All the tests were carried out on material less than B.S. 14 sieve size (1.2 mm). It was artificially split by wet sieving into two groups with a split size of 0.076 mm and then reconstituted in nine gradings as shown in Fig.7.25 as mixtures with 5, 15, 25, 40, 46, 52, 64, 76 and 88 per cent finer than 0.075 mm diameter.

The samples were compacted into the cells by kneading compaction to the required densities and water contents. The compacted samples were usually allowed to be saturated with de-aired water using a back pressure of 700 kN/m^2 for three days.

7.3.2.3. Norwegian Geotechnical Institute Permeability Tests.

The permeability tests conducted by the Norwegian Geotechnical Institute were carried out on till materials less than 20 mm diameter from all the dam sites reported. The test mould used was a modified 102 mm diameter by 116 mm high Proctor compaction mould as produced by Geonor and described by Kjaernsli (1968). This enabled the determination of compaction characteristics and permeability in one go. The permeability tests were constant head tests with hydraulic gradients of 4 to 8.

7.3.3. Applicability of Darcy's Law to the Tills.

The only velocity gradient investigations carried out were those of Younger and Lim (1969). The material they tested although naturally derived till was a reconstituted till with an artificial split in the fine sand size range but the resulting fine fraction was not untypical of many of the clayey silt fine fractions in naturally split graded till materials. As part of the investigation on these reconstituted materials, the average velocity for both increasing and decreasing gradients were determined and plots constructed of average velocity against applied hydraulic gradient as shown in Figs. 7.26 to 7.29 for widely different fines content.

From this data it was found that for tests carried out with only 5 per cent fines content there appeared little deviation from Darcy's behaviour in a wide sense, Fig. 7.26, but without exception, the average velocity of flow was noticeably lower at any particular gradient than that obtained in the second run with the same test specimen. Up to 40 per cent fines, deviations from Darcy behaviour were observed in the form of a less than proportional relationship at the lower range of gradients, Fig. 7.27. At 40 per cent fines the velocity gradient relationships was approximately linear, or more than proportional when the fines were only 6 per cent greater. At higher percentage fines content, Figs. 7.28 and 7.29, again a more than proportional relationship was obtained but with gradients less than about 2 to 4 than less than proportional relationships were quite often observed.

The data presented in Figs. 7.26 to 7.29 were for materials compacted dry of optimum, but for materials compacted wet of optimum a similar trend was found although a proportional rather than greater than proportional velocity gradient relationship was observed, particularly at the lower gradients.

In no case was there any evidence of a threshold gradient but the results do indicate that deviations from Darcy behaviour were occurring.

Younger and Lim (1969) suggest that as the highest fines content tested only exhibited approximately 25 per cent fines maximum, then the cause of the non-Darcy behaviour was unlikely to be due to the pore water having a "quasi crystalline" structure with non-newtonian flow characteristics. They suggested that a particle migration concept, would be more applicable, i.e. an actual change in soil fabric during flow. They considered that any loose particles, not rigidly fixed in position, could under application of a critical seepage force be moved by rotation or direct translation through the pore spaces until a constriction was met. Further increase in seepage force could effect further movement of some of the loose particles. The effect of particle migration in this case is to cause plugging and unplugging of flow channels in similar manner to that described by Martin (1962).

Comparison of the data obtained at and below hydraulic gradients of 1 also led Younger and Lim to suggest that a sudden application of a gradient even of only 1, may be sufficient to cause significant particle movement with consequent deviational behaviour. Sudden application of higher gradients would obviously have the same or greater effect.

As the gradings even at the highest fines content are not very rich in clay size particles it is to be expected that no dramatic differences in velocity gradient relationships between materials compacted wet and dry of optimum were to be found, i.e. no significant fabric differences existed between the materials compacted wet or dry of optimum.

Taking particle migration then to be the main cause of the deviational behaviour of this Backwater till, it is reasonable to suggest that other tills, particularly gap-graded tills, would be likely to exhibit similar behaviour. This would be particularly so if the hydraulic gradient applied was much greater than unity. In the in-situ tills which may have very open, loose fabrics, as discussed in Chapter 6, the possibility of particle migration appears to be a most probable occurrence.

7.3.4. Variations due to Changes in Moulding Water Content and Dry Density of Recompacted Tills.

The variations in permeability due to changes in water content and dry density, or void ratio, are of special interest in the construction of earth fill dams. The use of wet fill methods, in particular, cause high pore pressures to be set up and it is therefore of great importance to gain a knowledge of the possible variations in the compacted fill permeability.

Bernell (1957) has reported the variations in a typical Swedish sandy till. Fig. 7.30 shows the results of a number of permeability tests he conducted on the till in three test series in which the moulding water contents varied from the Proctor optimum value, 6 per cent, to the full saturation value 12 per cent. In each test, the samples were compacted at the same water content to a varying density. The permeability was determined after consolidation of the samples at a normal pressure of 200 kN/m^2. In Fig. 7.30 the permeability decreases are shown to steadily reduce with increasing water content, the lowest water content tested being the Proctor optimum value. Bernell concluded that the higher the water content above Proctor the lower the permeability at least in the range considered. He then assumes that the relation between void ratio and permeability may be assigned the equation:

$$e = e_o + C_p \log_{10} \frac{k}{k_o} \quad \text{.......................... Eqn. 7.16}$$

where k_o = the permeability at the void ratio e_o

C_p = the slope of the permeability line in a semi-logarithmic plot and is called the permeability index.

Bernell suggests that this permeability index generally decreases with increasing value of uniformity coefficient D_{60}/D_{10} but that for typical tills it is in fact fairly constant at about a value of 0.03.

In fact the data on which Bernell based his conclusions do not exactly coincide with the data obtained from the Cowal, Backwater or Norwegian Dam tills. Figs. 7.31 to 7.33 are typical of the relationships obtained and show, for constant compactive effort that the lowest permeability does not always occur at Proctor optimum value but very often at a moulding water content, above it. Table 7.4 shows the relationship between Proctor optimum water content and the water content at minimum permeability determined for Norwegian Dams by the Norwegian Geotechnical Institute, Sande (1973). It can be seen that minimum permeability in fact occurs up to 2.2 per cent in excess of Proctor optimum. It is suggested that this difference may be explained by possibly somewhat more than optimum moisture content being required to achieve complete dispersal of the fines during compaction. This involves the breakdown of any aggregations of fines and therefore involves a net decrease in the effective size of particle fabric units hence a reduction in the absolute dimensions of pore spaces as opposed to a net reduction in overall pore space.

Bernell's (1957) correlation of void ratio, or dry density against permeability does not take account of soil fabric and although the influence of this factor does not override the influence of void ratio, it does modify it to a sufficient extent that Bernell's permeability index loses much of its usefulness. This is likely to be more so in the tills containing clay size particles.

From this data it appears that soil fabric is a very important factor in the determination of the measured permeability of recompacted till. Over large variations in the gradings, the permeability does not change. This conclusion is in fact in sympathy with Bernell's (1957) statement that tills did not vary greatly in permeability with changes in their size uniformity coefficients, related of course in his case to overall gradings. It is thus suggested that only with conditions wherein the coarse particles dominate or begin to dominate the fabric in any particular till or when significant differences in the nature of the fine constituents between tills exists will permeability noticeably vary. Bernell (1957) suggests that tills can be classified with respect to permeability according to the groupings shown in Fig. 7.37. Accepting that the Swedish tills Bernell based his conclusions upon will, like the majority of other similar tills be well graded, matrix dominated or matrix controlled then the restricted range of permeabilities suggested does not appear unreasonable. Using his system of classification the available data from the Cowal, Backwater and Norwegian dam tills has been plotted, as is shown in Fig. 7.38. As can be seen the data generally falls into his range of predicted values but the broad classification he used does not allow this plot to be particularly useful.

To determine whether a better mode of presentation could be achieved it was decided to attempt to utilise the identity of the fine fraction in the permeability classification. Thus a plot of the minimum permeability for Proctor compactive effort against percentage fines was constructed with each point on the graph identified using Hazen's uniformity coefficient divided by the split size of the fine fractions in the tills $\left(\frac{D_{60}}{D_{10}} \cdot \frac{1}{D_{100}}\right)$.

The percentage fines was used to attempt to take into account the influence of the large gradational changes characteristic of these soils and the permeability fines relationships considered previously could be accommodated within the plot.

The data from the Cowal and Norwegian Dams tills are plotted in this manner in Fig. 7.39 together with the data from the Canadian Dams given by McDonald et al (1961). It is apparent that no absolute correlation exists between the description of the fines as given and the minimum permeability of the tills at Proctor compaction. Several other combinations of grain size indices were used to identify the fines but the best correlation obtained was that shown in Fig. 7.39. It is suggested that other factors such as void ratio, soil fabric, soil composition and testing errors all contribute to the discrepancies but that with the accumulation of further data this type of plot could prove useful. It certainly could be used to check the order of minimum permeability likely to be achieved with Proctor optimum compaction for any particular till.

It is evident from an assimilation of the data that the grading of the tills, their detailed fabric and their fines mineralogical composition are acting together in a complex manner. By using the fines gradational identity some trend can, however, be established between fineness and the particular permeability value chosen. The changes in permeability with moulding water content must also be considered and the minimum permeability is not necessarily at optimum water content, it may occur up to 2 per cent or so in excess of this. Thus the grading of tills may help to identify a specific permeability property such as minimum permeability at specific compaction, but it can not be easily applied in a way to predict the variations at other states away from this.

7.3.6. Differences Between Laboratory Reconstituted, Undisturbed and Field Recompacted Till Permeabilities.

As was discussed previously in Chapter 6, the mode of deposition of melt out tills can induce very open microfabric arrangements. By virtue of the amount of free water which is also around at the time of deposition, it is most likely that wisps, lenticles and beds of sand and gravels may be formed. These macrofabric features together with the very open microfabrics will greatly influence the in-situ permeability, however, when it is recompacted, these features will most probably be broken down and the soil fabric become much more uniform and most probably denser. Thus it is to be expected that recompacting till will have the effects of greatly reducing measured permeability and measured variations in this.

In practice with field compaction of till, the degree of uniformity achieved is not always that which might be expected. The variations in gradation certainly contribute to this but another factor is the segregation of particle sizes that occurs during placement, with the consequential development of "weak" macrofabrics. Typically partial segregation of particle sizes occurs in the upper, drier, part of each layer during placement of fill. If the till is dumped into water, the finer fraction will very often separate out almost completely, (Bukin, 1968).

Data supplied by Audy (1970) for the Montreal tills very clearly demonstrates the above points, Table 7.5. It can be seen from this data that the laboratory tests on undisturbed specimens and field permeability tests on undisturbed soil gave the highest measured values and that the average laboratory undisturbed permeability and the reconstituted till were the lowest. The laboratory reconstituted till and field compacted till data do show a remarkable degree of correlation, in this case.

7.3.7. Discussion.

The particular nature of the tills has been clearly shown to influence many aspects of the permeability of the tills. The recorded deviations from Darcy behaviour for Backwater till were attributed by Younger and Lim (1969) to particle migration and the evidence from the tests on Cowal till emphasised the possible widespread occurrence of this phenomena in other tills. It was also suggested that in gap graded tills this phenomenon could be quite a serious problem. The interaction of overall grading, soil fabric and composition of the fines were also all seen to interact in a complex manner. Bernell's (1957) suggested behaviour of tills was seen to be an over simplifation in terms of void ratio and moulding water content relationships and void ratio and permeability relationships. A new suggested method of classifying till permeability on the basis of minimum permeability for Proctor optimum compaction against percentage fine content utilising a numerical description of the fine fraction grading has been suggested and with further accumulation of data it is thought that this limited classification system may provide a reasonable means of checking or predicting till permeability data.

7.4. SHEAR STRENGTH CHARACTERISTICS OF BASAL MELT OUT TILLS.

7.4.1. General Considerations.

From Chapter 5 it is known that basal melt out tills are essentially coarse grained soils. Therefore when investigating their shear strength characteristics it is best to consider the variations that occur in their granular particle constituents rather than their clay size particles. The influence of any clay size fraction in the tills must not, however, be forgotten.

To date, no systematic study had been made in which all the various factors influencing the shear strength of coarse grained, cohesionless soils have been separated and fully quantified. However, numerous investigations have considered the influence of particular factors and from a combination of these various investigations it is possible to assemble the several factors on which shear strength depends as follows:

i) Mean and maximum particle size

ii) Particle shape

iii) Strength of individual particles

iv) Grain size distribution

v) Void ratio or density

vi) Soil fabric

vii) Mean normal stress.

Of these factors, the mean and often the maximum particle size, the grain size distribution and the void ratio are known to vary considerably in basal melt out tills. Particle shape and the strength of individual particle quite possible vary in the various tills but it is reasonable to suggest that within any particular till sheet they will remain fairly uniform. Till fabric has been shown to be somewhat variable in Chapter 6, but it is essentially a random variation as opposed to layering or jointing and it is thus reasonable to expect isotropic if variable strength properties for these soils. Also the mean normal stress variations that might occur in these soils could reasonably occur in any cohesionless soil and are not peculiar to the tills. Therefore in terms of distinguishing the influence on shear strength environmental factors peculiar to melt out tills, this factor need not be further considered. The other factors have controls acting on them which are influenced by the mode of formation and deposition and they will thus be considered in turn in the following sections, however, it is first necessary to establish the general concepts of the shear strength behaviour of cohesionless soils.

7.4.1.1. Shear Strength Concepts for Cohesionless Soils.

In general the shear strength of a cohesionless soil may be presented in the form:

$$\tau = \sigma \tan \phi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eqn. 7.17}$$

where τ = shear strength

σ = normal stress on the shear plans

ϕ = angle of shearing resistance

The angle of shearing resistance, is often evaluated by drained shear testing and the shear strength equation rewritten as,

$$\tau = \sigma \tan \phi_d \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eqn. 7.18}$$

where ϕ_d = drained angle of shearing resistance.

The value of ϕ_d consists of a frictional component ϕ_f and a volume change component ϕ_δ which leads to a more generalised failure criterion

$$= o \tan (\phi_f + \phi_\delta) \quad \ldots\ldots\ldots\ldots \text{Eqn. 7.19}$$

These two components have been analysed by a number of researchers including Taylor (1948), Bishop (1950) Ladanyi (1960), Poorooshasb and Roscoe (1961) and Rowe (1963). The ϕ_f component has been shown not to be an invariable material property but one which is influenced by many particle characteristics such as particle shape, particle size (often Hazen's effective size is considered to be the critical), gradation, relative density and mineral type. The identification of the ϕ_f parameter is nevertheless important in so far as in many engineering situations the dilatancy component does not or cannot be developed and the frictional component only operates. Unfortunately, a number of expressions for calculating the dilatancy contribution have been suggested since the original expression proposed by Bishop and Eldin (1953) however the majority agree that the dilatancy contribution is a function of the factor

$$\frac{d\Delta_v}{d\Delta 1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eqn. } 7.20$$

where $d\Delta v$ = change in volumetric strain to an increase in axial strain of d 1

The frictional component (ϕ_f) may however, be calculated from the principal stress ratio at the point of minimum volume during the test by assuming that the frictional resistance of the grains must be overcome before the material can proceed to dilate, Kirkpatrick (1961).

7.4.2. Test Materials and Procedures.

The tills tested as part of this study were Cowal, Corrour and Glen Kingie Scottish tills. The Cowal till was tested at several gradings at constant compactive effort and over a wide range of compactive efforts at 100 per fines content. The Corrour and Glen Kingie tills were tested at only one grading at one compactive effort.

The specimens were all 102 mm diameter by 204 mm high. The samples were compacted using the standard Proctor hammer in five layers and the density variations achieved by altering the number of blows per layer. The samples so prepared were tested in a standard triaxial cell under consolidated undrained conditions with pore pressure measurements or drained conditions using with fixed end. To ensure full saturation a back pressure of 280 kN/m^2 was always applied for the consolidated undrained tests.

Other data was again available for tills from Norwegian Dams from Sande (1973). The test procedure used for these soils is described in detail by Kjaernsli (1968) but it is essentially based on 102 mm diameter by 204 mm diameter fixed end triaxial consolidated undrained tests with pore pressure measurements. The specimens are prepared at Proctor optimum compaction generally at optimum moisture content + 2%.

Data from the Canadian dams as given by McDonald et al (1961) is also included in the analysis but no details of test procedures are known.

7.4.3. The influence of Particle Characteristics.

7.4.3.1. Particle Shape.

The influence of particle shape on the shear strength properties of cohesionless soils has been reported for several uniform mineral or lithology soils by Chen (1948), Morris (1959) and Koerner (1970a). Koerner in fact was primarly concerned with the properties of crushed quartz particles of different shapes and as many of the tills contains large proportions of crushed quartz it is suitable to consider this work in detail.

The triaxial tests carried out by Koerner (1970a) were performed using 102 mm diameter by 102 mm high samples with lubricated end platens and drained conditions at 206 kN/m^2 confirming pressure. The effect of particle shape, as measured by its sphericity and angularity, was studied on three different saturated quartz samples. Table 7.6 gives the source and relevant properties of each soil and it can be seen that the only variable is the shape. From this test programme the data shown in Fig. 7.40 was obtained. The data obtained by Koerner are in agreement with those determined by Chen (1948) and Morris (1959) and show that the less spherical and more angular soils have significantly higher ϕ_d values. The dilation component of all three soils is approximately the same thus the change in ϕ_d is in the frictional component of shearing resistance ϕ_f.

It has been shown in Chapter 6 that the shape of particles in tills may vary but many of the tills are known to be characterised by angular to sub-angular particles, Drake (1970). It is also suggested that within any one till shape will be reasonably constant although overall grading, dry density and other factors may vary. Thus it is to be expected that the findings of Koerner (1970a) will be applicable to tills. Therefore in any one till ϕ_f for any particular grading should remain a constant with ϕ_δ increasing with increase in relative density and ϕ_d increasing likewise.

Exceptions to the above statements inevitably exist and are associated with soils which contain flaky or platey particles, typified by mica and to a lesser extent chlorite. Koerner (1970b) has shown that in soils which contain flaky particles, at failure they can exhibit volume decrease rather than the volume increase as indicated above for bulky particles. Thus ϕ_f will be greater than ϕ_d for flaky particles and Koerner (1970b) has found the ϕ_f for these flaky mineral soils is greater than ϕ_f for bulky mineral soils, all other factors being equal. He suggests in fact that particle reorientation occurs for these flaky minerals and that this contributes to the strength at failure. The behaviour of tills composed of flaky mineral particles may therefore be expected to deviate from other tills which do not process them.

7.4.3.2. Particle Size.

The influence on the shearing resistance of a soil of variations in its mean size of D_{10} (Hazen's effective size) have been studied by Leslie (1963) Kirkpatrick (1965) and Koerner (1970a). Leslie and Kirkpatrick restricted their investigations to average sizes in the medium to coarse sand size grade while Koerner investigated effective sizes ranging from fine sand to gravel. These investigations are essentially in agreement in the size ranges where they overlap. They all suggest that in the medium to coarse sand, and from Koerner into the gravel range, the ϕ_f values increase only slightly or remain essentially constant but that ϕ_d increases with reduction in size. At much smaller effective sizes, in the fine sand range, Koerner, however, suggests a very rapid increase in ϕ_f Fig. 7.41. Koerner's tests were on crushed saturated quartz carried out in the manner described in Section 7.4.3.1. and ϕ_f was obtained by using the residual angle of friction. As they are not substantiated by other data and it is known that the angularity also increased with decreasing size the results at much smaller sizes are not yet fully confirmed.

With respect to tills, the variations in the sise fraction represented in various tills has been shown in Chapter 5 to be quite large thus any influences of mean or effective sizes will operate in them. The exact variation of the influences when the effective size is in the fine sand range or smaller is not yet fully understood but at greater sizes certainly ϕ_d and possibly ϕ_f will increase somewhat with decreasing size.

7.4.3.3. Particle Breakdown.

Particle breakdown occurs to some degree in all cohesionless soils during shearing. The degree of breakdown is dependant upon such characteristics as mineral composition, fabric, grading, friability, weathering, brittleness, hardness and particle shape, Leslie (1963). Of principle importance, however, is the stress level and in very high earth and rockfill dams imposed loads may be high and particle breakdown can be of great importance.

Skermer and Hillis (1970) suggests that in graded materials the effect of particles breakdown is to change the grading and bring it closer to the Fuller optimum curve. The effect of large amounts of particle breakdown may thus be able to radically change the fabric of the soil at failure from that initially.

The type of till under study is the product of direct comminution and it is likely that many of the particles shall contain flaws and weaknesses induced during this initial crushing operation. During shearing then at very high confining pressures particularly particle breakdown would almost certainly occur. The changes in grading and fabric so induced are bound to reflect on the measured shear strength parameters due to this. The particular trends induced by gradational and fabric changes which factors are discussed in later sections.

7.4.4. Shear Strength - Dry Density Relationships.

One of the fundamental characteristics of cohesionless soils subject to shear is the difference in the measured drained angle of shearing resistance ϕ_d with initial voids ratio or dry density of the soil. Typically the soil will exhibit higher values of ϕ_d for higher densities tending to reduce to become asymptotic to a value of low densities or high void ratios. This may be explained by the phenomenon of interlocking, always increased by increasing density. The net effect is to cause greater expansion with increasing density and so greater ϕ_d. In fact ϕ_f is dependant to some extent at least on interlocking thus it too increases somewhat with increasing density.

It is not possible to consider in isolation the influence of density or void ratio on the measured friction angle of soils as composition of the soil greatly influences the relationship. Composition in fact affects the friction angle in two ways. Firstly it affects the dry density that is obtained at any given compactive effort and secondly it affects the friction angle that is achieved for that density. The effect of composition may thus be studied either by comparing fixed densities or void ratios or by comparing fixed compactive efforts and often with respect to embankment construction the comparisons are often made at fixed compactive effort.

The principal use of tills considered in this study is in embankments and it has therefore been decided to compare different tills at fixed compactive effort, viz. Proctor optimum. Some of the tills contain miceous particles which, as discussed in Section 7.4.3.1. may cause peculiar relationships between ϕ_d and density or void ratio, Koerner (1970a). Consideration must therefore be given to the nature of basic relationship between friction angle and density in a miceous till and the possible implications of such mineralogical composition then be discussed.

7.4.5. Shear Strength-Gradation Relationship.

For soils with the same composition and mean or effective sizes, but different gradings, then for comparable compactive efforts, the better graded the material the smaller the initial void ratio and the larger the drained friction angle. It is thus suggested that an optimum grading exists which will exhibit the maximum angle of friction. Leslie (1963) Kirkpatrick (1965) and Koerner (1970a) all investigated the influence of this factor by varying the upper size tested while maintaining the mean or minimum size of the soils. However, of more particular interest to this study of split graded tills, Holtz and Gibbs (1956), Holtz and Ellis (1961) and Skermer and Hillis (1970) all studied the influence on measured shear strength changing the grading of a soil by mixing in varying proportions of coarse particles.

Holtz and Gibbs (1956) and Holtz and Ellis (1961) used the same river gravel mixed with a river sand and a sandy clay of low plasticity respectively, Fig. 7.42. The gravel particles were predominantly Gneiss, Granite and Schist of subangular to subrounded shape. Holtz and Gibbs compacted their soils to 70 per cent relative density, 93 per cent Proctor optimum while Holtz and Ellis compacted their soils to Proctor optimum density. The shear tests were carried out on 25 mm diameter by 570 mm high triaxial specimen under drained or consolidated undrained conditions with pore pressure measurements.

Skermer and Hillis (1970) tested four gradings of sand and gravel composing the mean gradation of the borrow area fluvial sand and gravel for the Mica dam, Canada, with a maximum particle size of 38 mm diameter. The soil was split on the 5 mm size and tested as 100 percent fines, 0 per cent fines and 35 per cent fines. The original grading was tested and this had 63 per cent fines on the 5 mm split size. The predominant rock types were Quartzite and Quartz with small percentages of Limestone and Mica Schist. The fines were composed of sub rounded to sub angular particles and the coarse particles were well rounded.

The consolidated drained tests carried out by Skermer and Hillis were at a confining pressure of 345 kN/m^2, using 70 mm diameter by 150 mm high specimens for the finest grading and 152 mm diameter by 304 mm high specimens for the others. The specimens were all sheared at a relative density of 90 per cent. The data from the three investigations have been presented as the percentage fines plotted against measured drained angle of friction (ϕ_d) and cohesion intercept (C_d) as shown in Fig. 7.43. It is apparent that in each case the gravel percentage was increased and the percentage fines reduced from 100 percent to 80 or 70 percent fines some small increases in ϕ_d occurred but at lower values of 50 to 35 per-cent fines, the increases were considerably greater. A corresponding decrease in cohesive intercept was noted in each case. The relative rapid increase in ϕ_d at the lower fines content was not however continued down to 0 per cent fines, as shown in Skermer and Hillis's (1970) data. It is thus suggested that the changes from matrix controlled to matrix dominated materials, as defined and discussed in Chapter 6, lead to a gradual increase in ϕ_d and maintenance or slight reduction in C_d but that the change from matrix controlled material to a well graded material lead to the large increase in ϕ_d and drop in C_d. With further reduction in fines from the well graded state the cohesion will drop rapidly and ϕ_d drop somewhat to the value of ϕ_d for the coarse particles alone. This suggested behaviour is in agreement with the deductions of Holtz and Gibbs (1956), Holtz and Ellis (1961) and Skermer and Hillis (1970).

In terms of the proportions of melt out tills, the data above suggests that the large variations in gradation discussed in Chapter 5 could lead to significant variations in measured strength depending on the range of percentage fines in which the variation in gradation occurs. Also the composition of the fines may induce a cohesive intercept and the variation in this property may be important to the performance of the till although the evidence from

Holtz and Ellis (1961), particularly, is that the variations in C_d are much less dramatic than those for ϕ_d.

7.4.6. Density Strength Variations in Cowal Till.

As suggested in Section 7.4.3.1., the possibility of significant mica contents in some of the tills causing unusual relationships between ϕ_d and density or ϕ_f and density was considered worthy of further investigation. Cowal till was known to have high mica contents, particularly in its fines constituents, thus a test programme was instituted on the 100% fines materials to establish the relationship between ϕ_d, ϕ_f and density.

No cohesion intercept was measured and Fig. 7.44 shows the data obtained for ϕ_d and it is clear that the relationship between ϕ_d and initial dry density is compatible with the general behaviour discussed in Section 7.4.3.1. for bulky grains.

The relationship between ϕ_f and dry density, where ϕ_f has been determined in accordance with Kirkpatrick (1961), is also that to be expected from a soil containing bulky grains and is always relatively smaller than ϕ_d and essentially constant or slightly increasing with increasing density. It is thus suggested that the mica content for even the 100 per cent fines content Cowal till is still relatively low and behaviour is thus unexceptional.

It is possible for other tills to have much higher contents of flaky particles which may lead to unusual density shear strength relationship but it is considered to be unlikely. The absolute nature of the relationship of these parameters is, however, quite complex and is not considered to be predictable in absolute value in any way.

7.4.7. Gradation - Shear Strength Relationships in Various Tills.

When considering the gradational variations in tills it is necessary to make allowance for the variations between tills in the nature of the fine fractions and within tills for the variation in the percentage fines. To establish firstly whether the tills exhibited the type of relationship between percentage fines and shear strength shown in Section 7.4.5., data were obtained for the Cowal till with different percentage fines compacted at Proctor compactive effort. No cohesion intercept was measured in the till and the data can thus be presented as shown in Fig. 7.45. It can be seen that the relationship exhibited is in agreement with that suggested by Holtz and Gibbs (1956), Holtz and Ellis (1961) and Skermer and Hillis (1970).

To determine then the relationship between gradation and shear strength for the various tills for which data was available, a plot of percentage fines against ϕ_d was again constructed but for each till, grain size indices were used to describe their fine fraction as follows

$$\frac{D60}{D10} \cdot \frac{1}{D100} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eqn. } 7.21$$

where $\frac{D60}{D10}$ = Hazens uniformity coefficient Cu

D100 = split size.

This grain size index is the same as was used for the permeability classification and as then, it was chosen as it appeared to pick out the more important points on the fines grading curve.

But from Fig. 7.46 it is apparent that no correlation exists. In fact the Scottish tills exhibited no cohesion while the Norwegian dam tills were recorded as having cohesion between 1.0 and 6.4 kN/m^2 and the Canadian tills between 19 and 46 kN/m^2. If only from that particular consideration it is not surprising that no correlation was found. In addition however, the tills without doubt varied considerably in their particle characteristics. Grain size indices of the fines and percentage fines are therefore inadequate descriptions of the tills.

No attempt was made to correlate ϕ_f with any grain size indices but it is assumed that no correlations would be found in this case either.

7.4.8. Discussion on the Variations in Shear Strength of Tills.

The data available for analysis relating to this aspect of the study are more sparse than for other aspects yet this undoubtedly is one of the most complex areas of study. Each till is known from Chapter 5 to vary considerably in grading and this has been widely established as an important yet variable influence on shear strength. The nature of the grading of the fines and coarse fractions contributing to the tills is known to be quite different between tills thus even if two tills have the same coarse and fine fraction gradations, it is likely that their shear strengths are dissimilar. To a certain extent the plot of percentage fines against drained angle of friction, Fig. 7.46, proves this point.

Considering each till individually, however, the investigations have shown that at any particular grading it is most likely that the tills will, when reconstituted at least, conform to a normal relationship between ϕ_d and dry density or ϕ_f and dry density.

The variation in strength with grading at any particular compactive effort will, it is further suggested be similar to that determined by Holtz and Gibbs (1956), Holtz and Ellis (1961) and Skermer and Hillis (1970). It will thus be dependent on the fabric arrangement of the coarse and fine particles, i.e. on whether the till is matrix controlled, matrix dominated or well graded. It is possible, as discussed in Chapter 6, that some tills will be clast dominated but the instances of this are not considered to be many. Accepting then the previous three fabric groupings to be the more common, it has been found that a more pronounced change in ϕ_d may occur when the change from matrix domiaated to well graded occurs than from matrix controlled to matrix dominated. The range of percentage fines in tills has been shown in Chapter 5 to cover these critical gradings thus it is likely that such variations will occur in practise.

The previous discussion and indeed the previous analysis has been concerned with laboratory testing on reconstituted tills. It is reasonable, however, to assume that field recompacted till will behave in a similar manner to laboratory reconstituted tills providing the mode of compaction is fairly similar and the resulting soil fabric is the same or nearly so. It is most unlikely however, that in-situ undisturbed tills will have similar strength behaviour as the soil microfabric and macrofabric could be quite different. Moreover, the noted variations in soil fabric in Chapter 6 suggests that the in-situ tills will have highly variable strength properties.

7.5. DISCUSSION AND CONCLUSIONS.

a) In Section 7.1 it was suggested that the nature of the fine fraction and the variation in the proportion of the fines in the composite till might be with other factors then detailed, a means of classifying tills. The investigations carried out in Sections 7.2, 7.3 and 7.4 have then attempted to establish the validity of this assertion, in terms of the tills variations in density, permeability and shear strength. It must be stated at the outset that these are but three of the many engineering properties that could have been investigated but they were three on which some data was available and they were three of the most fundamental properties of the tills.

b) With respect to the dry density variations in reconstituted tills, it has been shown that in any particular till at any particular proportion of fines, the dry density water content relationship was similar to that found in many other soils. However, when the dry density variations due to changes in compactive effort at any water content, such as optimum water content, were compared with the dry density variations due to gradational variations within the basic till composition, it was shown that gradational induced changes were as great as or greater than changes imposed by varying compactive effort. Thus the inherent variability in the proportion of fines, shown in Chapter 5 to be a characteristic of these melt out tills, could impose such large variations in dry density that, for example, quality control of compaction in embankments would have little meaning unless these gradational variations were accounted for before estimation of a sufficiency or otherwise of compaction was assessed. From this point of view the fundamental nature of the melt out till gradation greatly influences engineering behaviour.

c) With respect to undisturbed in-situ dry density, it was shown in Chapter 6 and in previous sections in this chapter that the melt out tills varied greatly in their in-situ density due to the gradational effects, described above, and due to variations, often very local, in the nature of the deposition process. This in-situ variability is therefore recognised as being a fundamental characteristic which makes investigation of the in-situ properties extremely difficult. The very loose nature of some portions of till deposits also found to be a feature of these materials can of course lead to particular local problems of slope stability, seepage, compressibility and shear strength with possible collapse and flow of tills under certain conditions.

d) The investigations of Younger and Lim (1969), reported in Section 7.3, on the permeability of artificially split graded Backwater till clearly demonstrated non - Darcy behaviour in the soil and it was suggested that this may be a property of many natural tills. In particular it was suggested that the particle migration phenomenon suggested by Younger and Lim could in gap graded tills, of which there are many, lead to striking deviations in velocity gradient characteristics. The common practice of applying relatively high gradients suddenly to test specimens could also greatly assist the development of the particle migration phenomenon and it was considered that the permeability data obtained for many of the tills, reported in Section 7.3, could have been influenced by this factor.

e) The analysis of the data pertaining to moulding water content and permeability revealed that the minimum measured permeability in the tills frequently occurred not at optimum water content but at values up 2 per cent or so above this. It was suggested that this was essentially due to a more uniform dispersal of fines in the soil having the net effect of reducing the pore size. The importance of soil fabric was thus indicated in this respect but in a much more positive manner it was also shown, in Section 7.3 that the fabric variations between undisturbed in-situ till, the reconstituted laboratory or recompacted field till would induce large differences in permeability for the same materials. So that the in-situ fabric variations in undisturbed tills, as discussed in Chapter 6 are clearly of great importance with respect to the permeability properties of these soils.

f) To the influences on till permeability of water content, dry density and fabric variations must inevitably be added to the influence of gradational changes. As an attempt to appreciate this influence, plots of percentage fines against minimum permeability at any grading under Proctor compactive effort were used. These permitted an appreciation of the influences of gradation and dry density to be to some extent considered together. From such plots it was clearly seen that the arrangement of particles was once again of considerable importance in the determination of measured permeability. It was in fact shown that when the till was matrix controlled or matrix dominated then the permeability did not vary a great deal but when the coarse fraction interacted fully with the fines, in the well graded state, and then dominated the soil, the permeability rose sharply. It was considered on the basis of the data obtained in the above tests that the percentage fines must be considered when establishing any classification of till permeability. A tentative system was thus suggested which was based on the percentage fines and the identity of the fines in terms of some grain size indices. This system was only related to minimum permeability at Proctor compactive effort, for as stated above the influence of moulding water content and dry density was not always the same in the tills and they represented further variables. Even though the suggested system is so limited it does not show other than a moderate degree of applicability.

g) The variations in shear strength of tills were more complex than in density or permeability and unfortunately the data available more limited. Nevertheless it was apparent that for the majority of tills with relatively low clay contents, which could thus be considered as cohesionless soils, the relationship between void ratio or density and the drained angle of friction (ϕ_d) and the frictional component of this (ϕ_f) would be a normal one. The possibility of unusual relationships between these parameters due to the possible presence of flakey particles was not entirely discounted but thought to be unlikely.

Although an attempt was made to compare the nature of the fines fraction and percentage fines with measured drained angles of friction for a number of tills in a manner similar to that used for the permeability variations, it was not found to be applicable at all. The large number of other factors influencing strength, such as particle shape, size, friability and mineralogical composition all served to reduce the value of this approach. The use of a plot of percentage fines against measured drained angle of friction in particular tills did serve however, to emphasise the importance on shear strength of whether the till was in a state of matrix control or domination or was well graded or clast dominated, much the same as had been found with respect to permeability. Such influences of fabric would of course be greatly emphasised between in-situ undisturbed till and reconstituted or recompacted tills.

h) Overall the investigations of the engineering properties of tills has shown that the nature of the fines in the tills, always accepting that the coarse fractions are fairly uniform, has a great influence but that the variation in fines content in the composite tills can have almost as great an effect. These variations reflect to a large extent in density variations and the consequences of these are that the engineering properties of the tills in the in-situ undisturbed state are highly variable and unpredictable. To a lesser but still to a very significant level, the reconstituted laboratory test specimens also show such variability and it is to be similarly expected in recompacted tills in the field.

Moreover, soil fabric variations in the undisturbed in-situ tills are known to be large and this increases the possible variability of engineering properties. Remoulding the tills to some extent reduces the importance of this factor but does not eliminate it, hence, an awareness of the mode of remoulding, the soil condition at remoulding and several other factors need be known before a true comparison of data can be made.

Although all melt out tills are produced in a similar manner and can be identified as a definite soil type they are typified more by their variability than by any other single factor. But by utilising the identity of their fines fraction, the percentage of these fines in the composite soils together with other factors mentioned in Section 7.1. it is suggested that at least a better understanding of the factors governing their variability can be achieved. In geological or engineering investigations these features of the tills may also be used to identify the differences between tills and the variations within tills.

CHAPTER 8. GENERAL CONCLUSIONS.

The investigations into the genetic influences on the nature and properties of basal melt out tills have been carried out in three inter related but distinct phases. The mode of formation of the particulate matter within the ice has been considered and related to the crushing of rock by industrial crushers. The resulting products have been compared and shown to have similar gradational characteristics. The mode of deposition of the tills has then been investigated and the resulting organisation of the particulate matter has been investigated over a wide range of particle sizes to establish the form and in some cases the function of these arrangements. Finally the implications of the nature and variation in particle gradation and geometric organisation have then considered in terms of the variations in some of their engineering properties.

The main findings of these studies may be stated to be as follows.

a) The action of glacial ice on rock debris contained within it is to crush and abrade the debris in a manner which is similar to that obtaining in an industrial crushing process. The resulting product thus has a multi modal particle size distribution which is an example of an abnormal log normal particle size distribution. The principal feature of such distributions is that they are composed of two, and sometimes more, distinct size distributions mixed in some proportion. By plotting such particle size distributions on log probability plots and size frequency plots it is possible to easily distinguish the basic distributions within the mixture.

The facility of distinguishing the fundamental size modes within the composite tills has therefore been applied and the basic nature of the Pleistocene and modern tills studied from a wide geographical area has been determined.

b) It has been shown that all the basal melt out tills which were the products of direct comminution do in fact have parent distributions which do not generally overlap greatly and so the separation of these distributions may be achieved by taking the split or mid gap particle sizes on the grading curves to be the separation point of the two fractions. On doing this the coarse fractions were seen to be gravelly sands or sandy gravels as the split or mid gap point was always found to be in the sand size range or the coarse silt size range, the latter being much the rarer phenomenon. The fine fractions were predominantly silty materials with a range of gradings from clayey silt to sandy silt.

c) A characteristic of the tills was that the percentage fine fraction in the mixture was highly variable often very locally but the nature of the fines was found to be very consistent in any one till sheet in which lithological variations were reasonably restricted. Another feature of the size distributions was that no pattern emerged of particular bedrocks influencing split size or the nature of the fines. It is suggested that this can be attributed to a change in the grindability of the particles always occurring in the coarse silt sand size range due to a possible change from polymineral to mono mineral fragments together with an increase in their surface energy causing them to collect in globules of water within and between ice crystals.

Basal melt out tills are therefore, by virtue of their mode of formation, characterised as split or gap graded soils in which the proportion of fines is highly variable. This produces large variations in their overall gradings. But within the variable mixture, the fine and the coarse fractions are very uniform within any one till and variations between tills appear controlled to a much lesser extent than might be expected by their lithology.

d) The soil model of particle arrangement that was postulated for split or gap graded till suggests that the tills could either be matrix controlled, matrix dominated, well graded, clast dominated or clast controlled. This model was shown to be essentially applicable to these soils. Deviations from the predicted density - grading relationship were found and were attributed to a higher degree of particle interaction than predicted by the model otherwise the pattern suggested was confirmed. On the basis of the measured proportions of the coarse and fine fractions in the tills it was suggested that the majority of tills were matrix dominated or controlled and a number were well graded or at least ranging in grading over these organisational states. A very few tills were found to be clast dominated.

e) Detailed investigation of clast organisation in undisturbed modern melt out tills showed that they inherited their spatial orientation from the active ice stress field and that they could respond to changes in this stress field up to the moment of release from the ice. Studies of the fabric of the fines in these tills showed they were organised during the melt out process of the ice. This could induce very open fabric arrangements which may or may not survive local variations in ice overburden and drainage conditions. In matrix controlled or matrix dominated tills, the matrix acts as the stress transference media during and after deposition thus glacial tectonic or locally imposed stress will be recorded in the matrix. For this reason it is suggested that the study of the organisation of particulate matter in glacial tills should be carried out at all levels in order to provide a fuller and better understanding of the depositional process associated with tills.

f) From density variations in the modern tills studied and the Cowal till it has been shown that the in situ dry density was highly variable and could in fact be less than achievable by dry pouring in the laboratory. Detailed observation of the microfabric in the modern and some other tills studied confirmed the variable nature of the degree of openness of the till fabric and showed that the distribution of coarse and fines within the soil was rather patchy, perhaps confirming the suggestion that the fines were entrapped in water within the ice. The microfabric features observed in the various tills were, however, fairly consistent from one till to another and when analysed according to a recently developed qualitative system, they were recognised as being similar to those viewed in many other natural soils from a wide variety of depositional processes.

g) The dry densities achieved in laboratory reconstituted till samples were shown to vary due to gradational variations by as much or more than due to changes in compactive energy. Thus the inherent variability in the proportion of fines in basal melt out tills will induce in in situ undisturbed and recompacted tills in the field very large variations in dry density. For engineering works through or on this material, whether it be undisturbed or recompacted, then dry density variations must be expected and allowed for in design. It is suggested that quality control of compacted till need include a measure of the variability of the proportion of fines otherwise the degree of uniformity of compaction cannot be established. From this point of view the fundamental nature of the basal melt out tills greatly controls its engineering behaviour.

h) The permeability of the tills in the reconstituted state was shown to deviate from Darcy behaviour by virtue of the possibility of particle migration during flow. This phenomenon was considered to be very likely in gap graded tills and also in the very loose in situ undisturbed tills where many particles would not be involved in load carrying thus they would more easily move. It is suggested that sudden application of relatively large hydraulic gradients in tests could also induce this non Darcy behaviour. In fact tests on Cowal till tended to support this.

i) The influence of gradational variations in relation to density variations was shown to be large for the tills, however, the influence of moulding water content was also shown to be significant, possibly in terms of the fabric arrangement induced in the till. When attempting to classify the variations in permeability between tills it was suggested that it was not possibly to show all possible variations and that only the minimum permeability of the tills at Proctor compactive effort could be used as a direct comparitor, or some other equally definable, easily determinable and specific value. The comparison was then based on the percentage fines and the grain size index classification of the fines in the till. Although the classification therefore took account of many of the factors influencing permeability only limited success was met. It is suggested that problems associated with the non Darcy behaviour and fabric variations attributed to the limitations on the success of this system of classification.

j) The large number of factors influencing the drained shear strength of the tills was recognised. The complexities of these were such that when the same approach to classification was used for shear strength as was used in permeability, no correlation was found between the percentage and nature of the fines and the drained angle of shear strength of the various tills. It was found that the relationship between dry density and drained angle of friction in any one till was quite usual and that the variation of the drained angle of friction with percentage fines at any state such as Proctor optimum was definable. In fact it was shown once again that the organisation of the particulate matter in the tills was crucial, in this case with respect to the strength in reconstituted laboratory tills, and it was therefore suggested that the shear strength of the in situ tills would be likewise influenced by these factors and by virtue of their greater variability in situ so the strength of in situ tills would be highly variable and unpredictable.

k) The complex interaction of the variation in gradation particle organisation and density of basal melt out tills, which variations are a direct result of their mode of formation and deposition, cause this particular material to be a highly unpredictable soil type. Recompaction of these materials reduces but does not always eliminate the particle organisation variations, however, the gradational and related density variations remain and the inherent variability of the till essentially remains. The approach taken in this investigation of recognising the fundamental nature of the gradational and particle organisation variations appears to be a means of better understanding and correlating the tills for geological and engineering purposes.

SUGGESTIONS FOR FUTURE RESEARCH.

1) The present work has shown an apparent lack of correlation between rock type and particle size distribution in the tills. The range of lithologies investigated was, however, somewhat restricted. Further investigation of the lithologic influences on till gradation should therefore be undertaken and include more detailed study of lithologic variations with particle size range within individual tills and comparisons of the nature of the fine and coarse fractions, their relative percentages and the split sizes amongst various tills.

2) The factors controlling the observed change in grindability above and below the split size in the tills should be further investigated to determine the relative importance of changes from polymineral to monomineral particles and of the changes in the water environment and distribution of fines in the englacial state.

3) The study of the organisation of particles at all size levels in tills should be further employed and applied to tills deposited by various known processes. This will permit an assessment of the ability of this approach to differentiate the range of glacial depositional processes and so evaluate its usefulness as an additional tool for the identification and differentiation of glacial deposits.

4) The present qualitative analysis of Scanning Electron Microscopy data should be developed and quantitative data sought in terms of the relative frequency of fabric features present and the spatial

orientation of these features.

5) The recommended approach of identifying the nature and percentage of fines in tills formed by direct comminution and measuring the variations in engineering properties within the limits of variation of these factors, should be applied in future investigations. Correlation between engineering properties and the nature and percentage of fines could then be sought on the basis of much more information than was available for the present work.

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