MINERALOGICAL AND GEOCHEMICAL STUDIES OF TILLS

IN

SOUTH-WESTERN SCOTLAND

by

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at

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To my wife,

ENAS,

and

my children,

AHMED and YASMEEN

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

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S U M M A R Y

Till deposits of the NW Glasgow area and Northern Ayrshire were studied. In Part I, previous research into Quaternary problems in these areas and the nature, origin and classification of till deposits are outlined, followed by a statement of the aims of the project and the techniques used.

Part II contains detailed data obtained from grain-size, clay mineralogical and major and trace element analyses of the matrices of three categories of NW Glasgow tills - Red, Weathered Grey and Grey. The Red and Weathered Grey tills have coarser-grained compositions than the Grey till. Mean size and skewness are the most diagnostic grain-size parameters for distinguishing between Red and Weathered Grey till on the one hand and Grey till on the other. All three categories contain kaolinite, illite and vermiculite. Chlorite is present only in the Grey till. The percentage of kaolinite is much lower and the percentage of vermiculite is higher in the Red till than in the Weathered Grey till. Three probable modes of origin of the clay minerals in the tills are proposed: direct inheritance, pre-glacial weathering and pedogenesis since till deposition.

All three categories of till have a high SiO_2 content, which is consistent with the tills having sources in the local sandstone bedrocks. With the exception of Zr, all the trace elements are preferentially concentrated in the silt and clay fractions. Zr appears to occur both in clay minerals and in the sand fraction as detrital zircon. Sr is concentrated in the calcium minerals and Ba in the K-feldspars.

Study of vertical profiles shows that leaching of fine-grained material and weathering of clay minerals are common. Weathering in the Red till is difficult to detect. However, the amount of vermiculite increases upwards in the profile at the expense of illite. In the case of profiles through both Grey and Weathered Grey till, chlorite disappears, and the amount of vermiculite increases up the profile at the expense of both illite and chlorite. The ratios Ga:Al_2O_3, MgO:Ni, FeO:Co and Ni:Co can be used to detect weathering trends in both Grey and Red till profiles.

Mineralogical and geochemical studies of bedrock in the NW Glasgow area, showing the presence of chlorite in Carboniferous shales and sandstones and its absence in Devonian (O.R.S.) sandstones, indicate that the Grey till was derived largely from Carboniferous shales and sandstones, and the Red till largely from Devonian sandstones.

Part III contains detailed data obtained by similar methods applied to the matrices of tills and associated Quaternary deposits in Northern Ayrshire. Marked similarities in the properties of samples of shelly till from five locations suggest similar sources for the shelly till at these locations. The shelly till has a high SiO_2 and a low clay content, suggesting that the proportion of shell-bearing marine clay in the shelly till is not nearly as great as previously thought. The high SiO_2 content in both the shelly and non-shelly tills of Northern Ayrshire reflects quartz-rich source rocks for these tills. The matrices of the non-shelly tills have higher CaO and CO_2 contents than the matrix of the shelly till. This may be due to the presence of finely ground limestone in the non-shelly till matrices.

Comparison of the properties of shell-bearing marine clays at Afton Lodge with those of the shelly till of N Ayrshire as a whole and with a shell-bearing deposit at Greenock Mains shows clearly that the last-mentioned is not a shelly till as formerly thought but is a marine sediment similar in composition to the deposit at Afton Lodge.

The matrices of Upper and Lower grey tills at Sourlie are similar in composition, indicating similar sources, probably mainly local Carboniferous shales and sandstones.

Finally, the thesis applies the results obtained to Quaternary stratigraphy. The properties of the matrices of red and grey facies of the proposed 'Wilderness Till' Formation of the Glasgow area can now be defined. The presence of Weathered Grey till overlain by Red till in the NW Glasgow area suggests at least a short period of exposure of Grey till before deposition of Red till on top of it. In Ayrshire, the discovery of shell-bearing marine deposits (at Greenock Mains) at c. 180m above present sea level and c. 30km inland from the present coast means that recent views regarding the maximum elevation and extent of Quaternary marine incursion in Ayrshire may have to be modified. The presence of these sediments also implies that the shelly till may have been derived from pockets of shell-bearing deposits picked up locally within inland Ayrshire rather than from the Firth of Clyde. The presence of shelly till at any given location, therefore, may not be indicative of any particular direction of ice movement, as formerly thought.

D E C L A R A T I O N

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Mamdouh Abd-Alla

PART I

INTRODUCTION TO THE RESEARCH PROJECT

CHAPTER 1

INTRODUCTION

1.1 General background to the research project

Mineralogical and geochemical studies of sedimentary rocks, although not so extensive as such studies of igneous and metamorphic rocks, have been made in many parts of the world in the course of the last twenty to thirty years. Despite this, the detailed mineralogy and, especially, the detailed geochemistry of tills, a group of sedimentary rocks of glacial origin, are not well known.

In view of the scarcity of mineralogical and geochemical information available on tills, and in view of the occurrence of large quantities of several varieties of till in the Glasgow area and adjacent parts of western Scotland, the detailed mineralogical and geochemical analysis of tills from selected parts of the Glasgow area and Ayrshire was considered to be an innovative and useful contribution to Quaternary research. Also, since these areas in the past have provided interesting and controversial problems in Quaternary stratigraphy, it was decided to examine at least briefly the potential of the application of the mineralogical and geochemical properties of the tills of these areas to the interpretation of the Quaternary history of these parts of south-western Scotland.

At the time that the research project was begun, early in 1985, about fifty samples of till from the NW Glasgow area were available in the Department of Geology at the University of Glasgow. These samples had been collected by Dr W.G. Jardine in the mid-1960s as opportunities arose, in shallow trenches dug in the provision of water and power services and in large-scale excavations opened in the course of building construction. Each sample collected had been assigned to one of three categories - Red till, Grey till, Weathered Grey till - on the basis of its colour and its field characteristics, but no laboratory analyses of the samples had been undertaken. No samples of till from Northern Ayrshire were to hand in 1985.

The preliminary results obtained from analysis of the fifty previously-collected samples suggested that it would be useful to extend the examination of tills of the NW Glasgow area to analysis of series of samples obtained from a number of vertical profiles in that area. The preliminary results also suggested that a useful contribution to the very limited information available on the tills of Northern Ayrshire would be made by analysing series of samples from carefully-selected sites in that part of western Scotland. The sites chosen for this part of the study in the NW Glasgow area were determined by the availability in 1986 of two suitable natural exposures in the Red till and by the chance excavation at that time of two building sites located in both Weathered Grey till and Grey till.

In Ayrshire the selection of sites for sampling was determined partly by the availability of suitable exposures, but a more important consideration was the presence, at each of the selected sites, either of a sequence of two or more superimposed tills or of till that had been described in the literature as a "shelly till". By chance, one of the selected Ayrshire sites, at Sourlie near Irvine, yielded organic-rich sediments both underlain and overlain by substantial thicknesses of till. Sourlie has proved to be an important interstadial site of Middle Devensian age. The biological data, sedimentology and certain aspects of the characteristics of the tills at that site will be recorded by other writers elsewhere. The mineralogical and geochemical data included in this thesis, however, are important contributions to the record of that site.

1.2 Geological setting of the field areas

The limits of the field areas, NW Glasgow and Northern Ayrshire, are defined in Chapter 1.4, below. The solid rocks underlying these areas, and therefore thought to be the main sources of the tills of NW Glasgow and Northern Ayrshire, are sedimentary and igneous rocks mainly of the Devonian (Old Red Sandstone) and Carboniferous Systems. Their areal distributions are shown in Figure 1.1, together with that of the Dalradian metamorphic rocks, which occur to the north-west of the zone of the Highland Boundary Fault. Dalradian rocks form a very minor component of the clast fraction of the tills of both the NW Glasgow area and Northern Ayrshire, but their occurrence in these tills is indicative of a general north-to-south or north-west to south-east movement of Highland ice over the Glasgow area and northern parts of Ayrshire in Late Quaternary times (see Chapters 3.2 and 3.3).

In broad terms, the Old Red Sandstone (Devonian) rocks outcrop to the north-west of Glasgow and in the western part of Northern Ayrshire. The rocks were laid down in semi-arid conditions on a continental land mass. They are mainly conglomerates and sandstones whose major components, respectively, are quartzite cobbles and quartz grains. Their colour usually is dull red, due to the oxidising conditions in which the rocks were formed.

The Carboniferous rocks of western Central Scotland consist of four major sedimentary units, the Calciferous Sandstone Series, the Carboniferous Limestone Series, the Millstone Grit and the Coal Measures, and a major igneous unit of lavas that are interstratified as a thick sequence within the Calciferous Sandstone Series (see note on Names of Devonian and Carboniferous rock units in section 1.4 of the text below).

In the Glasgow area, the Carboniferous rocks broadly form a large eastwards-plunging syncline, so that basaltic lavas outcrop as high ground to the north, west and south of the city, whilst the central area is underlain by limestones, shales and sandstones of the Carboniferous Limestone Series. The rocks of the Millstone Grit and Coal Measures occur mainly to the east and to the south of central Glasgow. As a result, rocks of these units are not found within the tills of the NW Glasgow area.

The sequence of major rock units in the Calciferous Sandstone Series and Carboniferous Limestone Series of the Glasgow District is shown in Table 1.1. In terms of lithology, the Lower Sedimentary Group and Upper Sedimentary Group of the Calciferous Sandstone Series consist, respectively, of thin argillaceous dolomitic limestones together with mudstones or shales and occasional sandstones, and of quartzitic conglomerates and quartz arenites. All of these rocks were deposited in terrestrial (lacustrine or fluvial) environments. In contrast, the rocks of the Lower and Upper Limestone Groups and the intervening Limestone Coal Group of the Carboniferous Limestone Series were deposited in environments that alternated between terrestrial and shallow marine conditions. Sandstones, shales, limestones and thin coal seams are present in all three Groups. The major difference between the Limestone Coal Group and the Groups immediately below and above it is the greater proportion of coal in the middle Group. In summary, the major bedrock types of the NW Glasgow area that were available for transport by the Quaternary ice masses and for subsequent deposition as the Grey till and Red till of that area were: Devonian red sandstones and conglomerates; basalts of the Clyde Plateau Lavas; quartz conglomerate and quartz-rich sandstones of the upper part of the Calciferous Sandstone Series; shales, limestones and sandstones (and, to a lesser extent, coals) of the Carboniferous Limestone Series (see Chapter 9).

As explained in Chapter 1.4, below, the extent of the area known as 'Northern Ayrshire' for the purposes of this research project is more difficult to define than the extent of the 'NW Glasgow area'. For the same reason, it is more difficult to give the geological setting of Northern Ayrshire than the geological setting of the Glasgow district. In broad terms, however, the north-western part of 'Northern Ayrshire' is underlain by Devonian sandstones, the north-eastern part by Carboniferous basaltic lavas, the south-eastern part by Silurian greywackes, and the central part of the area north of the Inchgotrick Fault (Kilmarnock to Strathaven, Fig. 1.1) by Carboniferous sedimentary rocks - mainly sandstones, shales and limestones. South of the Inchgotrick Fault, a mixture of Devonian sandstones and conglomerates and Carboniferous sandstones, shales and limestones are the main bedrocks except on the northern side of the town of Mauchline, where a small area of Carboniferous - New Red Sandstone lavas and bright orange-red aeolian sandstones underlies the southern margin of 'Northern Ayrshire'. Clearly, a great variety of source rocks for the tills of Northern Ayrshire was available during the various phases of Quaternary glaciation. The composition of the till at any particular site depends partly on the nature of the bedrock in the vicinity of the site, and partly on the direction in which the ice moved prior to deposition of the till at that site (see Chapter 3.3).

1.3 Organisation of the thesis

The thesis is divided into four Parts. In Part I, a brief introductory chapter, explaining the nature of the research project and giving the geological setting, is followed as a logical consequence by a chapter in which the nature, origin and classification of tills are examined. Chapter 3, in which previous studies of tills in the NW Glasgow area and Northern Ayrshire are outlined, is followed by a statement of the aims of the research project. These aims are more clearly definable in Chapter 4, after previous research has been considered, than in Chapter 1, where the setting of the project has not been fully given. Chapter 4 also describes the methods of investigation used in the course of the research.

Parts II and III present the data derived from grain-size, clay-mineralogical and geochemical analysis of the tills of, respectively, the NW Glasgow area and Northern Ayrshire. Part II also includes analytical data concerning bedrocks that underlie tills in the NW Glasgow area. In both Part II and Part III, the results of the grain-size, clay-mineralogical and geochemical analyses are discussed, and conclusions regarding the nature of the various tills of the two geographical areas are given.

Part IV of the thesis is concerned with the application of the results of the grain-size, clay-mineralogical and geochemical analyses to the possible solving of problems regarding the stratigraphical relationships of the tills and associated deposits of the NW Glasgow area and Northern Ayrshire. A final chapter is devoted to a summary of the results of the research project, conclusions reached and suggestions for further study of the tills of the two areas to which the study was directed.

1.4 Explanatory notes

A number of terms used frequently throughout the thesis are defined below. The system used in the numbering of samples is also explained.

NW Glasgow area

The area referred to in the text below as the 'NW Glasgow area' is shown in Figure 1.2. It consists of the north-western part of Glasgow District (formerly the City of Glasgow), through which the boundary between Red till (to the north-west) and Grey till (to the south-east) extends, together with adjacent areas of the (former) County of Dunbartonshire. Essentially, it covers the area in which approximately fifty samples of Red till, Weathered Grey till and Grey till were collected in the 1960s and, in addition, includes part of the ground to the west and north, where the source bedrocks of the Red till and minor components of the Grey till are located. Sites where vertical series of samples of till were collected in 1986 are also included in this area. One of the sites from which samples of bedrock were obtained for analysis (see Chapter 9) is located to the west and north of the area shown in Figure 1.2.

Northern Ayrshire

The area referred to in the text below as 'Northern Ayrshire' (or 'N Ayrshire') is more difficult to define than the NW Glasgow area. The former County of Ayrshire covers a very large area, and comprises three political divisions: Cunninghame (in the north), Kyle (in the centre) and Carrick (in the south). Geological Survey maps of Ayrshire on the scale of one-inch-to-one-mile, with their corresponding Memoirs, cover areas that correspond broadly with the political divisions, but also include parts of adjacent counties. Sheets 21 and 22 cover northern Ayrshire, Sheets 13, 14, and 15 cover central Ayrshire and Sheets 7 and 8 cover southern Ayrshire. The Ayrshire sites from which samples were obtained for study within the research project are located within the bounds of the Geological Survey's Sheet 22, the northern part of Sheet 14 and the north-western part of Sheet 15. The area concerned, therefore, is termed Northern Ayrshire for the purposes of this study. More exactly, the area extends from the coast of the Firth of Clyde in the west to National Grid 'easting' 070 in the east, and from National Grid 'northing' 025 in the south to National Grid 'northing' 050 in the north (Fig. 1.3).

Site and Location

Places where samples of till were collected for analysis are denoted in the text below by the terms Site and Location. The term Site denotes either a single, individual, Location or a group of adjacent Locations. For example, the Sorn Mains Site of Northern Ayrshire comprises three Locations, 5-1, 5-2 and 5-3, positioned within a few hundred metres of each other, whereas the Lochend Drive Site of the NW Glasgow area consists of only one Location, that where the sample with Field Number R42 was collected.

The Location at which each sample was collected either in the NW Glasgow area or in Northern Ayrshire is recorded by eight-figure National Grid Reference coordinates, except in the cases of the Sites at Broomhill Cross and Elderslie Dock, NW Glasgow area, where only six-figure coordinates are available from the records prepared in the 1960s by Dr W.G. Jardine.

Field Numbers used to identify samples of till and bedrock

Each of the 49 samples of till collected in the NW Glasgow area in the 1960s is identified by a Field Number (1 to 50, omitting No.46, which was a sample of water-deposited sand rather than till). In many of the Tables giving data relating to the tills of the NW Glasgow area, the Field Number of a sample bears the additional prefix R, WG or G. This indicates that, as the result of the laboratory analyses carried out in the course of the research project, the sample concerned was identified as belonging to, respectively, the Red, Weathered Grey or Grey category of till of the NW Glasgow area.

Each of the 25 samples of till collected from four sites (Laighpark, Clober, Kelvinside and Queen Margaret Hall) in the NW Glasgow area in 1986 is identified by a number such as 4-3. In these cases, the first number denotes the Site (individual Location) and the second number denotes the position of the sample within a vertical sequence of samples taken at the Site. In the example given above, the Site (4) is Clober, and the sample was the third to be taken (in a sequence of 5 collected upwards).

Each of the 64 analysed samples of till from Northern Ayrshire is identified by a number such as 6-4 or, in the case of samples from Sorn Mains Locations, 5-2-3. The number 6-4, for example, identifies the sample as being the fourth in a sequence collected at Location 6, at Greenock Mains Site. The number 5-2-3 identifies the sample as being the third in a sequence collected at Location 5-2 at Sorn Mains Site.

Each sample of till, therefore, has a unique number, although the 'style' of that number may vary greatly. For example, it may be WG14, 1-3, 5B-2 or 5-1-4. Details concerning till samples are given in appropriate chapters of Parts II and III below.

Names of Devonian and Carboniferous rock units

The names of Devonian and Carboniferous rock units used in section 1.2 of the text above and included in Tables 1.1 and 9.1 are those that have appeared in the literature (including Geological Survey maps) for more than fifty years (e.g. Clough et al. 1925; Bassett 1958; George 1958; Bluck 1973). Some of the terms now have no formal standing since they do not conform precisely to strict codes of stratigraphical nomenclature. They are preferred here, however, to those proposed recently (Paterson & Hall 1986) since, being better known and covering a wider range of the late Devonian and early Carboniferous rocks of western Scotland, they provide a more useful framework for the geological setting of this project.

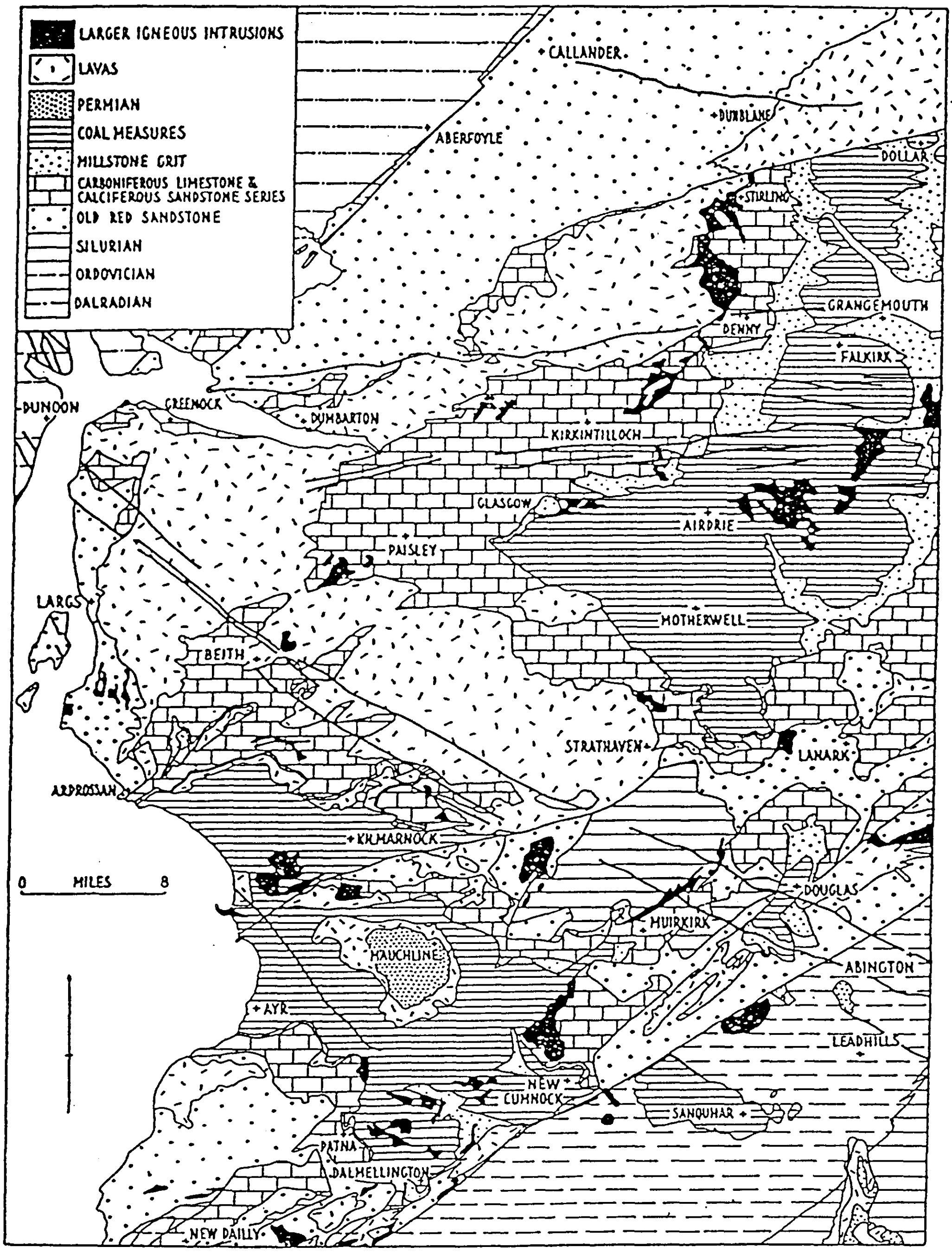


Figure 1.1 Outline map of the solid geology of the Glasgow area and northern part of Ayrshire (after George 1958).

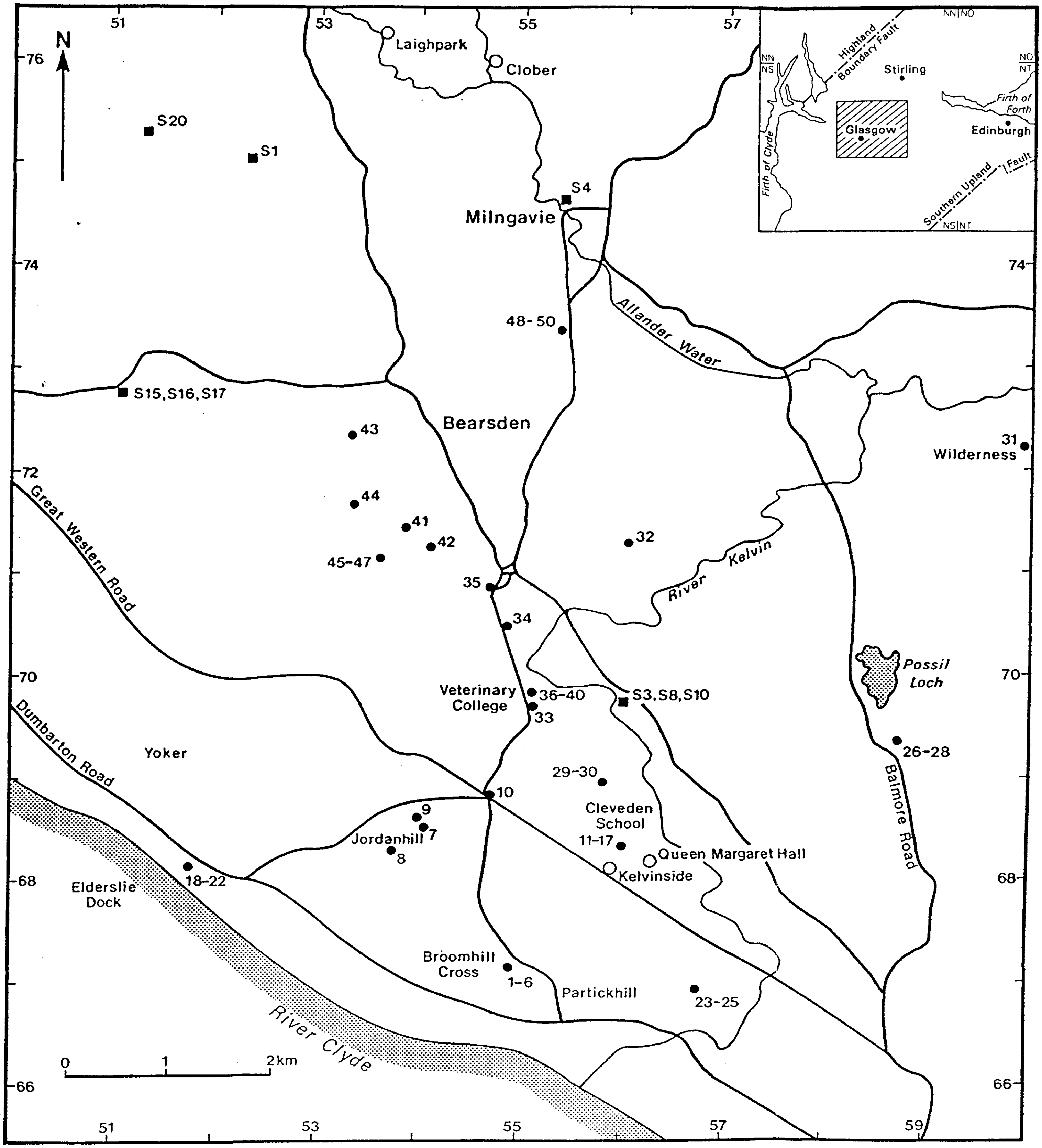


Figure 1.2 The NW Glasgow area, showing the distribution of till sample sites 1-50 (solid black circles), sites of profiles in Red and Grey tills (open circles) and sites where bedrock samples were collected (solid black squares). The positions of other locations mentioned in the text are also shown. National Grid reference coordinates are given on the edges of the map.

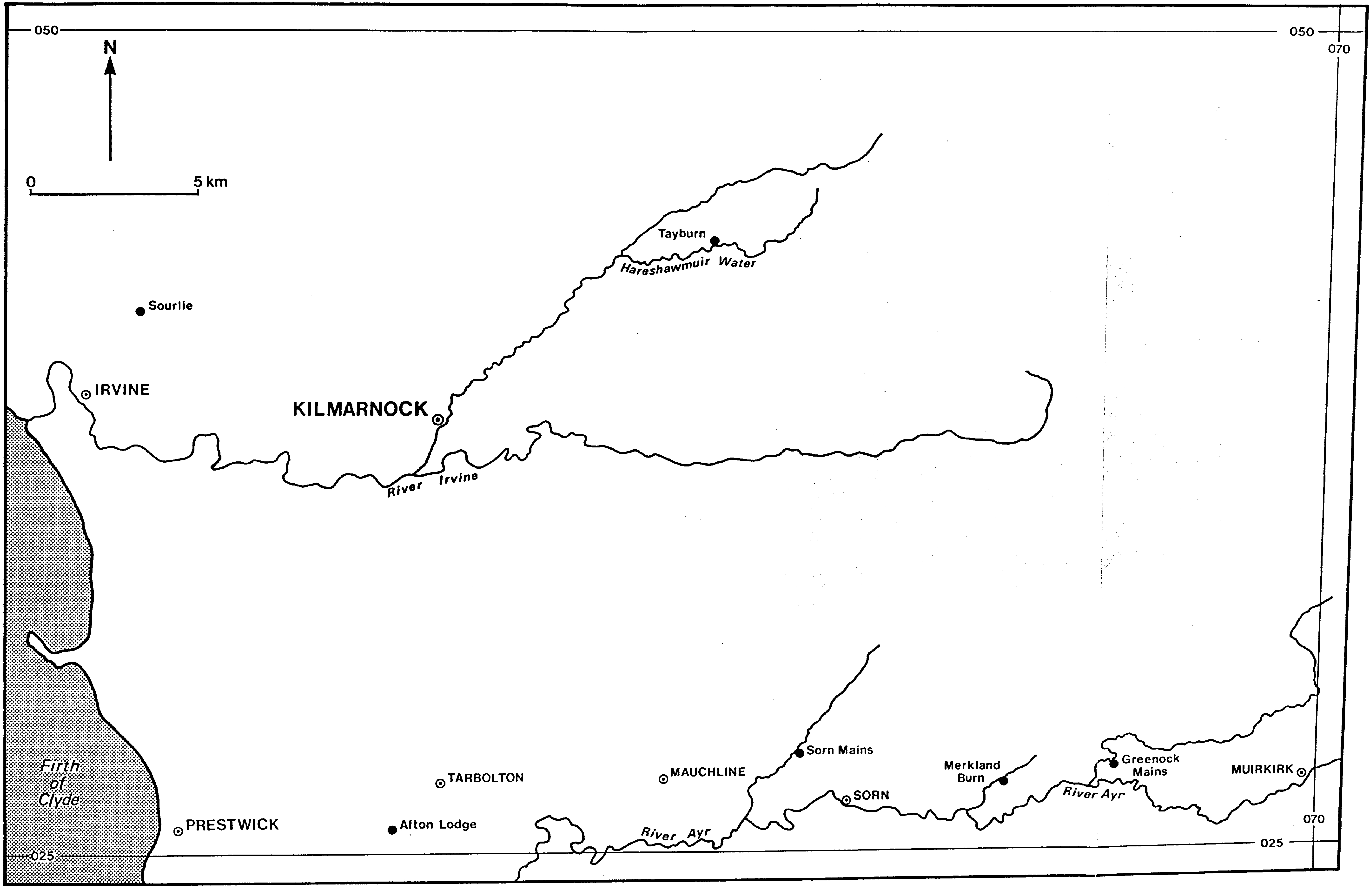


Figure 1.3 Distribution of sample sites in Northern Ayrshire.

Table 1.1 Generalised bedrock succession in the Glasgow area and Northern Ayrshire. Not to scale.

PERMIAN SYSTEM		Lower part of the New Red Sandstone
CARBONIFEROUS SYSTEM	Coal Measures	
	Millstone Grit	
	Carboniferous Limestone Series	Upper Limestone Group
		Limestone Coal Group
		Lower Limestone Group
	Calciferous Sandstone Series	Upper Sedimentary Group
		Clyde Plateau Lavas
		Lower Sedimentary Group
DEVONIAN SYSTEM	Upper Old Red Sandstone	
	Lower Old Red Sandstone	
SILURIAN SYSTEM		
	Dalradian rocks (metamorphic)	

CHAPTER 2

THE NATURE, ORIGIN AND CLASSIFICATION OF TILL

2.1 Introduction

Quaternary deposits formed in glacial environments are very important, because they cover wide areas of the earth's surface. Most of North America, particularly Canada, the entire northern part of Europe (over a third of Europe) and considerable portions of the other continents have been glaciated several times during the last two million years and covered by various thicknesses of till and other glaciogenic deposits (Woldstedt 1954; Charlesworth 1957; Flint 1957 and 1971; Goldthwait 1971; Rukhina 1973). The Quaternary glacial deposits are especially important in those areas because they provide parent material for much of the soil. They also comprise natural resources such as gravel, sand and clay for the building and construction industries, and they may be important in the development of water supply either as aquifers or seals, or in affecting the water-tightness of reservoirs, dams and canals.

2.2 Nomenclature

Various definitions of till deposits have been proposed. The definitions reflect the complex history of investigation. Some definitions were introduced during the 19th century from topographical features and adapted, sometimes being used in different ways by different authors, and still others have been introduced during recent years. It is seldom that exactly the same definition of a particular term is used by more than one author or group of authors, and this lack of agreement on nomenclature, combined with the complex and variable nature of the till deposits themselves, makes classification very difficult.

Although the definitions of till vary from one author to another, most authors stress the following characteristics of till: 1) a glacial origin; 2) the presence of a variety of rock and mineral fragments of various sizes, many of the clasts having been transported a considerable distance; 3) poor sorting, usually with bimodal or multimodal distribution; 4) lack of stratification, although some tills are foliated; 5) compactness or close packing (Dreimanis 1976, 14).

Till was defined originally (Geikie 1863, 185) as, 'a stiff clay full of stones varying in size up to boulders produced by abrasion carried on by the ice sheet as it moved over the land'. Since then, various authors have referred to till as being non-sorted (e.g. Goldthwait 1971, 4; Flint 1971, 154) or unsorted (e.g. Hatch et al. 1965, 60). Many tills indeed are poorly sorted, in that they include particles that vary greatly in size, but Dreimanis & Vagners (1971a) demonstrated that, whereas tills made up of material that has undergone only short-distance transport consist mainly of clast-size particles, the matrix tends to become predominant with increasing distance of transport. For a specific mineral or group of minerals of similar physical properties, the particle-size distribution is bimodal, one mode being in the clast grades and the other in the matrix, where there is a typical 'terminal grade' for each mineral as a result of glacial comminution.

In relation to this point, a problem that applies especially to till is the use of the terms 'clast' and 'matrix'. Dreimanis (1969) suggested that the boundary between clast and matrix should lie between 0.1 and 2.0mm, on the basis of his demonstration of the bi- or polymodal distribution of the individual petrographical components of till. Lindén (1975) used 2.0mm as the upper limit of the matrix. The boundary between matrix and clast used in the research project discussed in this thesis agrees with that of Lindén (1975).

In order to emphasise that till is a glacial deposit, the word 'glacial' has often been added (Dreimanis 1976, 14). Goldthwait (1971, 3), however, stresses that 'till is the only sediment stemming directly and solely from glacial ice'. Flint (1971, 148) gives the following definition of till: 'till is a nonstratified sediment (diamicton) carried on or deposited by a glacier (glaciogenic) and usually exhibits a multimodal grading curve'. Hence, according to Flint (1971), the term is both sedimentological and genetic.

Till has several synonyms. The most popular are: 1) the English term 'boulder clay'; 2) the French terms 'moraine' and 'moraine profonde', which are used in translated form in various non-English languages in Europe. Since neither boulders nor clay are main constituents of many tills, the term 'boulder clay' is losing its former popularity (Dreimanis 1976, 15).

As there is some confusion concerning the correct use of the terms 'drift', 'till' and 'boulder clay', the meanings of these words as used in this thesis are defined now. Flint (1971, 147) gives the following definition of 'drift': 'As used today the term glacial drift embraces all rock material in transport by glacier ice, all deposits made by glacier ice, and all deposits predominantly of glacial origin made in the sea or in bodies of glacial melt water, whether rafted in icebergs or transported in the water itself'. Geologists early subdivided drift into two supposedly distinct kinds: till or non-stratified drift, and stratified drift.

Nowadays the term till is often used as a synonym of boulder clay (cf. Geikie 1863; Woodward 1887; Holmes 1944). On this subject, however, Flint (1971, 148) wrote the following: 'Till, like drift is a term that long antedates the glacial theory. It is a Scottish word, used by generations of Scots countryfolk to describe a kind of coarse, obdurate land, the soil developed on the stony clay that covers much of northern Britain. The earliest detailed areal glacial studies published in Britain were Scottish. Hence the Scots term came into wide use rather than the English term boulder clay. This is fortunate because boulder clay is not a good designation for the range of deposits we know as till. It is not good because some till contains no boulders, some contains little or no clay and some (though probably not very much) contains neither boulders nor clay, but only silt, sand and pebbles'.

One can agree with Flint that till has a broader meaning than boulder clay. In this thesis the definition used by Rice (1963, 416) will be followed in part: 'Till. That part of a glacial drift consisting of material deposited by and underneath the ice, with little or no transportation by water; it is a generally unstratified, unconsolidated, heterogeneous mixture of clay, sand, gravel and boulders... Two kinds are recognised:

1. Glacier-till, deposited directly by glacier-ice, not by glacier-waters, though it may be locally modified by them. Contrasted with glacier sediment, it may be

    a) englacial - carried within the ice mass

    b) superglacial - borne on the ice surface

    c) subglacial - dragged along beneath the glacier and in this case called also ground-moraine or boulder-clay.

2. Berg-till, detrital matter deposited by icebergs. Called also subaqueous till or floe till'.

Till may be defined as sediment deposited by or from glacier ice without the intervention of running water. This genetic definition gives no effective sedimentological description, and any attempt to incorporate an indication of lithology or texture in a definition of till cannot be sustained because of the very widely variable nature of tills. Indeed, as Flint (1971, 154) states, 'Till is possibly more variable than any other sediment known by a single name'.

2.3 Genetic variability of till

Variability of till depends upon numerous factors. Usually the variety of rocks and minerals in till, and their particle sizes, are considered most important. These variables can be determined quantitatively, and therefore most of the applied classifications and descriptions of tills are based upon lithological and granulometric parameters (Lundqvist 1940; Elson 1961; Virkkala 1969; Broms 1973; Karrow 1976).

Dreimanis (1976, 17) states that 'It is too difficult to identify the origin or genesis of till. It involves a sequence of events, beginning with (1) erosion of rocks and minerals, or merely deformation of them by a glacier; (2) followed by transport of this eroded material in or upon a glacier; and then completed by (3) deposition of till by various mechanisms. There are so many variables involved in the above sequences, that it is doubtful if a person can be aware of all of them when interpreting the final product till from the genetic viewpoint'.

Although it is difficult to study glacial erosion, transport and deposition at glaciers active at present, such investigations are increasing (e.g. Bayrock 1967; Boulton 1968 and 1971; Goldthwait 1971; Derbyshire & McGown 1973). Most theories on the above-mentioned three processes, and resulting deductions on the origin of till, however, have been based mainly upon investigation of already-deposited recent or Pleistocene tills, or even pre-Pleistocene tillites. Glacial geologists are still engaged in a continuing process of evaluating the steadily accumulating information in order to construct a genetic classification of tills, and to establish useful criteria for differentiation not only of the various types of till but also of till from other diamictons (Harland et al. 1966; Dreimanis 1970; Flint 1971.).

2.4 Classification of till

The classification of till is often based on genesis and/or grain size, although stratigraphy and petrographical parameters have also been used. (It should be noted that many authors use the term 'texture' rather than 'grain size' when discussing tills.) A genetic classification proposed by Dreimanis in 1969 is shown in Figure 2.1. Since originally published, this classification has been developed further and several other types of till have been added.

The classes of deposits shown in Figure 2.1 are reminders that for a long time a genetic classification of till into two groups, basal/lodgement till and ablation till, was recognised (Flint 1971). A more sophisticated subdivision was made by Dreimanis & Vagners (1971a) and later was modified somewhat by Dreimanis (1978), who divided ablation till and basal till into two and three subgroups, respectively, and (in 1969) proposed a further separate main type, namely waterlaid till (Fig.2.2). Francis (1975) also suggested a modification of the classification proposed by Dreimanis & Vagners.

In order to distinguish between the various (genetic) subgroups of ablation and basal till, it is necessary to carry out detailed fabric analysis (Boulton 1970a and 1971).

When tills have been considered according to their modes of deposition, which reflect only part of their genetic history, two main types have been distinguished since the start of till investigations about a century ago (Dreimanis 1976, 24):

1) Superglacial, supraglacial, ablation or upper:
   till deposited on or from the surface of a glacier because of downmelting ice.

2) Subglacial, basal, lodgement or lower:
   till deposited beneath a glacier.

Most authors claim that ablation till is of coarse size grade, as fines may become washed out (Elson 1961; Lundqvist 1969: Flint 1971). Boulton (1968 and 1972b), however, demonstrated the absence of washing in some varieties of ablation till.

Since ablation tills are derived from englacial drift in areas of continental glaciation, their lithological composition may differ from that of basal till derived from basal drift. Ablation till usually contains more distantly-travelled material than does basal till (Shilts 1973 and 1976).

Boulton (1968 and 1972b) distinguished two varieties of superglacial till: 1) melt-out till; 2) flow-till. He applied the term 'melt-out till' to tills formed either on top of or underneath a glacier. The former variety of melt-out till belongs only to what is commonly called ablation till, while the latter variety of melt-out till corresponds to some extent with Elson's (1961) superglacial till.

Flow-till has been investigated, particularly by Boulton (1968 and 1971), on currently-active Svalbard glaciers, and found to be common in their terminal zone. It is usually derived from the ablation melt-out till which is fluid during thawing out of ice, and may move down-slope as mobile liquid flow, or as semi-plastic flow, or by creep (Boulton 1971).

It is difficult to observe and study the deposition of till underneath ice (Dreimanis 1976). Only a few investigations have been carried out underneath present-day glaciers, the most notable being those of Boulton (1970a; 1970b; and 1971). Slightly more numerous studies have been carried out in relation to recently-deposited tills, some exposed, some still partly hidden underneath the glacier's edge (Okko 1955; Donner & West 1957; Goldthwait 1971; Jewtuchowicz 1972). It follows from these comments that most deductions on the mode of formation of subglacial tills have been based upon studies of Pleistocene tills, assumed for various reasons to be of subglacial origin.

Until recently, most students of subglacially-deposited tills assumed that these tills had been deposited by lodgement or plastering processes underneath active moving glaciers. As a result, the term 'lodgement till' (Dreimanis 1970) has gradually replaced the term 'glacial till' that was used more commonly in the older literature (Chamberlin 1894; Gillberg 1955). The densest variety of lodgement till is called 'comminution till' by Elson (1961).

Classification schemes, based directly or indirectly on till genesis, are discussed below in varying degrees of detail. It should be noted that facies classification models are now available for some modern glacial environments (Boulton & Eyles 1979; Eyles 1979; Boulton

1980; Martin 1980). Also, examples of classifications of till based on grain size may be found in publications by Lundqvist (1940), Elson (1961), Virkkala (1969) and Follestad (1973). Lundqvist's classification is weakened, in Vorren's (1979) view, by requiring so many words to describe certain till types. Vorren (1979) himself proposed a simple grain-size classification of till, based on the clay, silt and sand content, as shown in Figure 2.3.

Recently, Dreimanis (in Schlüchter 1982) suggested a classification system of till that may be constructed as shown in Figure 2.4. It considers mainly the processes of deposition, but it also takes account of the environments of transport and deposition, and of the derivation of till. It recognises five main types of till, which may have been deposited in somewhat different ways and environments. Two main groups of till are distinguished: primary or ortho-tills, and secondary or allo-tills. This grouping was proposed in 1981 almost simultaneously by Boulton & Deynoux (1981) and Dreimanis (1983). Dreimanis included subaquatic melt-out tills in the secondary tills, contrary to Boulton & Deynoux. Ortho- and allo-tills are further subdivided into three main types: lodgement till, melt-out till and flow till. Briefly, these types and in addition, deformation till and sublimation till, can be defined as shown in Table 2.1 (from Lundqvist 1984).

As noted above in considering their classification on the basis of genesis, tills are deposited in a number of different ways. Such characteristics as lithological composition and fabric (the latter discussed separately in Chapter 2.5) are dependent upon the particular mode of deposition. Elson (1961) noted that the character of a till depends on the lithology of the material from which the till has been derived, on the position in which that material has been transported in the glacier and on the mode of deposition. Whereas Holmes (1941) saw till deposition mainly in terms of lodgement, and Harrison (1957) saw it mainly as the result of melting in situ, Elson (1961) stated that two types of till are recognisable: lodgement till, formed subglacially by 'plastering-on', and ablation till, formed on the surface of the ice by the accumulation of melted-out englacial debris. The lithological distinction between these two types of till has been appreciated for about a century in Britain and North America (Goodchild 1875; Torell 1877; Stone 1880; Upham 1891), and has been described in detail more recently on the basis of work carried out in southern Sweden by Gillberg (1955). Harrison (1957) concluded that till was deposited as a result of melting out at the base of ice and he also envisaged the deposition of wet till by flow beyond the ice margin. From work carried out in Svalbard, Boulton (1970b, 235) described tills 'produced either by top or bottom melting of a block of buried debris-rich ice, and ... not deformed by subsequent creep or flow at the surface'. He gave these deposits the name 'melt-out till.' At first, melt-out till was classed as supraglacial by Boulton (1971). In a later classification, Boulton (1972a) recognised the existence of both supraglacial and subglacial melt-out till.

Francis (1975) summarised the general characteristics of the principal varieties of till. All tills tend to have a wide range of particles sizes compared with most other sediments. This diversity is also reflected in the mineral composition of most tills, because they commonly contain clay, silt and sand, and significant proportions of particles of larger diameters.

2.5 Fabric of till

Many writers have concerned themselves with the fabric of tills.

The term 'till fabric' was introduced by Holmes in 1941 and was used to denote 'the space relations among the component rock and mineral fragments in undisturbed till'.

Pebbles in tills tend to have long axes oriented parallel to the direction of ice flow. The shapes and surface markings of clasts have been used to illustrate the mode and position of their transport by ice (Drake 1972), and also to demonstrate the abrasion of stationary clasts beneath sliding ice (Okko 1955; Boulton 1978). Such forms as 'bullet-shaped' boulders (Boulton 1978) and associated strongly-preferred orientation of clast long axes parallel to the direction of ice movement (Mills 1977; Humlum 1981) are evidence of deposition of till by lodgement.

Andrews & Smith (1970) considered that flow within the matrix of deposited thick basal till layers, which would be faster than that of the contained pebbles, may be responsible for the formation of the long-axis subfabrics. Lindsay (1970), however, stated that the clast fabric is the result of numerous processes operating englacially, subglacially and post-depositionally, i.e. during transport, during deposition and as a sequence of processes of compaction, mass movement or water sorting.

2.6 Conclusions

Till is the ubiquitous glacial deposit by which every former glacier is most surely traced. It is poorly-sorted sediment of mixed sizes (clay to boulders), characterised by the presence of a variety of rock and mineral fragments. Some grains and stones are striated, and very elongate clasts often have predominant orientations (Goldthwait 1971, 19).

Deposition may be <u>either</u> subglacially beneath a glacier as basal (lodgement) till or superglacially (supraglacially) on or from the surface of a glacier by ablation as flow till or melt-out till.

Till is one of the most variable of sediments and this variability is caused by: 1) the variety of rocks, minerals and reworked sediments of which till is composed; 2) the various ways in which these materials have been incorporated in or on a glacier; 3) the way in which these materials have been transported. Post-depositional changes can also influence the properties of till. It is obvious, therefore, that the composition of a till deposit depends on the nature of the terrain crossed by the ice that deposited the till.

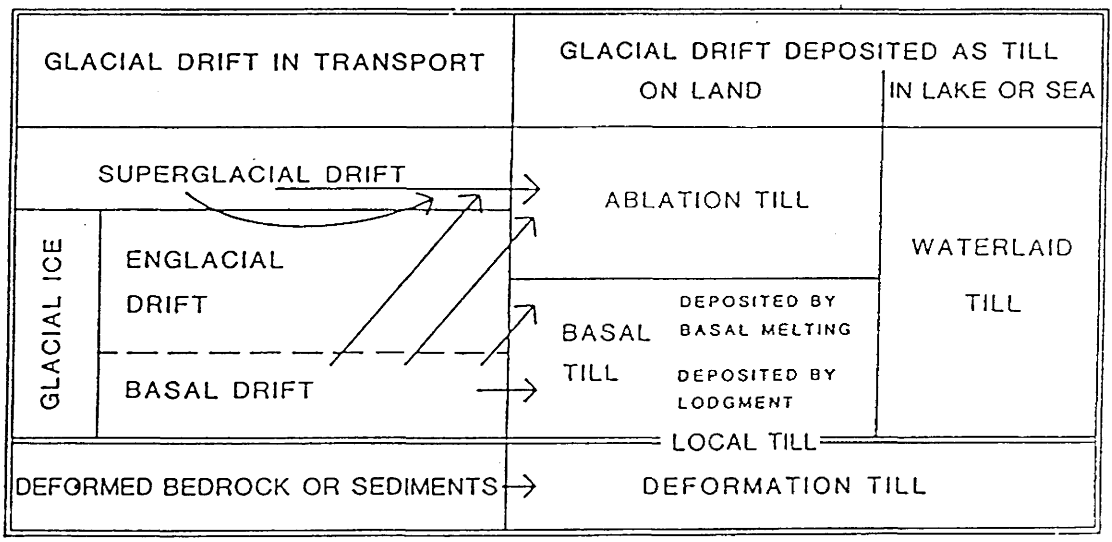


Figure 2.1 Genetic classification of till proposed by Dreimanis in 1969.

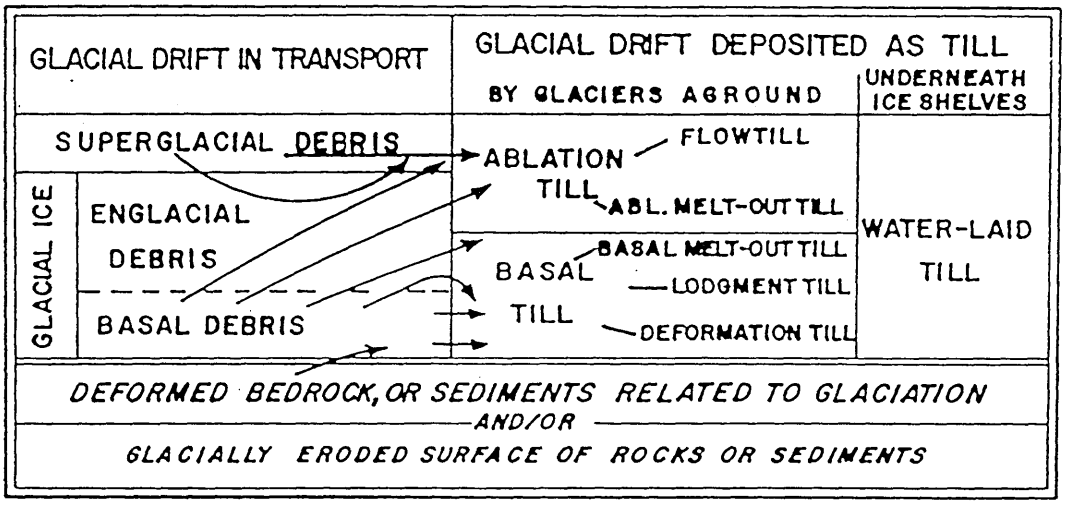


Figure 2.2 Genetic classification of tills and their relationships to glacial drift in transport (after Dreimanis 1978).

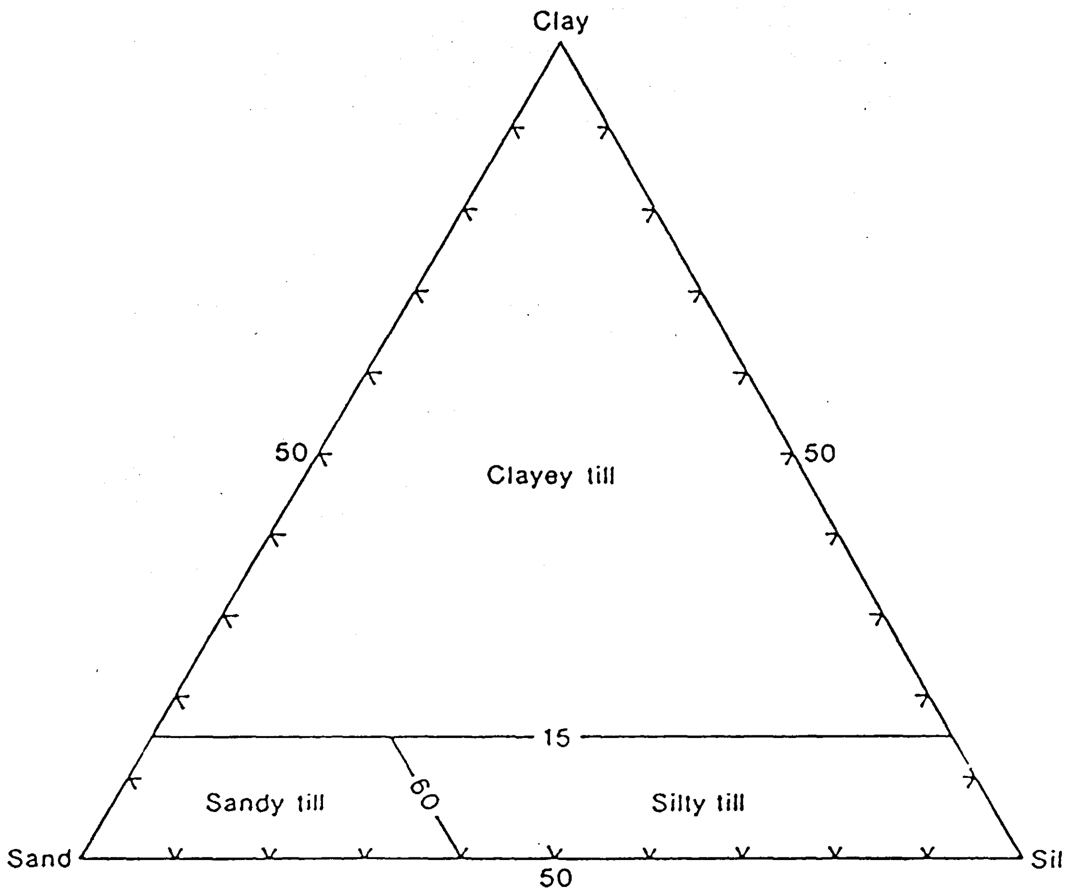


Figure 2.3 Textural classification of till, based on the <2mm grain-size distribution (after Vorren 1979).

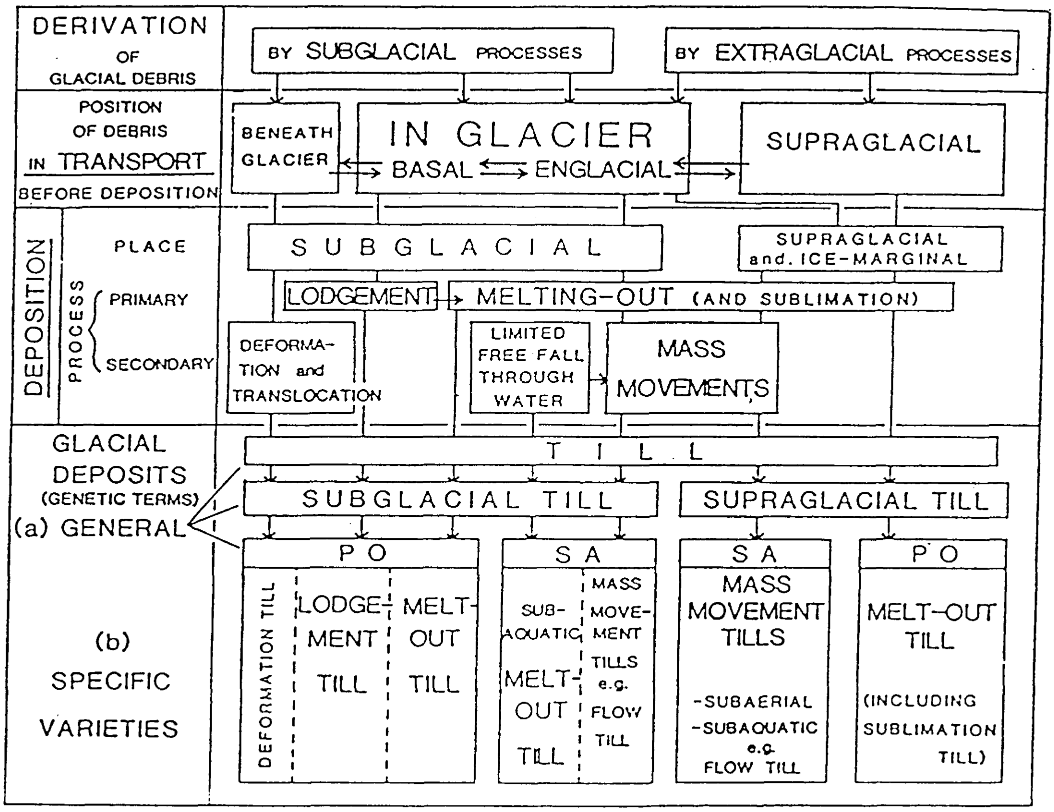


Figure 2.4 Factors that influence the formation and deposition of tills (upper half), and tentative depositional genetic classification of tills (lower half), according to Dreimanis (<u>in</u> Schlüchter 1982, Table 1). PO = primary or ortho-tills; SA = secondary or allo-tills.

Table 2.1 Till types and definitions. Based on Lundqvist 1984, 13–14.

Type of till	Definition
Lodgement till	Deposited from the sliding base of a dynamically active glacier by pressure melting and/or other mechanical processes. The product is usually a dense basal till with well-developed fabric and often a distinct sub-horizontal fissility.
Melt-out till	Deposited in the course of slow release of glacial debris from ice by melting, without sliding or deforming internally, either at the base or the surface of a glacier. The product is a fairly dense till with preserved fabric, often laminae and lenses of sorted sediments and a fine-grained coating of its clasts.
Sublimation till	Formed in a similar way to that of melt-out till at the surface of a glacier in arid polar climate.
Flow till	Formed in the course of redeposition of debris immediately upon release from the ice by gravity-controlled processes: flow, slumping, sliding, etc. The fabric, density and structure of the till are altered as a consequence.
Deformation till	Formed by translocation of material dragged beneath the glacier sole. It consists mainly of material making up the basement of the glacier, which has been deformed and to some extent mixed with displaced material.

CHAPTER 3

PREVIOUS STUDIES OF TILLS IN THE NW GLASGOW AREA AND NORTHERN AYRSHIRE

3.1 Introduction

Tills have been studied in various parts of the world for more than a hundred years. The tills of the Glasgow area and Ayrshire were some of the first to be studied. Their earliest investigations date to the early years of the 19th century. Since then, many distinguished geologists, such as Sir Archibald Geikie, Professor James Geikie and Sir Edward Bailey, have been involved in the mapping and interpretation of the till and associated Quaternary deposits of western Scotland. In this chapter a summary is given of previous studies that have been made of the tills of the north-western part of the Glasgow area and of the northern part of Ayrshire. The summary includes reference to conclusions that have been drawn from time to time concerning the sequence of Quaternary events in the two areas. The summary also indicates the methods of study that have been used in the past to record the characteristics of the several varieties of till that are present in NW Glasgow and N Ayrshire. A result of the latter part of this survey is that it is clear that, despite the long period over which investigation of the tills of the Glasgow area and Ayrshire have been made, by 1985 there was available comparatively little detailed mineralogical information and an even smaller amount of geochemical data on these tills. The present study, therefore, contributes substantially to the store of factual information on the tills of parts of western Scotland. In addition, the data recorded in the course of the research project may be of use in up-dating the interpretation of the sequence of glacial and associated events that took place in NW Glasgow and Northern Ayrshire during the Quaternary period.

3.2 NW Glasgow area

More than seventy years ago it was noted by the Geological Survey that two distinctly different varieties of till are present in the north-western part of the Glasgow area, a dark-blue or grey till with boulders and pebbles of Carboniferous sedimentary rocks, and a red or purple till with a stone content predominantly of Highland rocks and basalts of Carboniferous age (Clough et al. 1911, 184-185). No explanation was given for the presence of two tills rather than one within the area, but it was stated that the 'red till is found north of a line drawn between Maryhill and Yoker' and that 'East of Yoker a dark blue boulder clay suddenly appears' (Clough et al. 1925, 225). Menzies (1981, 161) suggested that the position of the boundary between the two tills as reported by Clough et al. is only partially correct. Jardine had been more specific. He stated that the thickness of the red till 'increases in a northwesterly direction, from about one metre or less near a SW-NE orientated line extending approximately from Partickhill railway station (555, 666) to Possil Loch (585, 698) to several tens of metres in the burghs of Bearsden and Milngavie' (Jardine 1973, 162). This statement does not question the observation by the Geological Survey that the grey till occurs only to the east of Yoker. It does suggest, however, that between Yoker and Partickhill, a distance of 3-4km, there is a zone within which the grey till is covered by a variable thickness of red till. The zone extends north-eastwards, approximately parallel to the SW-NE oriented line between Partickhill and Possil Loch that marks the south-eastern limit of the red till (Fig. 1.2). Menzies (1976, 152) supported this suggestion when he wrote '...in Maryhill (567 689) red till was observed overlying grey till'.

Jardine (1973) also summarised what had already been more fully recorded by the Geological Survey, namely, that most of the low hills on which central and western Glasgow is built are drumlins consisting mainly of the grey till mentioned above. The grey till was said to have a sandy clay to clay matrix, probably derived from local Carboniferous rocks - white or buff sandstones, shales, limestones and occasional ironstones - and the stone fraction also comprises mainly local Carboniferous rocks, but occasional Highland rocks, Carboniferous basalts and Old Red Sandstone (ORS) fragments are present. In contrast, the red till was said to have a sandy clay matrix, derived apparently from ORS rock fragments and Carboniferous basalts. The stone content was thought to be dominantly of Highland rocks, ORS rock fragments and Carboniferous lavas, but occasional small fragments of local Carboniferous shale and white or buff sandstone are also present.

In the late 1960s and early 1970s the nature and mode of origin of the red till, within the zone where it occurs together with the grey till, were subjects of debate. Interpretations were influenced by the claim by Sissons (e.g. 1963; 1964) - later proved erroneous - that a 'Perth Readvance' of ice had occurred at a time between that of the main Late Devensian glaciation and that of the Loch Lomond Readvance. According to Jardine (1973, 163), one view was that 'the red till may be an ablation deposit, inferentially a product of the ice sheet which deposited the grey till of central Glasgow as lodgement till, another is that the red till is the deposit of a separate ice readvance which followed at least partial uncovering of the grey till by ice'. A more recent explanation of the differences in characteristics and colour of the two tills being due to 'bedrock variations associated with ice transport and accompanied dilution and enrichment of local bedrock sources' (Menzies 1981, 161) is now widely held.

Much of the information concerning the nature of the red till and grey till of the NW Glasgow area has been derived from borehole data obtained in the course of investigation of the area by the British Geological Survey and commercial companies (Menzies 1976, Volume 3; Menzies 1981). In 1980, a borehole computer database for Scotland was initiated by the British Geological Survey (McMillan et al. 1984). Some of the uses to which the database may be put within a stratigraphical context have been discussed by Browne & McMillan (1985). According to Browne & McMillan (1985, table 1), the 'Wilderness Till' of the Glasgow area is a lithological unit (Formation) that was deposited during the main Late Devensian glaciation. At Erskine Bridge, located near the western extremity of the area considered in this project, and at the 'type' site at Wilderness, in the northern part of the area considered here, the Wilderness Till has the characteristics of the red till discussed above. At Erskine Bridge this till has a Devonian (Old Red Sandstone) source. In parts of the Glasgow area south of Wilderness and east of Erskine, the Wilderness Till is said to correspond to the grey till considered above, being '... dark brownish grey at Broomhill and Baillieston (coal-bearing Carboniferous source)' (Browne & McMillan 1985, 17).

Most of the published information on the nature of the red till and grey till is descriptive rather than analytical, but limited laboratory analysis of the tills has been made. The particle size distribution of red (lodgement) till exposed at Geilston (NS 3410 7777), near Cardross between Dumbarton and Helensburgh, was determined by Rose (in Jardine 1980, 27 and fig. 2.4). A thesis by Menzies (1976) entitled 'The Glacial Geomorphology of Glasgow with particular reference to the Drumlins' included analysis of the distribution of Carboniferous, Old Red Sandstone and Highland (metamorphic rock) pebbles in till samples that were obtained almost entirely from British Geological Survey and commercial boreholes. The particle size distributions of the red and grey tills of the NW Glasgow area were also determined by analysis of a total of about 20 samples from boreholes. The results, together with a map showing percentage variation in the pebble lithology of the till in the Glasgow area, are given by Menzies (1981, figs. 4 and 5).

3.3 Northern Ayrshire

Previous studies of tills in Northern Ayrshire are summarised in Memoirs and a Report of the British Geological Survey (Richey et al. 1930; Eyles et al. 1949; Goodlet 1970), a Memoir of the Soil Survey (Mitchell & Jarvis 1956) and a doctoral thesis on 'The Glaciation of Central Ayrshire' (Holden 1977). An important early account of the tills is contained within 'The Drift or Glacial Deposits of Ayrshire' (Smith 1898), a publication that records the occurrence of till, and its relationships with other Quaternary deposits, at numerous sites throughout Ayrshire.

Many of the earliest studies of tills in Ayrshire, as elsewhere in Scotland, attributed the deposition of till to the action of floating ice. By the end of the 19th century, however, with the acceptance of the 'Glacial Theory' of Agassiz, it was recognised that the tills of

Ayrshire owe their deposition to the action of glacier ice that originated in the south-western Highlands (tills of N Ayrshire) or in the Southern Uplands (tills of S Ayrshire). In part of Central Ayrshire there is 'debatable ground' (J. Geikie 1894) where the Highland and Southern Uplands ice streams met. This area lies south of the southernmost sites included in this study, but its presence is of importance because it provides evidence of the influence of the Southern Uplands ice mass on the direction of flow of Highland ice in the southern part of the area with which this study is concerned.

Theories regarding the direction of ice flow in N Ayrshire have been based partly on the orientation of glacial striae and drumlins, and partly on the presence of 'erratic' clasts within the till. The most important of these erratic clasts are Highland (metamorphic) rocks and fragments of marine shells. Their significance in the interpretation of the glacial history of Northern Ayrshire is incorporated into the account that follows.

Richey et al. (1930, 318) pointed out that, ignoring in the first instance the possibility that during the Quaternary period there were successive glacial episodes in Ayrshire separated by non-glacial intervals, it may be said that marked changes in the direction of ice flow across N Ayrshire took place from time to time. These authors suggested that an early ice flow from the west can be detected in the southern part of the area whilst, at a later date, ice flow from the north-east and, latterly, from the north-west occurred in the northern part of Ayrshire. Goodlet (1970), writing in a later Geological Survey Report, suggested a different interpretation of the evidence, namely that, 'ice ... crossed the county boundary in the north-east and spread westwards over the low ground between Kilmarnock and the coast. ... At a later stage Highland ice advancing southwards in the hollow now occupied by the Firth of Clyde thickened up and pushed its way laterally onto the present land area entering Ayrshire from the north-west' (Goodlet 1970, 46) (see also Fig. 3.1).

The main evidence of ice flow from the west, according to Richey et al. (1930, 320-327) and Eyles et al. (1949, 124-127), is the presence of clay deposits containing marine shells in parts of the southern part of N Ayrshire that are long distances inland from the present coast of the Firth of Clyde. The nature and origin of the clay deposits have been matters of dispute for around 100 years. Smith (1898), and even J.W. Gregory as late as 1927, attributed these deposits to marine submergence up to about 300 metres above present sea level. The Geological Survey writers of the 1930s and 1940s, however, adopted the view that the shell-bearing deposits are the result of transport by 'land ice', and suggested a direction of movement of Highland ice southwards along the floor of the northern part of the Firth of Clyde, followed by west to east movement across the southern part of N Ayrshire during the period in which the shell-bearing clays were deposited (Fig. 3.2).

An important aspect of the Geological Survey's interpretation of forty years ago (Eyles et al. 1949) is that no distinction in mode of emplacement in their present positions was made between shell-bearing sediments that clearly are till deposits and those that at present are regarded as in situ marine clays. It was noted (Eyles et al. 1949, 126-127) that, 'As a rule the shells are scattered sporadically in the boulder clay, but richer deposits, where the matrix is a blue-grey almost stoneless clay, have been noted at two localities in the neighbourhood of Tarbolton and at a third near Catrine. ...These masses of shelly clays, clearly distinct from ordinary boulder clay, are regarded as portions of the sea-floor transported in a frozen condition and deposited as erratics. Their occurrences are too isolated for them to be considered as representing a marine deposit in situ of preglacial or interglacial age'.

Holden (1977) disagreed with Eyles et al. (1949), by taking the view that the shell-bearing sediments of the southern part of N Ayrshire comprise two deposits that differ distinctly in origin - a shelly till and a marine shell-bearing clay. He identified exposures of the latter at Afton Lodge (one of the two localities mentioned by Eyles et al. 1949, 126) and near Catrine. The remainder of the shell-bearing 'drifts' of Ayrshire he regarded as shelly tills. Holden claimed to have shown conclusively that the ice moved from north-east to south-west over the area where the pockets of marine clays are preserved; at Afton Lodge they are located on the lee side of a major (igneous) obstruction to ice flow. It follows from his claim that the shell-bearing marine clays could not have been picked up by ice from the Firth of Clyde (Holden 1977, 111). It should also be noted that a major conclusion arising from Holden's work is that the shelly tills of the southern part of N Ayrshire were deposited by ice that, in general, moved from north to south rather than west to east over that part of Ayrshire. The shells that occur in the Ayrshire tills, therefore, in Holden's view, were not picked up by ice from the floor of the Firth of Clyde, but from further north, presumably from the area of the Estuary of the Clyde. Support for this view, and for that of the marine origin of the 'high-level shell-bearing clays' of Ayrshire was given recently by Sutherland (1981, fig. 1 and p.249; 1984, 180). It is of interest to note that Goodlet's (1970, fig. 4) diagram showing the direction of ice movement over southern Scotland also shows the main direction of ice movement in Ayrshire as being from the north and east, and towards the west. Reference to the publication by Goodlet does not appear within either the text or the bibliography of Holden's doctoral thesis.

Holden's view that ice flow was dominantly from the north during deposition of all the tills of the southern part of N Ayrshire corresponds with the observation by the Geological Survey writers of the 1930s and 1940s that, following deposition of the shelly till by west to east flow, 'a later current from the north-east ... left a strong stamp on the physiography of the greater part of the district' (Richey et al. 1930, 318), 'the district' here being the part of N Ayrshire covered by Sheet 22 of the Geological Survey One-Inch map series. The evidence in favour of two quite different directions of ice flow is partly the orientation of striae and drumlins, and partly the existence of two superimposed tills at certain locations. One area where these two varieties of evidence are claimed to be present extends from Kilmarnock for about 7km north-eastwards to the vicinity of Hareshawmuir Water (Fig. 1.3). Near Tayburn, Smith (1898, 51) found a few marine shells in till, whilst the Soil Survey (Mitchell & Jarvis 1956, 29) recorded the presence of two superimposed tills in that area, the lower being a shelly till (the shells supposedly carried eastwards from the Firth of Clyde), and the constituents of the upper till being mainly local in origin. At two Locations, named Tayburn 5B and Tayburn 7B in this study, two superimposed tills were recorded and sampled on the banks of Hareshawmuir Water.

The Tayburn locations were not included in Holden's studies of N Ayrshire tills. His research was concerned with the southern part of N Ayrshire. In the majority of the exposures he examined, only one till was observed, and that till commonly contained 'fragments of marine shells and angular clasts of sandstones, dolerites and schists' (Holden 1977, 32). In a limited part of Ayrshire, however, between Sorn and Muirkirk, Holden recorded 'a lower till unit which contains

Highland erratics and shell fragments ... overlaid by a considerable thickness of sand and gravel and an upper till unit which contains only local material' (Holden 1977, 176). The multi-sequence exposures were regarded as representing only a minor readvance of the Highland ice that occupied that part of Ayrshire. Holden was of the opinion that there is no evidence to suggest that the southern part of N Ayrshire was affected by more than one major advance of ice. The sites of Sorn Mains, Greenock Mains and Merkland Burn, which are considered in this research project, are located within the limited part of Ayrshire where Holden recorded multi-sequence exposures.

With regard to the methods used to collect data, and the nature of these data, these aspects of previous research on the tills of N Ayrshire may be summarised as follows. Smith's (1898) account of the tills and other Quaternary deposits of Ayrshire records locations where tills have been found, and the thicknesses of till units at sites where Smith found vertical sequences that included tills. Where appropriate, the account also records the presence and identity of marine shells within the till, and gives the altitude of the exposure. The Geological Survey, since its earliest studies of N Ayrshire, has recorded directions of orientation of striae and of drumlins on its published maps, and has made general comment on the nature of the constituents of the stone-fraction of till at a number of exposures. The presence of shell fragments within the till has also been recorded, where relevant. Till analysis by Holden is more specific. At several selected sites the following characteristics were recorded for samples of till (exact positions of samples analysed, especially in terms of altitude, were not recorded): stone orientation, including Chi square test and dip strength calculation; particle size in terms of percentage of gravel, sand and silt/clay;

nature of the constituents of the stone fraction, as percentages of Highland, Southern Uplands and local rock types, and a statement of whether or not shell fragments are present in the till.

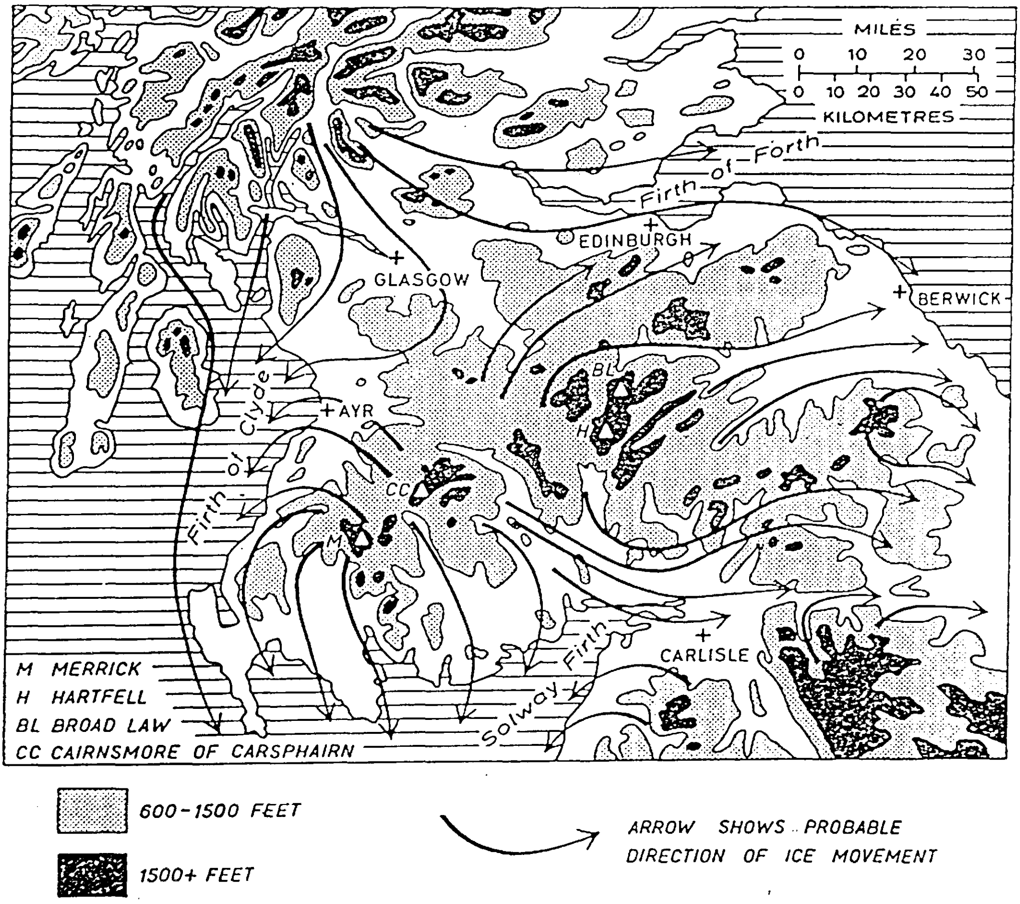


Figure 3.1 Directions of ice movement over southern Scotland suggested by Goodlet (1970).

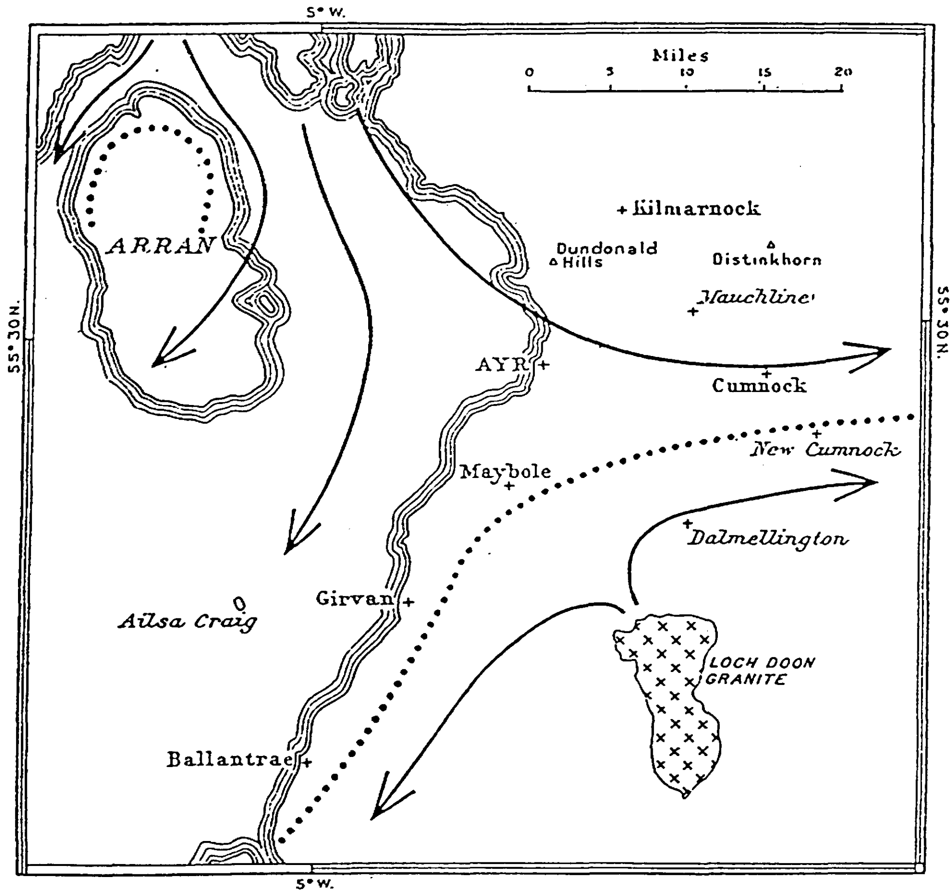


Figure 3.2 Map indicating ice currents during accumulation of shelly till in Ayrshire, according to Richey et al. (1930). Areas free of Highland boulders are outlined by dots.

CHAPTER 4

AIMS OF THE RESEARCH PROJECT, AND METHODS OF INVESTIGATION

4.1 Aims of the research project

The nature, origin and classification of tills were discussed in Chapter 2, and previous research on tills of the NW Glasgow area and Northern Ayrshire was summarised in Chapter 3. Combining the information contained in these chapters, it is clear that both the Red till and the Grey till (including the Weathered Grey till) of the NW Glasgow area are lodgement tills - although in the late 1960s one of several theories regarding the origin of the Red till was that it is an ablation deposit. Similarly, with the possible exception of the shelly till of the Sourlie site, which in places has some of the characteristics of a flow till, all the tills of Northern Ayrshire that are considered in this project are thought to be lodgement tills.

In the project, therefore, where contrasts and similarities between the properties of two or more till samples are noted, direct interpretations can be made, because the tills concerned do not differ in origin.

With this point clarified, the aims of the research project may be stated under two main headings (4.1.1, 4.1.2). The further aim, of applying the results of the mineralogical and geochemical analyses of the tills to the tackling of problems of Quaternary stratigraphy in the NW Glasgow area and Northern Ayrshire, is the subject of Chapter 14.

4.1.1 Aims of studies of tills of the NW Glasgow area

A general aim of the research project in relation to the NW

Glasgow area is:

Aim 1 To present detailed grain-size, clay mineralogical and geochemical data for the matrices of the three categories of till that occur in the NW Glasgow area, and to examine these data by the use of standard mineralogical and geochemical methods of comparison.

As regards more specific aims, as explained in Chapter 1.1, some of the samples of till from the NW Glasgow area that were available when the research project was begun in 1985 were thought to be of Red till, others of Grey till, and yet others of Weathered Grey till. The samples had been allotted to these three categories in the 1960s on the basis of their field appearances, especially on the basis of their colours (as recorded in Munsell Soil Color Charts). In many cases a given sample was clearly 'Red till', 'Grey till' or 'Weathered Grey till'. There was, however, a substantial number of field situations (near to the 'feather edge' of the Red till) where there had been difficulty in assigning a till sample to a particular category. For this reason, it was decided that a specific aim of the project should be:

Aim 2 To assign each of the till samples of the NW Glasgow area to one of three categories (Grey till, Weathered Grey till, Red till) that are distinguishable on the basis of their grain size, clay mineralogy and geochemical characteristics.

Distinction between Red till and Weathered Grey till is especially difficult in the field. It is important therefore to establish, if possible, the criteria by which the Red till and Weathered Grey till may be distinguished objectively (by using laboratory data) rather than subjectively (on the basis of field observations). Aim 3, therefore, is:

Aim 3 To determine the mineralogical and geochemical criteria on which the Red till and the Weathered Grey till may appear similar and, conversely, on which they may be distinguished from each other.

Following from the above, it is possible that the post-depositional alteration of Grey till to Weathered Grey till has produced changes in composition that lead to there being similarities between the Weathered Grey till and the Red till. A further aim, extended to include possible post-depositional alteration of the Red till, therefore, is:

Aim 4 To determine the mineralogical and geochemical changes that occur through the vertical profile of (a) the Grey till, in combination with the Weathered Grey till, and (b) the Red till.

At some sites within the NW Glasgow area, Red till was recorded (in the 1960s) as resting on Grey till. At other sites, Weathered Grey till was recorded as overlying Grey till. At a few sites, Red till was recorded as overlying a thin zone of Weathered Grey till which, in turn, overlay Grey till. In view of the reassessment of the categories to which several of the till samples should be assigned, a fifth aim is:

Aim 5 To reconsider the sequences of tills at sites in the NW Glasgow area where two or more of the categories of till are superimposed.

As discussed briefly in Chapter 3.2, the mineralogical compositions of the Red till and the Grey till have been attributed to these tills being derived, respectively, mainly from Devonian (Old Red Sandstone) rocks and Carboniferous rocks. These deductions apparently are based on limited mineralogical analysis of the tills and largely on field assessment of the characteristics of the bedrocks, there being only a few published mineralogical and geochemical analyses of either the tills or bedrocks. To test the inferences concerning the provenances of the tills, samples of Devonian and Carboniferous bedrocks, collected from within the NW Glasgow area and from its environs to the north and west, were subjected to mineralogical and geochemical analysis. The aim of this part of the project may be stated thus:

Aim 6 To examine the relationship between the mineralogical and geochemical compositions of the Devonian (Old Red Sandstone) and Carboniferous bedrocks of the NW Glasgow area and the corresponding compositions of the Red and Grey tills of the same area.

4.1.2 Aims of studies of tills of Northern Ayrshire

As stated in Chapter 1.1, a general aim of the studies in Northern Ayrshire is to increase the amount of information, especially analytical data, on the tills of that part of western Scotland. It should be noted that, because the analysed samples from Northern Ayrshire were collected solely for the purposes of the project, some of the aims of this part of the project are directed towards problems that exist at a specific site or group of sites. Aim 7, however, is wide in its scope:

Aim 7 To present detailed grain-size, clay mineralogical and geochemical data for the matrices of tills present at selected sites in Northern Ayrshire, and to examine these data by the use of standard mineralogical and geochemical methods of comparison.

Thick deposits of till containing fragments of the shells of marine molluscs etc., i.e. shelly till, are present at one or more Locations within the Sites investigated at Greenock Mains, Merkland Burn and Sorn Mains. These deposits are part of a shelly till that is widespread in Northern Ayrshire (see Chapter 3.3.), but whose characteristics are not well known. A major objective of the study, therefore, is to determine the properties of the shelly till. Two major aspects of this objective are given in Aim 8:

Aim 8 (a) To determine the mineralogical and geochemical properties of the shelly till at individual field Sites, by comparison of the properties of samples from more than one Location within these Sites.

(b) To determine the mineralogical and geochemical properties of the shelly till of Northern Ayrshire, by comparison of the properties of samples of the till from several field Sites.

At Tayburn and at Location 5-3 at Sorn Mains, a grey till is superimposed on a red till. Shelly till is present at Locations 5-1 and 5-2 at Sorn Mains and the presence of shelly till in the vicinity of

Tayburn has been reported (Smith 1898, 51). The possibility of one of the tills at Tayburn and at Location 5-3 at Sorn Mains being generally similar in its properties to the shelly till of Northern Ayrshire therefore should be examined, although none of the four tills concerned is visibly shelly. This and related items of interest are included in Aim 9:

Aim 9 To examine the nature of, and relationships between, two superimposed tills at Tayburn and at Location 5-3, Sorn Mains, and to determine whether or not one of the tills at each site resembles the shelly till of Northern Ayrshire in its mineralogical and geochemical properties.

At Sourlie, an Upper grey till overlies a thinly-developed pink-brown 'shelly' till which, in turn, overlies organic-rich silts/clays and unfossiliferous gravels that rest on a Lower grey till. Aims of the project related to the sequence at Sourlie are:

Aim 10 To determine the mineralogical and geochemical similarities and differences between the Upper and Lower grey tills at Sourlie.

Aim 11 To determine the mineralogical and geochemical similarities and differences between the pink-brown 'shelly' till at Sourlie and the shelly till that is present at other Sites in Northern Ayrshire.

At the majority of the Ayrshire sites, vertical sequences of till samples were collected. The reasons for this are given in Aim 12:

Aim 12 To determine the mineralogical changes that occur through vertical profiles in (selected) tills of Northern Ayrshire, and to determine, if possible, whether or not any changes observed (a) have been caused by weathering, and (b) suggest that the weathering of a lower till took place prior to deposition of an overlying upper till.

As noted in Chapter 3.3, shell-bearing clays present at Afton Lodge, a short distance ENE of the town of Ayr, have been regarded, largely on the basis of field evidence, either as part of the shelly till deposits of Ayrshire (Eyles et al. 1949, 126-127) or as marine sediments that are quite distinct from the shelly till deposits (Holden 1977). Samples of the Afton Lodge shell-bearing clays were analysed with a view to providing laboratory data on the similarities and differences between the Afton Lodge clays and the shelly tills of (Northern) Ayrshire. Aim 13, therefore, is:

Aim 13 To determine the mineralogical and geochemical properties of the shell-bearing clays at Afton Lodge, and hence to determine the similarities and differences between the properties of these shell-bearing clays and the shelly tills of Northern Ayrshire.

4.2 Methods of investigation

4.2.1 Field sampling and recording

The research project was designed in such a way that the maximum amount of time could be devoted to obtaining a large number of mineralogical and geochemical data by means of laboratory analysis. About twenty days, however, were spent in the field, mainly in Ayrshire, collecting samples of tills and recording the positions of these samples within till bodies and, where relevant, the relationships of the till bodies to other Quaternary deposits. Details of sampling procedures and related data for the NW Glasgow area and Northern Ayrshire are these:

NW Glasgow area

The pattern of collection of samples of till (49 in all, one of the original 50 samples - No.46 - being of sand) in the NW Glasgow area in the 1960s was neither geographically regular nor deliberately randomised, but depended on the availability of suitable natural sections or, more commonly, artificial excavations. Wherever possible, samples were collected from depths greater than one metre below the ground surface, to avoid the possibility of reworked material being included. The positions of the samples within the NW Glasgow area are shown in Figure 1.2, and Site names, National Grid References and Munsell Color determinations are given in Table 4.1. Records of the field relationships of the samples collected at sites where more than one category of till (Red, Weathered Grey, Grey) was identified in the field are included in appropriate parts of Chapters 5 to 8 and Chapter 14.

In 1986, twenty-five samples were collected from four sites where profiles in Red till (Laighpark and Clober sites) and in Weathered Grey till together with Grey till (Kelvinside-Great Western Road and Queen Margaret Hall-Winton Drive sites) were exposed at that time. In each of these cases, samples were collected at regular intervals within a vertical sequence. Details are given in Table 4.1.

Samples of bedrock were also collected in the NW Glasgow area. The positions of sites from which samples of bedrock were collected were determined largely by the rather limited availability of exposures of solid rock within the area being studied. For this reason, some of the bedrock samples probably are not truly typical of the major lithological units that underlie the NW Glasgow area. For example, the limestone samples were collected from two thin layers that are exposed in the bank of a stream (Cleddans Burn), at NS 5107 7278, a short distance east of Hardgate. Stratigraphically, the sampled limestone layers probably are a few metres lower in the Lower Carboniferous sequence than the Hurlet Limestone, a thick-bedded limestone that was encountered below the Glasgow area in numerous boreholes and shafts sunk in the past. Exposures of the Hurlet Limestone itself were not available at the time the samples of bedrock were collected in 1986. The positions of most of the sites where samples of bedrock were collected within the NW Glasgow area are shown in Figure 1.2, and further data concerning the samples are given in Tables 9.1, 9.2 and 9.3.

Northern Ayrshire

During 1986, six sites in Northern Ayrshire were visited (most of them on more than one occasion), and samples were collected from one or more locations at each of the sites. The positions of the sites are shown in Figure 1.3. As noted in Chapter 1.1, the selection of five of the sites to be sampled depended partly on the availability of suitable exposures, but more especially on the presence of either two superimposed tills or shelly till (or a combination of these requirements) at each of the selected sites. At the sixth site, Afton Lodge, the purpose of sample collection was to enable analyses to be made of clays that Holden (1977) had identified as *in situ* high-level, shell-bearing clays, probably marine in origin (see Chapter 3.3). At most of the sites, scale drawings of the steeply-sloping 'cliff' faces, showing the stratigraphy and positions of samples collected, were made on the basis of measurement with a 30m tape. At Sourlie, the positions of locations and samples were provided by Irvine Development Corporation engineers on the basis of highly accurate Electronic Distance Measurement (EDM) instrumental surveying. Site data for Northern Ayrshire are summarised in Table 4.2, and details are given in appropriate parts of Chapters 10 to 13.

At the five sites where tills were collected, a 'systematic' sampling plan (May & Dreimanis 1976, 101) was used to collect 64 samples, between 1.5 and 2.0kg in weight, along 12 steeply-inclined 'cliff' exposures. To evaluate vertical variation at locations of major stratigraphical significance, in most cases samples were taken at 50cm or 100cm (1m) vertical intervals at such sites; each bulk sample was taken over a vertical range of 25cm.

The following precautions were taken to avoid contamination in the course of sample collection:

1) Faces of cliffs were cleared of slumped material.
2) The outermost 20cm of exposed till in a cliff face was removed before a sample was taken.
3) All joint surfaces were removed from a block of till before the block was retained as the whole or part of a sample.
4) No samples were collected from the zone of leaching at the top of a cliff.

4.2.2 Laboratory procedures

4.2.2.1 Sample preparation

Before each till sample was analysed, it was dried at 105-110°C in the oven.

4.2.2.2 Mechanical analysis of the till matrix (<2mm), sand-silt-clay fraction.

Grain-size analysis was performed on the till matrix, using dry sieving and pipette analyses (Fig. 4.1). Following standard practice, 2.0mm was taken as the granule-sand boundary, 0.063mm as the sand-silt boundary and 0.002mm as the silt-clay boundary. The sand fractions (-1.0 to 4.0 phi) were sieved through one phi interval screens, and mud fractions (finer than 4.0 phi) were pipetted, all according to standard methods (Folk, 1968).

After removal of most of the stones by hand picking, the dry till sample was disaggregated by gentle crushing, using a rubber-headed pestle and mortar with the minimum force. Great care was taken not to crush individual particles. As pebbles larger than 2mm were picked from the samples during the crushing, the material analysed was mainly less than 2mm in diameter.

Using a sample-splitter, representative samples (each weighing about 100gm) were obtained. The samples were soaked individually overnight in calgon. Thereafter, they were carefully treated ultrasonically for 20 minutes and then mechanically stirred for 30 minutes. The soaked samples were wet-sieved separately, using the 4.0 phi (0.063mm) sieve, applying the procedure of Folk (1968). The mud fraction (silt and clay) that passed through the sieve was collected in a 1000ml graduated cylinder, whereas the sand fraction that remained in the sieve was separated, dried and weighed.

The sand fraction, separated as mentioned above, was analysed by dry sieving while the mud fraction was pipetted. The methods adopted in this analysis were those of Folk (1968) and Carver (1971).

Folk (1968) recommended the use of $\frac{1}{4}\,\phi$ or $\frac{1}{2}\,\phi$ interval of sieving and considered the one phi interval to be inadequate in providing useful data. Swan <u>et al</u>. (1978), however, in their evaluation of the

Folk and Ward graphic measures, established that obtaining data at intervals less than whole phi is not justified if graphic statistical parameters are to be used. This has been taken into consideration in the present work and, for the dry sieving, a nest of clean stainless screens with subdivisions -1 ϕ, 0 ϕ, 1 ϕ, 2 ϕ, 3 ϕ and 4 ϕ was built, the coarsest-grid screen being on top. The dried and weighed sand fractions were poured separately on to the top screen and shaken in the Ro-Tap for about 15 minutes. Each sieve was then emptied on to a large sheet of paper and each fraction weighed.

Although tedious and time-consuming, the technique is straightforward, except for the following special procedure. Splitting into sand and mud in the laboratory is never totally efficient. Some material belonging to a finer-size class will always remain with the coarser fraction and show up as a pan fraction after sieving. To allow for this discrepancy, it became necessary to add the value of the pan fraction to that of the mud before pipetting, as shown in Figure 4.1. The calculated weight of the pan fraction was also subtracted from the original weight of sand.

The mud fraction which passed through the 4 ϕ (0.063mm) sieve was placed in a 1000ml graduated cylinder. Distilled water was added until the volume was exactly 1000ml. After determining the temperature, the appropriate withdrawal times were read from a table calculated from Stokes's law (Folk, 1968). The silt fraction was sampled in whole phi intervals. In each case, the pipette analysis was terminated before the clay fraction was sampled because of the length of time required for the fine particles to settle from the suspension. Thus, the last sample was pipetted at exactly 5cm depth, after about 4 hours and 6 minutes at temperature 20^{o}C, and this sample was used to determine the amount of clay in the cylinder.

Cumulative weight percentages were calculated for each pipette withdrawal and these results, together with those from the size analyses of the sand fractions, were represented graphically by probability-ordinate cumulative curves. The unsampled clay distribution was interpolated as suggested by Folk (1968). This was done by extending the cumulative curve in a straight line from the last data point to 14 ø at 99.99%.

Statistical parameters of Mz (graphic mean grain size), σ_I (inclusive graphic standard deviation), Sk_I (inclusive graphic skewness) and K_G (inclusive graphic kurtosis) proposed by Folk & Ward (1957) were then calculated from values intercepted at specific percentiles (ø 5%, ø 16%, ø 25%, ø 50%, ø 75%, ø 84% and ø 95%) on the cumulative curves. A triangular diagram for the sand-silt-clay composition (after Folk, 1968) was used to classify samples. Results of this study are given in Chapters 5 and 10.

4.2.2.3 X-ray diffraction examination of clays

The analytical procedure is shown in Figure 4.2. The clay mineral constituents of each of the till samples were identified using the X-ray diffraction technique. Material coarser in grade than 2 μm was removed from the samples so that the characteristics of the clay minerals were better observed.

The samples were suspended in distilled water and treated ultrasonically for 15 minutes. The sand fraction was separated from the clay-silt fraction by wet sieving through a 0.063mm sieve. The clay fraction (<2 μm) was separated from the silt fraction (2-63 μm) by the pipette method without using dispersing agents (see Fig. 4.1).

The <2 μm fraction separated from each sample by the pipette method was used for the preparation of oriented aggregates on glass slides, adopting the sedimentation technique described by Weaver (1967). Sedimentation and drying took place at room temperature.

X-ray diffraction analysis of the clay fraction was carried out using a PW 1012/20 Phillips diffractometer having a Ni-filtered Cu $K\alpha$-radiation at 40 KV, 20 MA potentials, a scanning speed of 2^o per minute and chart speed of 2^o 2 θ per inch. The X-ray investigation was made by scanning the area 2 - 30^o, 2 θ. Three diffraction patterns were obtained for each sample: 1) untreated, i.e., air-dried slide without any treatment; 2) glycolated, i.e. saturated with ethylene glycol; 3) heated to 450^o for 45 minutes. After the X-ray diffraction effects had been recorded at room temperature, the sample was saturated with ethylene glycol vapour for 24 hours at 60^oC and then examined for new diffraction effects. After the second X-ray examination, the sample was heated to 450^oC for 45 minutes, air quenched and X-rayed again.

4.2.2.4 Chemical analysis of the till matrix (<2mm)

The bulk of the major element and the entire trace element compositions of the samples were determined by X-ray fluorescence analysis. Wet chemical analysis was used to analyse the rest of the major elements. Detailed descriptions of the X-ray fluorescence and wet chemical methods are given below.

X-ray fluorescence analysis (XRF)

All the major and trace element determinations were carried out by the University of Glasgow Geology Department's Phillips PW 1450/20 sequential automatic X-ray spectrometer.

1. Major elements analysis

X-ray fluorescence analysis was used to determine ten major element oxides (SiO_2, TiO_2, Al_2O_3, Fe total, MnO, MgO, CaO, Na_2O, K_2O and P_2O_5). Major element analyses were performed on fused glass beads (Harvey et al. 1973). The beads were made by fusing 0.375gm of 100 mesh sample powder and 2.000gm of flux (lithium tetraborate).

All the major element measurements by XRF were made in duplicate and averaged, using a peak-background measure to define the intensity for each element when compared with a ratio pellet. The absolute concentrations were calculated by comparison with international (NBS) and internal (Glasgow) calibration standards using a computing routine devised by Dr C.M. Farrow. These standards are run with every batch of samples, to act as a check on machine operation.

2. Trace elements analysis

Trace elements compositions (Zr, Y, Sr, U, Th, Rb, Pb, Ga, Zn, Cu, Ni, Co, Cr, Ba, Ce and La) were determined on pressed pellets (Leake et al. 1969) comprising 6.0gm of 250 mesh sample powder and 1.0gm of thermal binder (phenol formaldehyde).

Wet chemical analysis

The inadequacies of the XRF techniques necessitate the qualitative determination of FeO, H_2O and CO_2 in rock samples by conventional chemical analysis. FeO was determined by titration of standard potassium dichromate solution with rock solution made by dissolving a measured amount of rock powder in sulphuric and hydrofluoric acids. The FeO percentage determined by titration is used to calculate the amount of Fe_2O_3 present, using the following relationship:

$$Fe_2O_3 = \text{FeO total (XRF value)} - (1.112 \times \text{FeO titration result})$$

The amounts of H_2O and CO_2 in the samples were determined by the H_2O/CO_2 apparatus, using the Penfield method of combustion, adsorption and gravimetry.

4.2.2.5 Thin sections (Petrography of the bedrocks)

For general information on the petrography of the bedrocks of the NW Glasgow area, thin sections of bedrock specimens from that area were prepared. As explained in Chapter 4.2.1, above, the bedrock samples collected and, therefore, the thin sections made from them, cannot be regarded as truly representative of the bedrocks in the area studied, but they are considered adequate for the purpose of this study. In all, thirty thin sections were examined.

4.2.2.6 Quantitative mineralogical composition of the bedrocks

XRD analysis of the bedrocks was based mainly on 'powder mounts' the preparation of which requires fine-grained, homogenous material of less than 200 mesh grain size (Klug & Alexander 1954; Brown, 1961). All samples have to be crushed down to a minimum of 200 mesh before being suitable for XRD. The sample powder was mounted in aluminium holders measuring 0.2 x 1.0 x 2.0cm, as flat-surface powder cakes. Approximately 0.5gm of each sample was needed. It was backloaded with the 'face' against a clean, smooth glass slide.

The method employed here was along the lines suggested by Moore (1968) and modified by Larsson (1970). Quantitative mineral data were obtained by subjecting each sample to diffraction analysis from 4^{o} to 45^{o} $2\ \theta$ at a goniometer speed of 2^{o} per minute. The peak heights of the diagnostic reflections of each of the minerals present were measured in mm above the background and then multiplied by the appropriate mineral intensity percentage factor (Larsson 1970; see also Table 4.3), and finally normalized to total 100% of the minerals present.

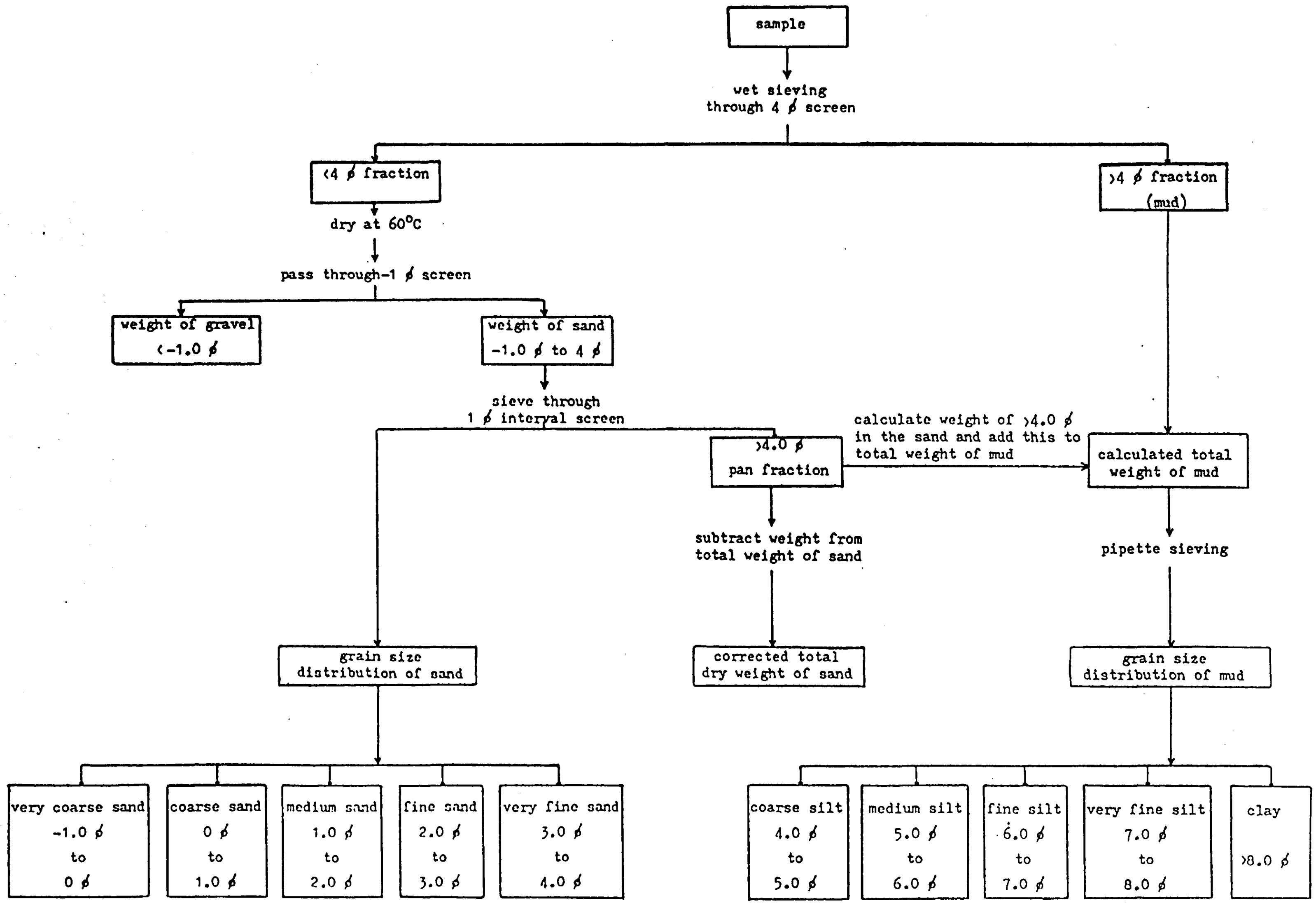


Figure 4.1 Laboratory procedure for grain-size distribution analysis

Sample

↓

Ultrasonic disaggregation in distilled water suspension

↓

Wet sieving through a 63 µm sieve

↓

Separation of clay fraction (< 2 µm) by pipette method

↓

Preparation of oriented samples of clay fraction

↓

Air-dried at room temperature X-ray: "untreated sample"

↓

Ethylene glycolated X-ray: "glycolated sample"

↓

Heated to 450°C for 45 minutes: "heated sample"

Figure 4.2 Laboratory procedure for clay mineral investigation.

Table 4.1 Samples collected in NW Glasgow area.

Field number	Site name	National Grid Reference	Munsell Color
1	Broomhill Cross	NS 548 671	5 YR 4/2
2	Broomhill Cross	NS 548 671	5 YR 4/1
3	Broomhill Cross	NS 548 671	10 YR 3.5/1
4	Broomhill Cross	NS 548 671	5 YR 4/2
5	Broomhill Cross	NS 548 671	10 YR 3.5/1
6	Broomhill Cross	NS 548 671	10 YR 2.5/2
7	Jordanhill area	NS 5410 6857	10 YR 2/1
8	Jordanhill College	NS 5376 6830	5 YR 4/1
9	Jordanhill area	NS 5395 6859	10 YR 5/1
10	Anniesland Cross	NS 5471 6879	10 YR 4/1
11	Cleveden School	NS 5602 6833	10 YR 3/1
12	Cleveden School	NS 5602 6833	10 YR 4/2
13	Cleveden School	NS 5599 6837	7.5 YR 5/2
14	Cleveden School	NS 5602 6833	10 YR 3/2
15	Cleveden School	NS 5598 6833	10 YR 3/1
16	Cleveden School	NS 5598 6833	5 YR 4/4
17	Cleveden School	NS 5596 6835	7.5 YR 4/4
18	Elderslie Dock	NS 517 681	5 YR 5/2
19	Elderslie Dock	NS 517 681	10 YR 4/1
20	Elderslie Dock	NS 517 681	7.5 YR 5/2
21	Elderslie Dock	NS 517 681	5 YR 5/2
22	Elderslie Dock	NS 517 681	10 YR 3/1
23	Queen Margaret Union	NS 5673 6687	10 YR 2/2
24	Queen Margaret Union	NS 5673 6687	7.5 YR 4/2
25	Queen Margaret Union	NS 5673 6687	10 YR 2/2

Table 4.1 (continued)

Field number	Site name	National Grid Reference	Munsell Color	
26	Balmore Road	NS 5881 6918	10 YR	3/1
27	Balmore Road	NS 5881 6918	10 YR	3/1
28	Balmore Road	NS 5878 6930	7.5 YR	5/6
29	Weymouth Drive	NS 5576 6897	7.5 YR	5/0
30	Weymouth Drive	NS 5582 6895	5 YR	4/1
31	Wilderness pit	NS 5992 7220	5 YR	3/4
32	Killermont golf course	NS 5601 7126	5 YR	3/3
33	Dawsholm Park	NS 5508 6979	10 YR	5/1
34	Switchback Road	NS 5478 7046	5 YR	3/4
35	Canniesburn Hospital entrance	NS 5473 7084	5 YR	3/2
36	Veterinary College	NS 5509 6982	5 YR	3/2
37	Veterinary College	NS 5509 6982	7.5 YR	3/2
38	Veterinary College	NS 5509 6982	5 YR	4/1
39	Veterinary College	NS 5509 6982	5 YR	3/3
40	Veterinary College	NS 5514 6981	5 YR	3/1
41	Pendicle Road, Bearsden	NS 5387 7146	5 YR	4/3
42	Lochend Drive, Bearsden	NS 5411 7123	5 YR	3/4
43	Upper Westbourne Drive, Bearsden	NS 5328 7233	5 YR	3/4
44	Garscadden Hill	NS 5334 7168	(2.5 YR (5 YR	4/2 to 4/3
45	Garscadden Mains	NS 5364 7115	5 YR	4/3
47	Garscadden Mains	NS 5364 7115	5 YR	3/3
48	Burnbrae Hotel	NS 5529 7334	5 YR	5/3
49	Burnbrae Hotel	NS 5535 7332	5 YR	3/3
50	Burnbrae Hotel	NS 5530 7329	10 YR	4/1

Table 4.1 (continued)

Field number	Site name	National Grid Reference	Munsell Color	
10-1	Kelvinside	NS 5581 6807	7.5 YR 10 YR	3/2 to 3/2
10-2	Kelvinside	NS 5581 6807	7.5 YR 10 YR	3/2 to 3/2
10-3	Kelvinside	NS 5581 6807	7.5 YR 10 YR	3/2 to 3/2
10-4	Kelvinside	NS 5581 6807	10 YR	3/1
10-5	Kelvinside	NS 5581 6807	10 YR	3/1
10-6	Kelvinside	NS 5581 6807	10 YR	3/1
10-7	Kelvinside	NS 5581 6807	10 YR	3/1
10-8	Kelvinside	NS 5581 6807	10 YR	3/1
11-6	Queen Margaret Hall	NS 5633 6817	7.5 YR 10 YR	3/2 to 3/2
11-5	Queen Margaret Hall	NS 5633 6817	7.5 YR 10 YR	3/2 to 3/2
11-4	Queen Margaret Hall	NS 5633 6817	7.5 YR 10 YR	3/2 to 3/2
11-3	Queen Margaret Hall	NS 5633 6817	7.5 YR 10 YR	3/2 to 3/2
11-2	Queen Margaret Hall	NS 5633 6817	7.5 YR 10 YR	3/2 to 3/2
11-1	Queen Margaret Hall	NS 5633 6817	10 YR	3/1
1-6	Laighpark	NS 5360 7615	5 YR	3/4
1-5	Laighpark	NS 5360 7615	5 YR	3/4
1-4	Laighpark	NS 5360 7615	5 YR	3/4
1-3	Laighpark	NS 5360 7615	5 YR	4/4
1-2	Laighpark	NS 5360 7615	5 YR	4/4
1-1	Laighpark	NS 5360 7615	5 YR	4/4
4-5	Clober	NS 5460 7590	5 YR	3/4
4-4	Clober	NS 5460 7590	5 YR	3/4
4-3	Clober	NS 5460 7590	5 YR	4/4
4-2	Clober	NS 5460 7590	5 YR	4/4
4-1	Clober	NS 5460 7490	5 YR	4/4

Table 4.2 Samples collected in Northern Ayrshire. At each Location the samples are shown in order, with the uppermost at the top and the lowermost at the bottom of the list.

Site and Location	Type of sediment	Sample number	National Grid Reference
Greenock Mains, Location 2	Upper till	2 - 10	NS 6369 2780
		2 - 9	
		2 - 8	
		2 - 7	
		2 - 6	
		2 - 5	
		2 - 4	
Greenock Mains, Location 2	Lower "shelly till"	2 - 3	NS 6363 2779
		2 - 2	
		2 - 1	
Greenock Mains, Location 6	Lower shelly till	6 - 1	NS 6331 2768
		6 - 2	
		6 - 3	
		6 - 4	
		6 - 5	
		6 - 6	
		6 - 7	
		6 - 8	
Merkland Burn, Location 8	Upper red till	8 - 10	NS 5908 2716
Merkland Burn, Location 8	Shelly till	8 - 1	NS 5908 2716
		8 - 2	
		8 - 3	
		8 - 4	
		8 - 6	
Merkland Burn, Location 8	Lower red till	8 - 7	NS 5908 2716
		8 - 8	
		8 - 9	

Table 4.2 (continued)

Site and Location	Type of sediment	Sample number	National Grid Reference
Sorn Mains, Location 5-1	Shelly till	5-1-1	NS 5369 2802
		5-1-2	
		5-1-3	
		5-1-4	
		5-1-5	
		5-1-6	
Sorn Mains, Location 5-2	Shelly till	5-2-5	NS 5371 2793
		5-2-4	
		5-2-3	
		5-2-2	
		5-2-1	
Sorn Mains, Location 5-3	(upper) grey till	5-3-2	NS 5385 2815
Sorn Mains, Location 5-3	(lower) red till	5-3-1	NS 5385 2815
Sourlie, Location 3	Upper grey till	3 - 5	NS 3364 4148
		3 - 4	
		3 - 3	
		3 - 2	
		3 - 1	
Sourlie, Location 3	Lower grey till	3 - 8	NS 3372 4147
		3 - 7	
		3 - 6	
Sourlie, Location 13	Upper grey till	13 - 6	NS 3361 4147
		13 - 5	
		13 - 4	
Sourlie, Location 13	Shelly till	13 - 3	NS 3361 4147
		13 - 2	
		13 - 1	

Table 4.2 (continued)

Site and Location	Type of sediment	Sample number	National Grid Reference
Tayburn, Location 5B	(upper) grey till	5B - 8 5B - 7 5B - 6 5B - 5	NS 5107 4345
Tayburn, Location 5B	(lower) red till	5B - 4 5B - 3 5B - 2 5B - 1	NS 5107 4345
Tayburn, Location 7B	(upper) grey till	7B - 2	NS 5095 4333
Tayburn, Location 7B	(lower) red till	7B - 1	NS 5095 4333
Afton Lodge	marine clay	12 - 1* 12 - 2* 12 - 3*	NS 4157 2587

* samples not collected in vertical sequence at Afton Lodge

Table 4.3 Relative mineral intensity percentage factors of minerals in the X-ray diffraction diagrams (after Larsson 1970).

Mineral	Measured peak (Å)	Mineral intensity percentage factor
Mica-illite	10.00	1.21
Hornblende (Amph.)	8.34	0.59
Chlorite	7.06	0.70
Quartz	4.24	1.11
K-feldspar	3.24	0.53
Plagioclase	3.19	0.79
Calcite	3.03	0.64
Dolomite	2.89	0.42
Hematite	2.70	0.52

PART II

TILLS OF THE NW GLASGOW AREA

CHAPTER 5

GRAIN-SIZE ANALYSIS OF TILLS OF THE NW GLASGOW AREA

5.1 Introduction

For many years, grain-size analyses have been used by geologists in attempts to characterise the depositional environments of clastic sediments, although, in contrast, data that suggest that grain size parameters are not environmentally sensitive have also been presented (Shepard & Young 1961; Schlee et al. 1964; Gees 1965; Sevon 1966; Swan et al. 1978).

5.1.1 Brief history of grain-size analysis of tills

One of the earliest attempts to define grain-size distribution in till was that of Crosby (1892), who analysed sixteen till samples from twelve drumlins of the Boston area, U.S.A., by sieving and decantation methods, in order to compare the volumes of various till fractions with the volumes of the resulting outwash bodies. Later, Udden (1914), on the basis of eight till samples from Illinois and Iowa, concluded that size distribution is the result of crushing rather than sorting. In 1933, Krumbein reported data for nearly 50 samples in NE Illinois and concluded that cumulative curves for tills frequently are polymodal because of incorporation of previously-sorted sediments. He noted grain-size homogeneity in various till sheets and attempted some stratigraphical interpretation and correlation. Kruger (1937) analysed 50 till samples from Minnesota. He believed that the tills were generally heterogeneous and that uniformity in grain size and composition in an exposure was an anomaly. Deane (1950) reported on more than 100 analyses as an aid to till classification in the Lake Simcoe area of Ontario. He concluded that the composition of tills varies remarkably over short distances so that mechanical analysis alone cannot be relied upon to distinguish the age relationships of tills.

Within the following few years, the idea that individual till sheets are in fact often homogeneous over large areas (Krumbein 1933) became firmly established. Shepps (1953) included size analysis in his documentation of the properties of various tills, and he began to apply statistics to the results. Legget (1942) had advocated the use of triangular plots of sand-silt-clay percentages as a saving in time over the drawing of cumulative curves. In 1958, Shepps suggested the plotting of sand and clay percentages on a rectangular graph instead of on a triangular plot, and he devised the 'size factor' as a substitute for median diameter. Dreimanis & Reavely (1953) concluded that grain size was one important parameter for distinguishing between two widespread till sheets near Lake Erie.

The size frequency distribution is a fundamental physical property of a clastic sediment. It provides some indication of the kinetic energy conditions within the environment of deposition. Statistical parameters from size analyses have been used to distinguish between different environments by several authors (Folk & Ward 1957; Passega 1957; Friedman 1961 and 1967; Sahu 1964). For the most part, these works have dealt with sandy deposits of aqueous origin. Little has been done with diamictons of glacial origin.

The size range most often analysed is the till matrix (Karrow 1976). For practical reasons, analysis normally does not include gravel sizes since the sample size needed for proper statistical representation of the gravel fraction is too unwieldy.

The physical properties of tills, and particularly grain-size analyses of the till matrix (< 2mm fraction), have been used extensively for identifying and correlating till units during recent years (e.g. Kempton 1963; Johnson 1964; Kempton & Hackett 1968a and 1968b; Schlüchter 1977; Vorren 1977; Butler 1983; Ehlers 1983; Haldorsen 1983).

5.1.2 Purposes of grain-size analysis of tills of the NW Glasgow area

In the present research project, grain-size analysis of the matrix of till samples from the NW Glasgow area and Northern Ayrshire was carried out as standard practice because such analysis provides quantitative data concerning the sampled tills and thus contributes to the body of knowledge regarding the properties of these tills. Also, as seen below, grain-size analysis, and the properties of the analysed sediments that it reveals, allows reliable distinctions to be made between two or more samples that appear similar in the field. Furthermore, comparison of the grain-size distribution of till deposits is of great importance because grain-size variations may indicate either differences in the source areas of the tills concerned or differences produced by weathering.

As noted above, for the purposes of comparison with other tills, it is most useful to consider the grain-size parameters of the matrix of a till. Grain-size analyses of the matrices of samples of the Red, Weathered Grey and Grey tills of the NW Glasgow area therefore were made. The purposes of these investigations were to:

1) Obtain an overall view of the grain-size distribution of the matrices of the three different categories of till - Red, Weathered Grey and Grey.
2) Evaluate the relationship between grain-size distribution and petrography in both the Red and Grey categories of till.

3) Record the grain-size parameters of the three categories of till.

4) Evaluate the degree to which the grain-size parameters can be utilised in differentiating distinct categories of till.

5) Consider the relationships between the various grain-size parameters of the tills.

6) Determine reliable criteria for the division of the tills of the NW Glasgow area into units with distinctive characteristics.

The results of grain-size analysis of samples of the tills of the NW Glasgow area are given below, using a number of standard methods of presentation. The most commonly used method of displaying the results of grain-size analysis is by giving a plot of cumulative weight percentage against grain size, the latter being expressed on a logarithmic scale. Krumbein (1938) suggested that for this purpose grain size is best expressed in phi units. In the results presented below (Chapter 5.2), the phi-grade scale of Krumbein (1934) is used. The grain-size class nomenclature and grain-size parameters (mean size, inclusive graphic standard deviation, inclusive graphic skewness and inclusive graphic kurtosis) that are calculated are those defined by Folk & Ward (1957).

5.2 Results of grain-size analysis

5.2.1 Grain-size cumulative curves

The results of the mechanical analyses of the samples are shown in Table 5.1. The data are arranged as percentages by weight in the various grades. The data may be more readily visualised in graphic form. The cumulative curve for each sample is first drawn separately. Then the curves representing each category of till are summed on the same paper to facilitate comparison (Figs. 5.1 to 5.3). It should be noted that the curves as a whole move across the chart fairly smoothly, and constitute a broad band in which most of the curves are approximately parallel. There are, however, several exceptions.

From the cumulative curves, it is clear that the till matrices have extremely irregular size distributions, and the presence of several secondary maxima in the curves render them polymodal in aspect. Such polymodal curves for size distribution in till matrices may be due to a mixture of constituents from several sources.

5.2.2 Grain-size distribution; sand-silt-clay composition

In this section, the sand-silt-clay composition of the Red, Grey and Weathered Grey tills is examined, using a number of tabular and graphical methods of representation.

Based on material less than 2mm in diameter, the average Red till has 59.38% sand (2.00 - 0.063mm), 34.24% silt (0.063 - 0.002mm) and 6.81% clay (< 0.002mm) (Table 5.2). Corresponding values for average Weathered Grey till are 53.31% sand, 41.11% silt and 5.68% clay and corresponding values for Grey till are 41.50% sand, 47.26% silt and 11.24% clay.

The average values of the sand, silt and clay fractions of the different categories of till are significantly different. The Grey till samples are characterised by higher clay and silt contents and a lower sand content than both the Red till and the Weathered Grey till. This fact is seen clearly in the histograms presented as Figure 5.4.

The average values shown in Table 5.2 and Figure 5.4 for the sand, silt and clay fractions of the three categories of till in the NW

Glasgow area were derived from the detailed data recorded in Table 5.3. When these data are plotted on a sand-silt-clay triangular diagram (after Picard 1971) in Figure 5.5b, the following observations may be made:

1) The matrices of the analysed Red till samples are dominantly silty sand.
2) The matrices of the samples of the Weathered Grey till vary from silty sand to sandy mud.
3) The matrices of the Grey till samples are mainly silty mud and sandy silt, with some sandy mud.

The triangular diagram also illustrates well the fact that both the Red till and the Weathered Grey till samples have more coarse-sized and fewer fine-sized grains than the Grey till samples (a point discussed above as a result of study of data presented in Table 5.2 and Fig. 5.4). This same fact is seen very clearly also in histogram form in Figure 5.6. One possible explanation of this grain size distribution is that the finer sizes of grain were not produced in both the Red and the Weathered Grey till during ice transportation or, if they were, they were washed away before and during sedimentation. The lower values of the clay and silt content in the Weathered Grey till than those in the Grey till support the idea that finer-grained material may have been washed out of the Weathered Grey till since the time of its deposition.

When the grain size distributions of the samples of the Grey till and the Red till matrices are compared in yet another way, that of Figure 5.7, it is clear that the Grey till is markedly finer-grained than the Red till. Flint (1957) stated that boulder clay containing mostly fine-grained material can indicate an underlying bedrock composition of minerals that are easily eroded by glacial ice. An initially fine-grained bedrock would yield a mainly fine-grained boulder clay over a short distance of transport by ice. On this basis, it is arguable that the distinctly higher contents of silt and clay in the Grey till relative to the Red till indicate that the Grey till has been derived mainly from the local fine-grained Carboniferous rocks, whilst the Red till has been derived mainly from the Old Red Sandstone bedrock, which is rich in sand-sized sediments. Previous studies of the pebble lithology of Glasgow tills by Menzies (1981) support this suggestion.

5.2.3 Variation of grain-size parameters

A qualitative comparison of cumulative curves may serve to bring out general relations, but it is desirable to have some means of comparing the samples on a more quantitative basis. Such a device is available in the statistical treatment of the data, which furnishes a series of values for each sample.

Inman (1952) suggested the measurement of mean size, standard deviation, skewness and kurtosis, parameters based on the 16th, 50th and 84th percentiles, using phi units. These were extended by Folk & Ward (1957) to detect bimodality, especially in the tails of the distribution, by addition of the 5th, 25th, 75th and 95th percentiles. These phi percentiles and the four grain-size parameters determined for the analysed samples are given in detail in Tables 5.3 and 5.4. The distribution of the grain-size parameters of the NW Glasgow tills is shown in Figures 5.8 to 5.11. In Table 5.5, the ranges, mean values and standard deviations for the grain-size parameters are given.

5.2.3.1 Mean size (Mz)

The standard graphic measure for determining overall size is the graphic mean, given by the formula:

$$Mz = \frac{(\phi16 + \phi50 + \phi84)}{3} \quad \text{(Folk \& Ward 1957).}$$

The Wentworth (1922) size scale is converted into phi units and is used in interpreting the results of the graphic mean diameter as follows:

Mz	-1 - 0 = very coarse sand	0 - 1 = coarse sand
	1 - 2 = medium sand	2 - 3 = fine sand
	3 - 4 = very fine sand	4 - 5 = coarse silt
	5 - 6 = medium silt	6 - 7 = fine silt
	7 - 8 = very fine silt	>8 = clay

The graphic mean covers all the possible sizes from clay to the very coarse sand sizes. The average mean sizes, Mz, are 3.96 phi (equivalent to 0.064mm), 4.16 phi (equivalent to 0.056mm) and 4.85 phi (equivalent to 0.035mm) for Red till, Weathered Grey till and Grey till respectively. The average mean size clearly separates the Red till from the Grey till deposits. Mz values for the Grey till are $4.22<Mz<5.22$ and for the Weathered Grey till $3.90<Mz<4.68$, whilst those for the Red till are $3.56<Mz<4.48$. It is clear that the Mz values are variable, ranging from very fine sand to coarse silt for both the Red till and the Weathered Grey till, whereas Mz values for the Grey till range between coarse and medium silt (Fig. 5.8). The average Mz value seems to be a diagnostic parameter for distinguishing between the Grey till on the one hand and the Red till and Weathered Grey till on the other.

In general, the overall average mean size of the Weathered Grey till is coarser than that of the Grey till. As suggested already, this probably reflects washing away of the fines from the Weathered Grey till during and after sedimentation of the Grey till.

5.2.3.2 Inclusive graphic standard deviation (σ_I)

This measure of sorting is given by the formula:

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

The formula includes 90% of the distribution and is the best overall measure of sorting. Folk (1968) suggested the following verbal classification scale for sorting:

σ_I $< 0.35\ \phi$ = very well sorted

$0.35 - 0.50\ \phi$ = well sorted

$0.50 - 0.71\ \phi$ = moderately well sorted

$0.71 - 1.00\ \phi$ = moderately sorted

$1.00 - 2.00\ \phi$ = poorly sorted

$2.00 - 4.00\ \phi$ = very poorly sorted

$>4.00\ \phi$ = extremely poorly sorted

In the present study, the samples analysed exhibit comparatively poor sorting. All the three till categories are very poorly sorted ($2 < \sigma_I < 4$). The mean σ_I values are 2.51 ϕ, 2.60 ϕ and 2.64 ϕ for Red till, Weathered Grey till and Grey till respectively. σ_I values for the Red till are $2.13 < \sigma_I < 2.8$ and for the Weathered Grey till $2.39 < \sigma_I < 2.71$, whilst those for the Grey till are $2.48 < \sigma_I < 2.85$. The σ_I values of the Red till samples are more widely scattered than those of the Weathered Grey till and Grey till (Fig. 5.9). The σ_I value does not seem to be a diagnostic parameter for distinguishing between the various categories of till.

5.2.3.3 Inclusive graphic skewness (Sk_I)

To measure the asymmetry of the grain-size distribution of a sediment, Inman (1952) suggested two measures of skewness which Folk & Ward (1957) combined to obtain the inclusive graphic skewness:

$$Sk_I = \frac{(\phi16 + \phi84 - 2\phi50)}{2(\phi84 - \phi16)} + \frac{(\phi5 + \phi95 - 2\phi50)}{2(\phi95 - \phi5)}$$

This is the best skewness measure to use because it determines the skewness of the 'tails' of the cumulative curve, not just the central portion. Symmetrical curves have $Sk_I = 0.0$; those with excess fine material have positive skewness values and those with excess coarse material have negative values. The more the skewness value departs from 0.0, the greater the degree of asymmetry. The following verbal limits of skewness are suggested by Folk (1968):

Sk_I	+1.0 to +0.3 ϕ	strongly fine skewed
	+0.3 to +0.1 ϕ	fine skewed
	+0.1 to -0.1 ϕ	near symmetrical
	-0.1 to -0.3 ϕ	coarse skewed
	-0.3 to -1.0 ϕ	strongly coarse skewed

For the samples analysed in the present project, skewness covers the range from the strongly coarse to the fine skewed values. Skewness values of the Red till indicate that all samples have a strong tendency to negative skewness ($-0.52<Sk_I<-0.1$); the Sk_I values are widely scattered, coarse skewed to strongly coarse skewed (Fig. 5.10). Skewness values of the Weathered Grey till samples are also widely scattered ($-0.28<Sk_I<+0.13$), ranging from fine skewed through near symmetrical to coarse skewed. Sk_I values of the Grey till have a strong tendency to positive skewness ($-0.07<Sk_I<+0.34$), most of the Grey till samples having a fine skewed to near symmetrical distribution.

The distribution of skewness in the Red till and the Grey till is significant. The change from negative skewness in Red till samples to (mainly) positive skewness in Grey till samples (Fig. 5.10) indicates that the Sk_I value is a valuable diagnostic parameter for distinguishing between the Red and Grey tills.

5.2.3.4 Inclusive graphic kurtosis (K_G)

Folk & Ward (1957) proposed the graphic kurtosis parameter

$$K_G = \frac{(\phi 95 - \phi 5)}{2.44(\phi 75 - \phi 25)}$$

as a means of measuring the ratio between the sorting in the extremes of the grain-size distribution curve and the sorting in the central portion of the curve. If the central portion is better sorted than the tails, the curve is said to be excessively peaked or leptokurtic; if the tails are better sorted than the central portion, the curve is flat peaked or platykurtic. In describing the values of kurtosis the following limits are suggested by Folk (1968):

K_G			$<0.67\ \phi$	= very platykurtic
	$0.67\ \phi$	to	$0.90\ \phi$	= platykurtic
	$0.90\ \phi$	to	$1.11\ \phi$	= mesokurtic
	$1.11\ \phi$	to	$1.50\ \phi$	= leptokurtic
	$1.50\ \phi$	to	$3.00\ \phi$	= very leptokurtic
			$>3.00\ \phi$	= extremely leptokurtic

All the Grey till ($0.66<K_G<0.81$) and Weathered Grey till ($0.66<K_G<0.83$) samples are platykurtic, with K_G values <0.9. The K_G values of the Red till ($0.67<K_G<1.27$) samples are very widely scattered, ranging from platykurtic to leptokurtic (Fig. 5.11). Generally, the K_G values appear to give a good impression of till matrix grain-size distribution. However, K_G does not appear to be a valuable diagnostic parameter.

5.2.4 Relationships between the grain-size parameters

Scatter diagrams have been constructed for all six mutual relationships between the four parameters - mean size, sorting, skewness and kurtosis. Some of the diagrams suggest a linear correlation. To test the validity of this suggestion, a regression analysis was performed.

5.2.4.1 Plot of mean size versus sorting (Fig. 5.12a)

A weak linear correlation is indicated between Mz and σ_I. The regression line is given by $\sigma_I = 2.19 + 0.09$ Mz. The correlation coefficient is $r = 0.30$. Generally, this relationship shows that the larger the mean size (in mm), the better the degree of sorting.

5.2.4.2 Plot of mean size versus skewness (Fig. 5.12b)

A linear correlation between Mz and Sk_I is indicated by the scatter diagram. The regression line is given by $Sk_I = -1.80 + 0.40$ Mz. The correlation coefficient is $r = 0.87$. Generally, this relationship indicates that the finer the size, the more positively skewed is the till; i.e. relatively coarse till matrices have a negative skewness. This relationship is considered to be an effective discriminator between the Grey till and the Red till.

5.2.4.3 Plot of mean size versus kurtosis (Fig. 5.12c)

A linear correlation between Mz and K_G is indicated by the scatter diagram. The regression line is given by $K_G = 1.42 - 0.14$ Mz. The correlation coefficient is $r = -0.57$. Generally, this relationship indicates that the smaller the mean size (in mm), the more platykurtic is the till.

5.2.4.4 Plot of sorting versus skewness (Fig. 5.13a)

A linear correlation between σ_I and Sk_I for the three categories of till is indicated by the scatter diagram. The regression line is given by $Sk_I = -1.55 + 0.57\ \sigma_I$. The correlation coefficient is $r = 0.37$. Accordingly, this correlation indicates that poorly sorted tills have a positive skewness (excess of fine material) and *vice versa*.

5.2.4.5 Plot of sorting versus kurtosis (Fig. 5.13b)

A linear correlation between σ_I and K_G is indicated by the scatter diagram. The regression line is given by $K_G = 1.83 - 0.40\ \sigma_I$. The correlation coefficient is $r = -0.48$. The relationship indicates higher K_G values (more leptokurtic curves) with better sorting. In geological terms, Vorren (1977) explained this by suggesting that the better sorted tills may contain re-worked sand material. This also gives a leptokurtic grain-size distribution. In this connection, the concentration of the Grey till plots in the lower right area of the diagram (Fig. 5.13b) should also be noted. This is due to relatively low K_G values and high σ_I values. This may be of additional help in distinguishing Grey till from Red till.

5.2.4.6 Plot of skewness versus kurtosis (Fig. 5.13c)

A linear correlation between Sk_I and K_G is indicated by the scatter diagram. The regression line is given by $K_G = 0.78 - 0.29\ Sk_I$. The correlation coefficient is $r = -0.54$. Accordingly, this correlation indicates that relatively higher K_G values correspond with negative skewness. Also, the diagram (Fig. 5.13c) shows the concentration of Red till samples in the left part of the diagram. This is due to the high K_G values and negative skewness of the Red till samples. This may be of additional help in distinguishing Grey till from Red till.

5.2.5 Vertical profiles

With a view to ascertaining whether the Red and Grey tills are uniform in a vertical sense, several samples were collected systematically above each other in four till profiles. Two of the profiles were in Red till, and the other two in Grey till (with Weathered Grey upper parts). The results of the grain-size analysis and the values of the grain-size parameters (Folk & Ward 1957) are shown in Tables 5.1 and 5.3. The sequence of samples, the grain-size distribution of sand-silt-clay and the grain-size parameters are shown in Figures 5.14 to 5.17.

5.2.5.1 Grey till profiles

The two Grey till profiles that were studied were Queen Margaret Hall - Winton Drive (NS 5633 6817) and Kelvinside - Great Western Road (NS 5581 6807).

In both vertical sections, Grey and Weathered Grey till were exposed. The matrix colour could be used as a distinguishing feature. The lower part of the Grey till profiles was a uniform very dark grey colour, 10YR 3/1. Till samples taken from nearer the surface were slightly more variable in colour. Most were dark brown (7.5YR 3/2) to dark greyish brown (10YR 3/2). This variation in colour may reflect different degrees of weathering in the Grey till, because some of the higher samples of the Grey till in the two profiles were dark brown (7.5YR 3/2). However, it could also result from local variations in the original colour of the till.

Cumulative curves

Figures 5.18 and 5.19 show the particle-size distribution of the till matrix (<2 mm) at various depths through the two Grey till profiles. At the Queen Margaret Hall site, the cumulative curves indicate a progressive upward depletion in silt and clay fractions, with a corresponding increase in the sand fraction. This change does not appear suddenly at one level in the profile, but is gradual and probably suggests that the finer material was in part washed out due to factors such as drainage conditions since the time of deposition. At the Kelvinside site (Fig. 5. 15) there are large differences between the particle-size distributions of the samples. In particular, the samples from between 225 and 325cm depth are more silty and clayey and less sandy than those above these levels. This is not likely to have resulted from weathering, and probably indicates that the till at this site was originally less uniform in composition than at Queen Margaret Hall.

Sand-silt-clay composition

Figures 5.14 and 5.15 show that, generally, the percentage of sand decreases downwards through the two profiles. The decrease at Queen Margaret Hall is sharp, the sand percentages changing from 40% in the uppermost sample to about 25% in the lowermost sample at 175cm depth. In contrast, the decrease in sand percentage at the Kelvinside profile is gradual, changing from about 40% in the uppermost samples to about 30% in the lowermost samples at 375-425cm depth.

Grain-size parameters

The mean size (Mz) changes from coarse silt in the top part of the Queen Margaret Hall profile (Weathered Grey till samples) to medium and fine silt in the lower part of the profile. Overall, the mean size changes from coarse silt in the top part of the Kelvinside profile to medium silt in the lower part of the profile, but shows some fluctuation through the profile. Generally, the mean size shows coarsening upwards through the two profiles.

The inclusive graphic standard deviation (σ_I) decreases downwards through the Queen Margaret Hall profile (Fig. 5.14), whereas in the Kelvinside profile the σ_I value shows very obvious oscillation between high and low values (Fig. 5.15). Although all the samples in both profiles are very poorly sorted, the sorting shows a slight improvement downwards in the Queen Margaret Hall profile.

The inclusive graphic skewness (SK_I) value for the Queen Margaret Hall site shows obvious variation between fine skewed and near symmetrical skewed in the upper part of the profile and fine skewed and strongly fine skewed in the lower part of the profile (Fig. 5.14). The Sk_I value for the Kelvinside site ranges from near symmetrical in the uppermost part of the profile to fine skewed in the lower part of the profile.

The kurtosis (K_G) value generally increases downwards through the two profiles (Figs. 5.14 and 5.15), although all samples are platykurtic.

5.2.5.2 Red till profiles

The two Red till profiles that were studied were Laighpark (NS 5360 7615) and Clober (NS 5460 7590). In both profiles the tills were fairly uniform in colour; reddish brown (5YR 4/4). However, the uppermost part of the two profiles was dark reddish brown (5YR 3/4), possibly because of a slight oxidative weathering of the uppermost part of the Red till.

<u>Cumulative curves</u>

Cumulative curves for samples collected at various depths in the Laighpark and Clober till profiles are shown in Figures 5.20 and 5.21 respectively. In both profiles, the distribution curves indicate a progressive downward depletion in sand, with a corresponding increase in the silt and clay fractions. The changes are gradual and probably resulted from washing down of the fine material through the Red till.

<u>Sand-silt-clay composition</u>

Figures 5.16 and 5.17 show that the silt plus clay content is low in the uppermost parts of the two Red till profiles, and tends to increase gradually downwards from about 30% in the uppermost samples of the Laighpark profile to about 50% in the lowermost samples at 225cm depth, whereas in the Clober profile the silt plus clay content increases from about 40% in the uppermost sample to about 60% in the lowermost sample at 250cm depth.

<u>Grain-size parameters</u>

The mean size (Mz) shows coarsening upwards through the Laighpark profile, changing from coarse silt (4ø - 5ø) in the lower part of the profile to very fine sand in the uppermost part (Fig. 5.16). At Clober the mean size does not change noticeably in a vertical sense at depths of less than 200cm. However, the mean size decreases below this depth, changing from very fine sand (3ø - 4ø) at 200cm depth to coarse silt (4ø - 5ø) at 250cm depth (Fig. 5.17).

Although in both profiles all the samples are very poorly sorted, the sorting value (σ_I) shows a slight improvement upwards in the Laighpark profile (Fig. 5.16). In contrast, in the Clober profile, the sorting value increases upwards (Fig. 5.17), indicating a worsening in sorting.

The value of the inclusive graphic skewness (Sk_I) generally decreases downwards at Laighpark, changing from strongly coarse skewed in the uppermost sample to coarse skewed and near symmetrical in the rest of the samples downwards (Fig. 5.16). At Clober, all the samples are coarse skewed, and the Sk_I value generally decreases downwards throughout the profile (Fig. 5.17).

The kurtosis value (K_G) generally decreases downwards throughout the profile at Laighpark (Fig. 5.16), changing from very platykurtic in the uppermost sample to platykurtic in the lower samples. In contrast, at Clober the K_G values generally increase downwards through the profile (Fig. 5.17). All the samples are mesokurtic ($0.9<K_G<1.11$).

5.2.5.3 Discussion

In general, the study of the grain-size distributions and grain-size parameters in the vertical profiles shows that the silt plus clay content increases downwards through both Grey and Red till profiles, and the corresponding sand content tends to decrease in the same direction. Also, the mean size (Mz) exhibits a coarsening-upwards trend, changing from a fine silt and medium silt to coarse silt in the two Grey till profiles, and from very coarse silt to very fine sand in the two Red till profiles. This probably reflects a gradual downward leaching of the fine material (silt and clay) during and after the deposition of the Grey and Red till sequences.

Generally, the inclusive graphic standard deviation of the studied samples from the four profiles shows very poorly sorted till. The Weathered Grey till samples are relatively the least well sorted. However, sorting shows a slight improvement downwards in the two Grey till profiles and in the Clober Red till profile, although the till at depth is still poorly sorted.

The values for the inclusive graphic skewness in the two Grey till profiles are positively skewed (with excess fine material), whereas in the two Red till profiles the corresponding values are negatively skewed (with excess coarse material). Generally, skewness values tend to increase downwards in the four profiles.

The inclusive graphic kurtosis (K_G) is platykurtic ($0.67<K_G<0.90$) for most of the samples in the four profiles.

The study of the profiles shows that in both the Grey till and the Red till the sand-silt-clay composition, the mean size (Mz) and the skewness (Sk_I) change noticeably in a vertical sense.

5.3 General conclusions

The following general conclusions result from analysis of 49 samples from sites distributed widely throughout the NW Glasgow area, together with analysis of 25 samples from four sites where profiles in Red till (two sites) and Weathered Grey and Grey till (two sites) were examined:

1) Based on the average grain-size distribution of the sand, silt and clay fractions, the Red till consists of 59.38% sand, 34.24% silt and 6.81% clay. Corresponding figures for the Grey till are 41.50% sand, 47.26% silt and 11.24% clay. The Weathered Grey till has 53.31% sand, 41.11% silt and 5.68% clay.
2) The Grey tills are distinctive in their relatively high silt and clay content and (mainly) positive skewness. On the other hand,

the Red tills are characterised by high sand content and (entirely) negative skewness.

3) Increasing amounts of sand grade in Weathered Grey till relative to Grey till, as grain size (in mm) increases, is mainly due to washing away of the finer grades during and after sedimentation.

4) Folk & Ward (1957) grain-size parameters have been calculated for all the samples investigated. Mean size and skewness seem to be the most diagnostic parameters for distinguishing between the Grey till on the one hand and the Red till and the Weathered Grey till on the other.

5) Values of the K_G distributions fall within the range 0.7 to 0.9 for 95% of the samples from the three different categories of till. This means that grain-size distribution curves for the tills are usually platykurtic, or even strongly platykurtic, i.e. very flattened with weakly projecting peaks.

6) Regression analysis indicates a linear correlation between the four grain-size parameters. As sorting becomes poorer, skewness has more positive values, kurtosis decreases and mean size (in mm) increases.

7) There is a strong positive relationship between skewness and mean size; as the mean size (in mm) decreases, the skewness has more positive values. In contrast, there is a negative relationship between kurtosis and both mean size and skewness; as the kurtosis increases, the mean size (in mm) decreases and the skewness has more negative values.

8) The sand-silt-clay distribution changes noticeably in a vertical sense. In general, the fine-grade material (silt and clay) tends to increase downwards through the profile. This probably indicates that downward leaching of the finer grades of material affected both the Red and Grey till.

9) Of the grain-size parameters, mean size and skewness change noticeably in a vertical sense. In general, the mean size (in mm) tends to decrease downwards, whereas the skewness tends to increase downwards in a Red till or Grey till profile.

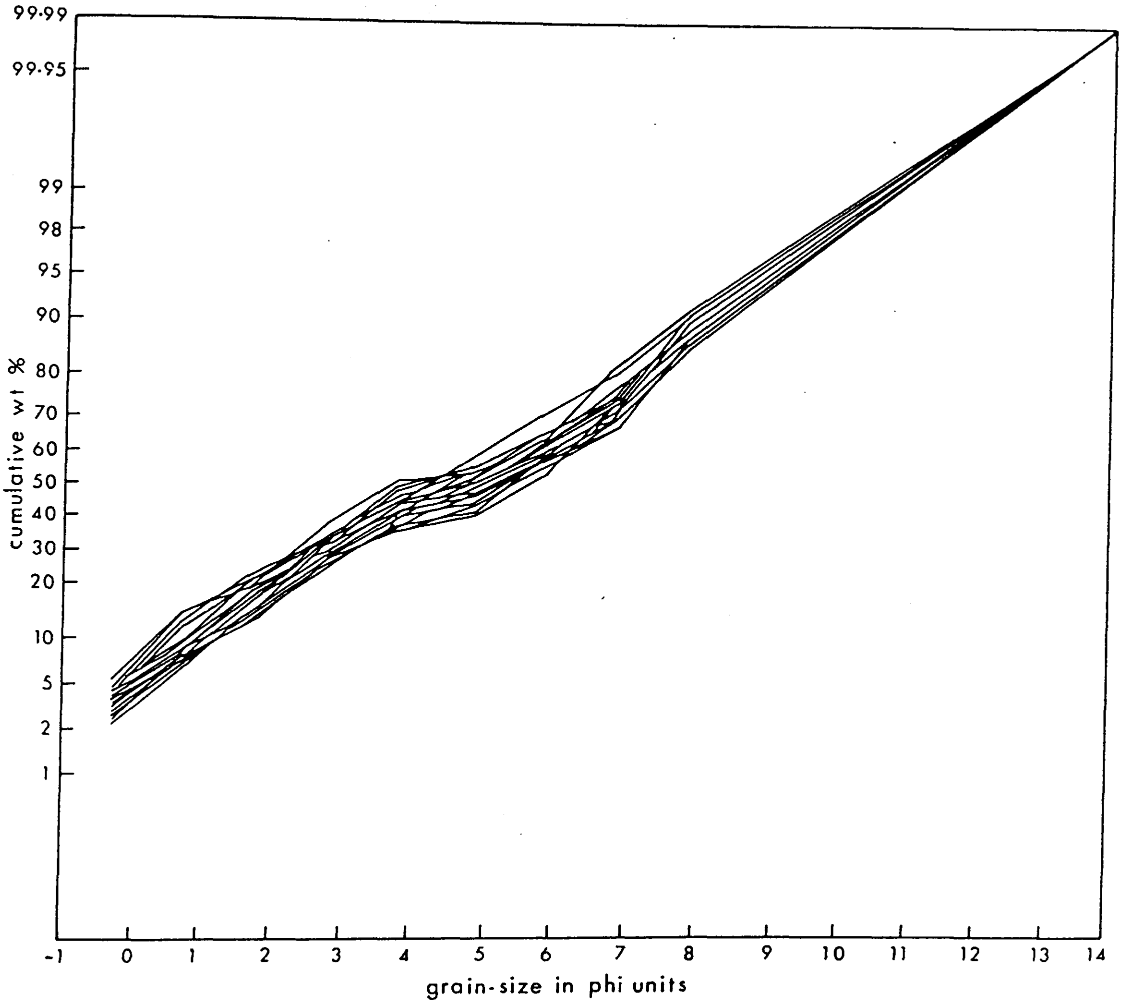


Figure 5.1 Cumulative frequency curves for the matrix (<2mm) of Red till samples from the NW Glasgow area.

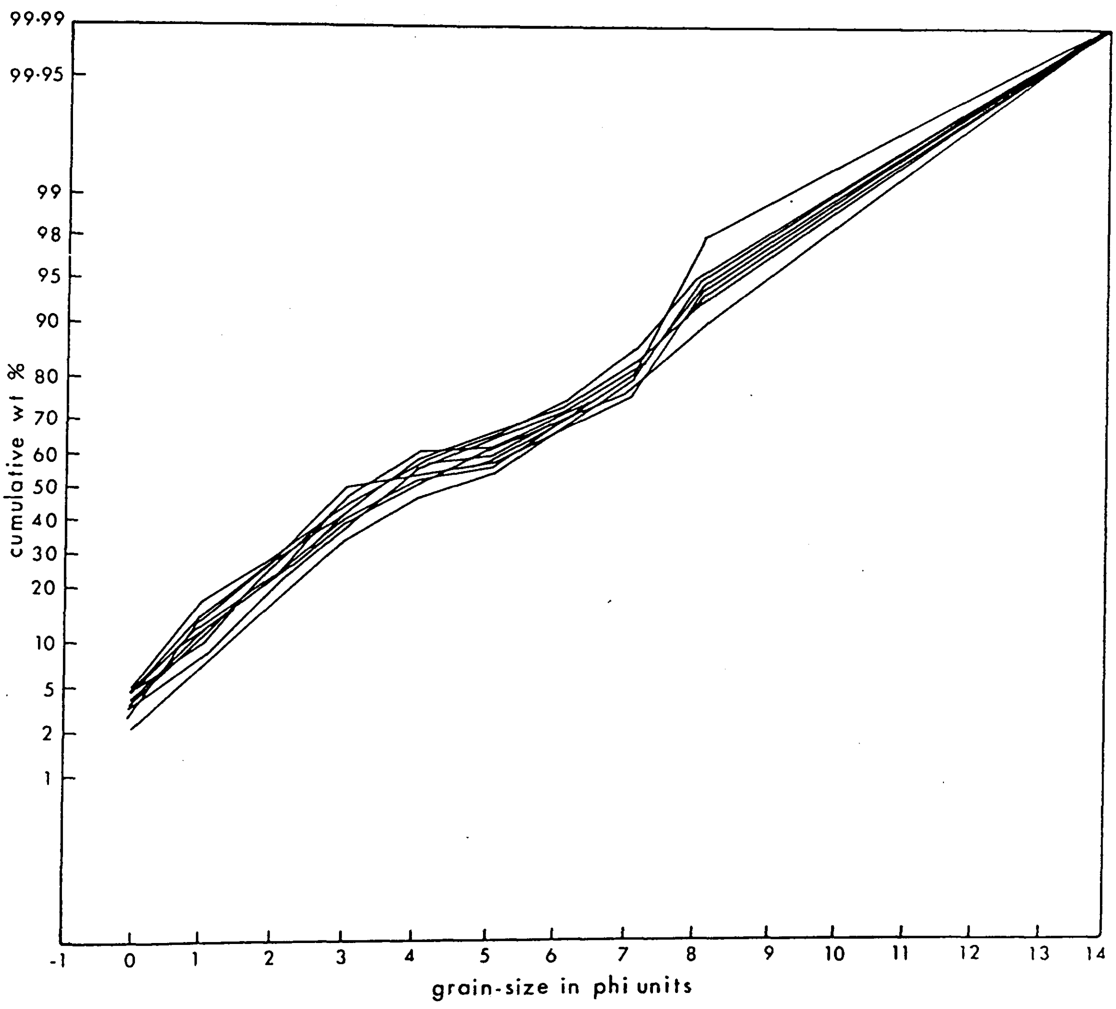


Figure 5.2 Cumulative frequency curves for the matrix (<2mm) of Weathered Grey till samples from the NW Glasgow area.

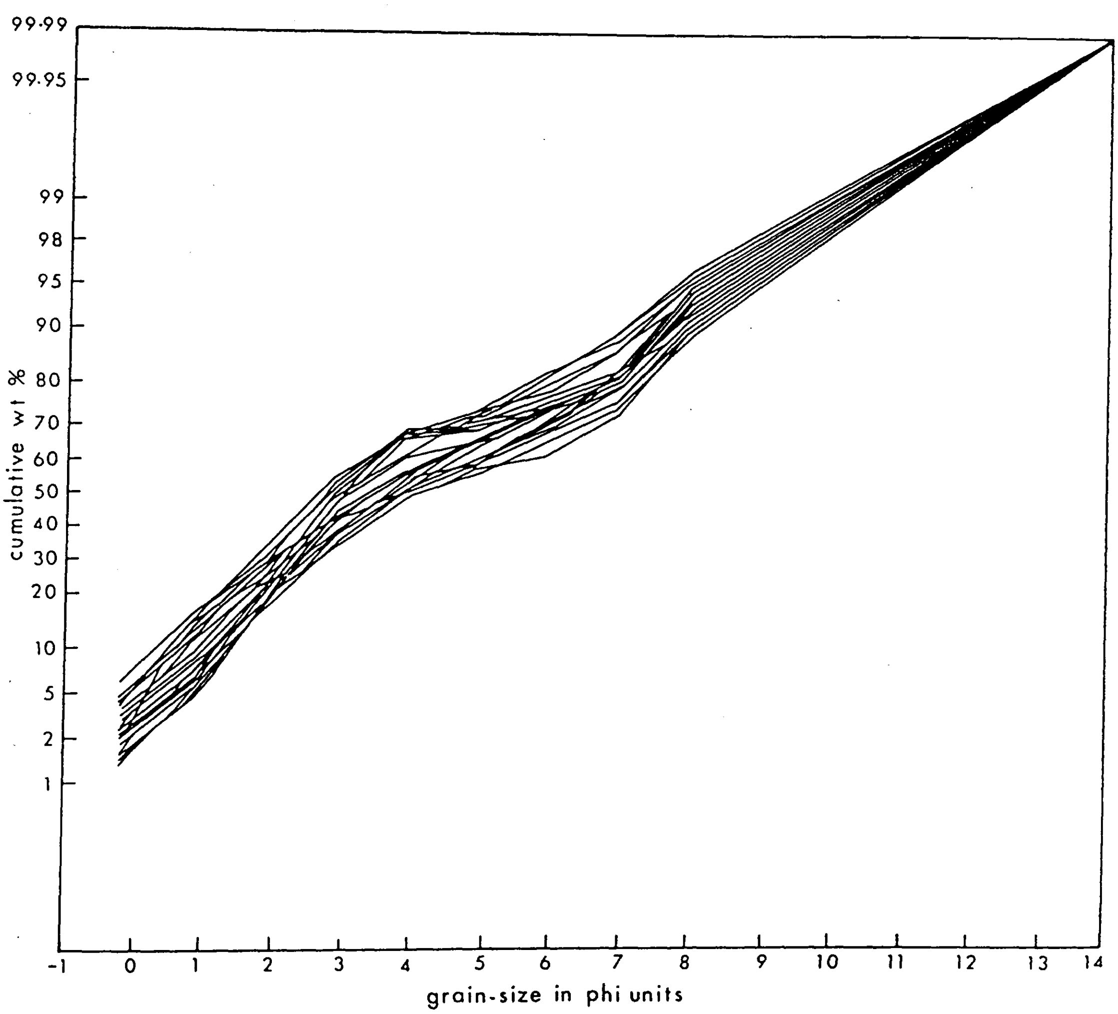


Figure 5.3 Cumulative frequency curves for the matrix (<2mm) of Grey till samples from the NW Glasgow area.

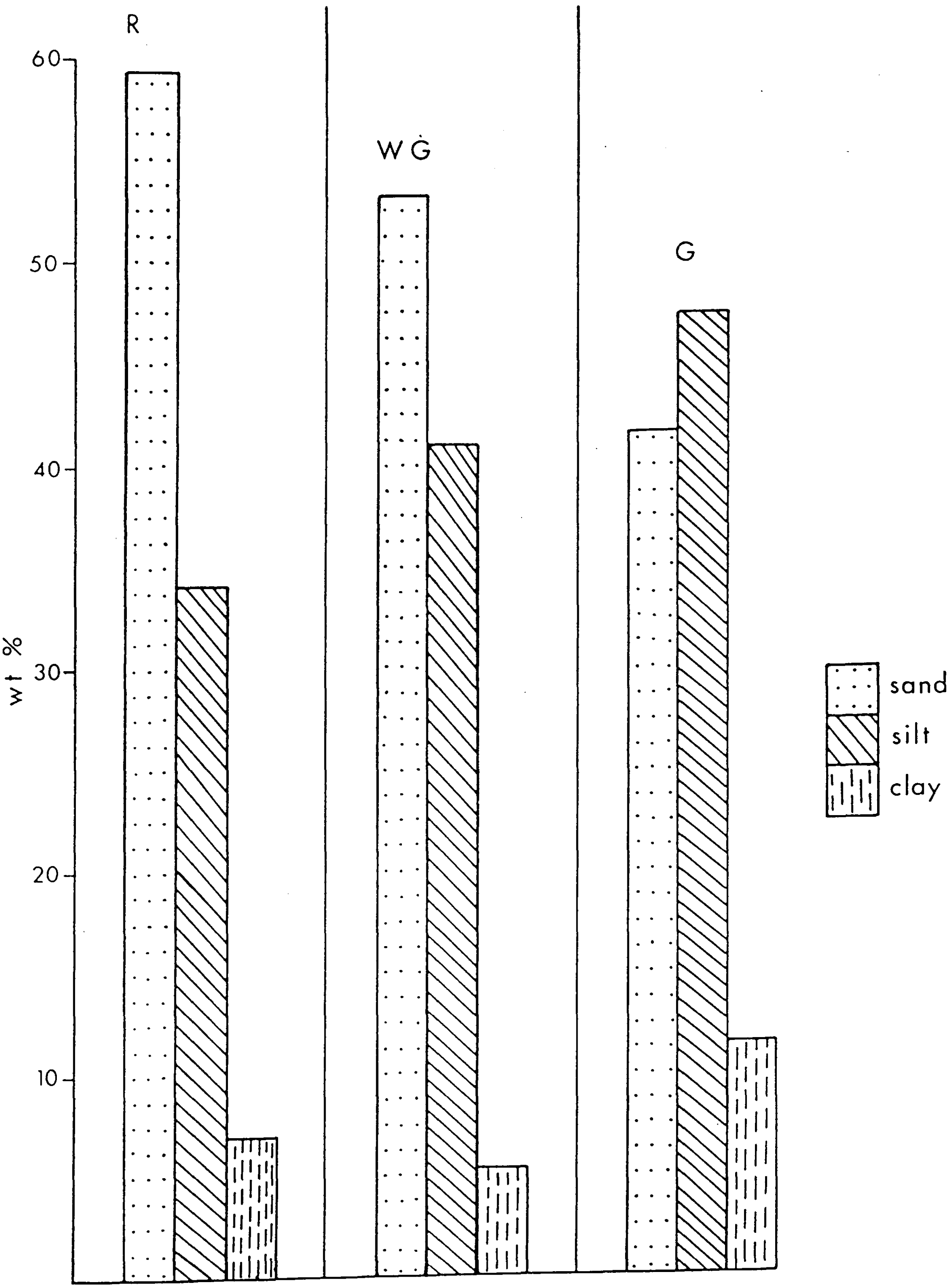


Figure 5.4 Histograms showing average sand, silt and clay percentages in the three categories of till in the NW Glasgow area.

R, WG, G

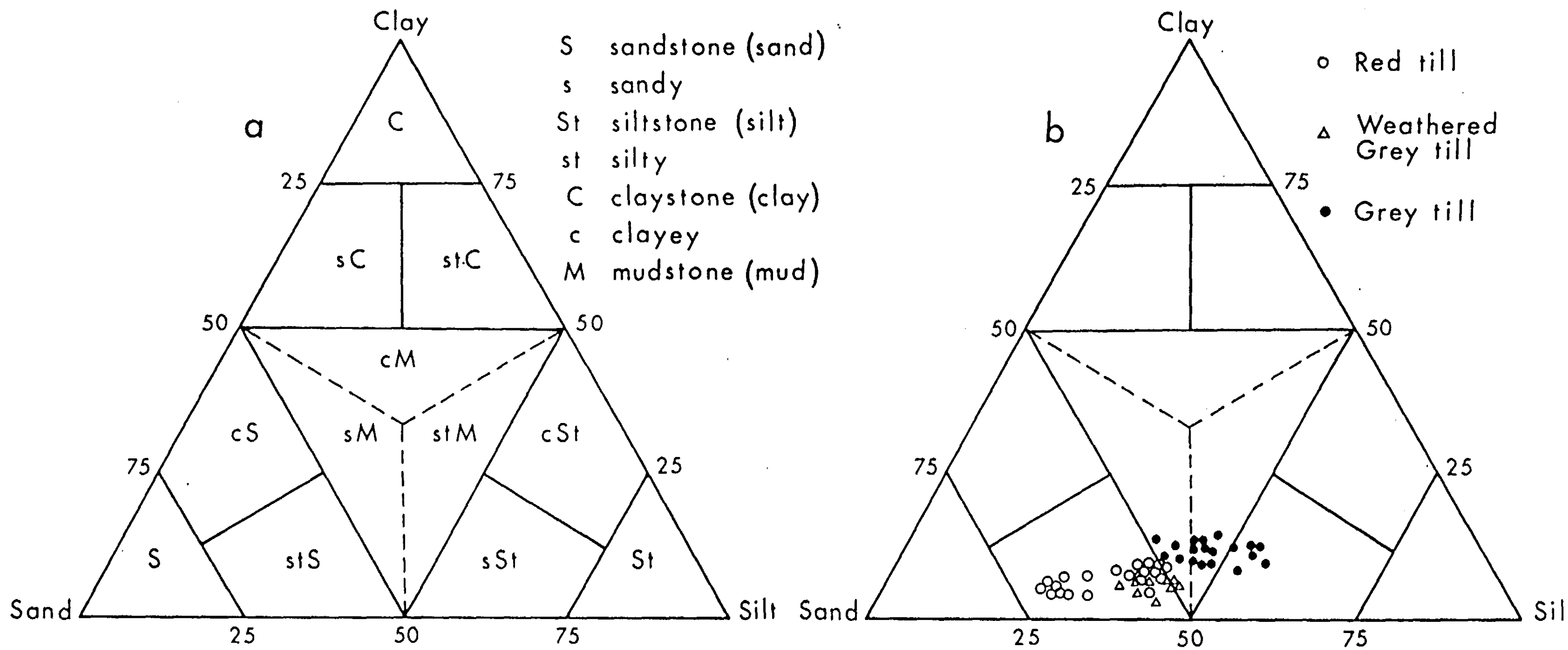


Figure 5.5 a: Sand-silt-clay triangular diagram, after Picard (1971).

b: Sand-silt-clay composition of the matrix (<2mm) of the three categories of till deposits in the NW Glasgow area.

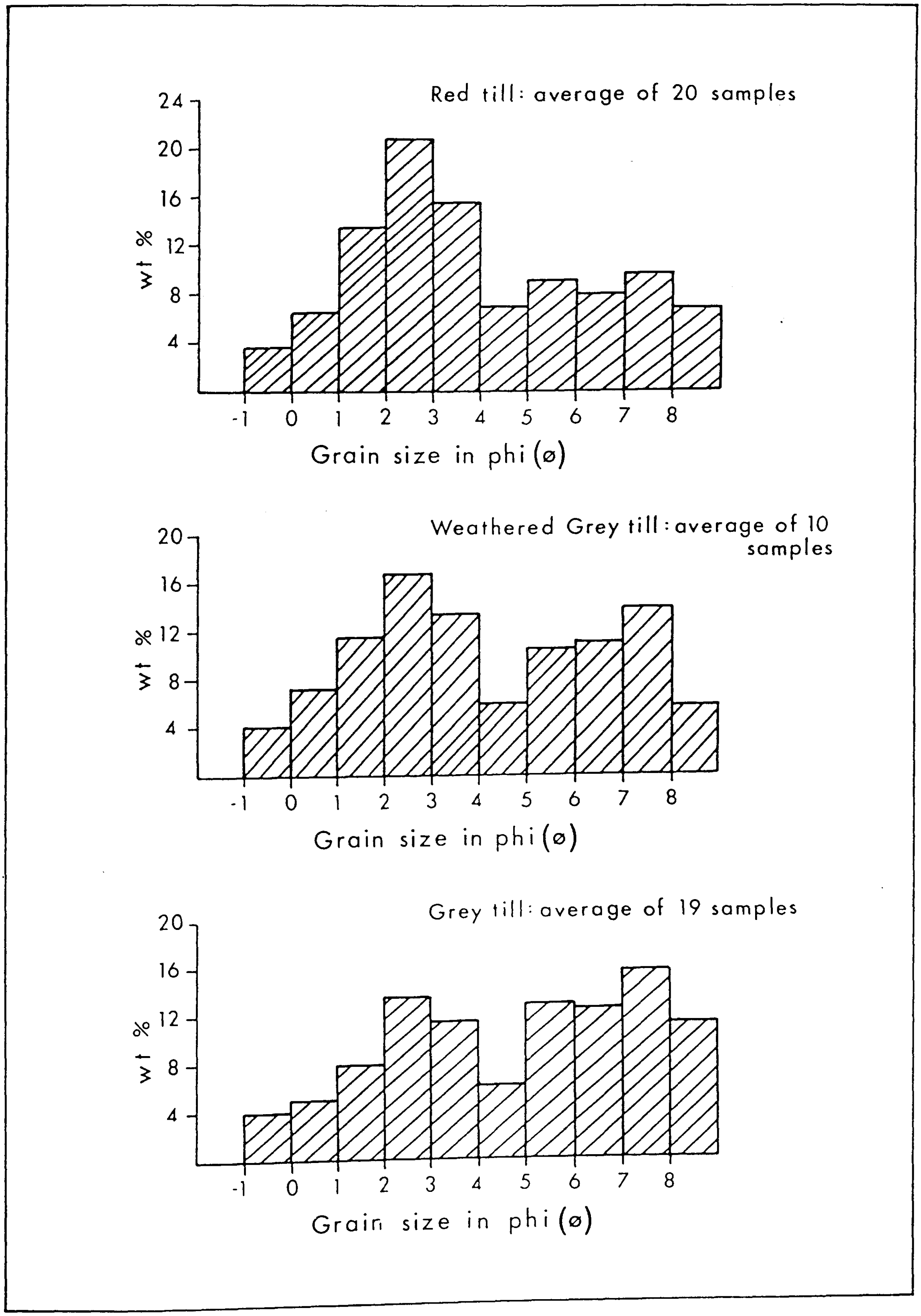


Figure 5.6 Histograms showing the average grain-size distribution by weight percent of the matrix (<2mm) in phi class intervals from -1 ø to >8 ø for the Red, Weathered Grey and Grey tills of the NW Glasgow area.

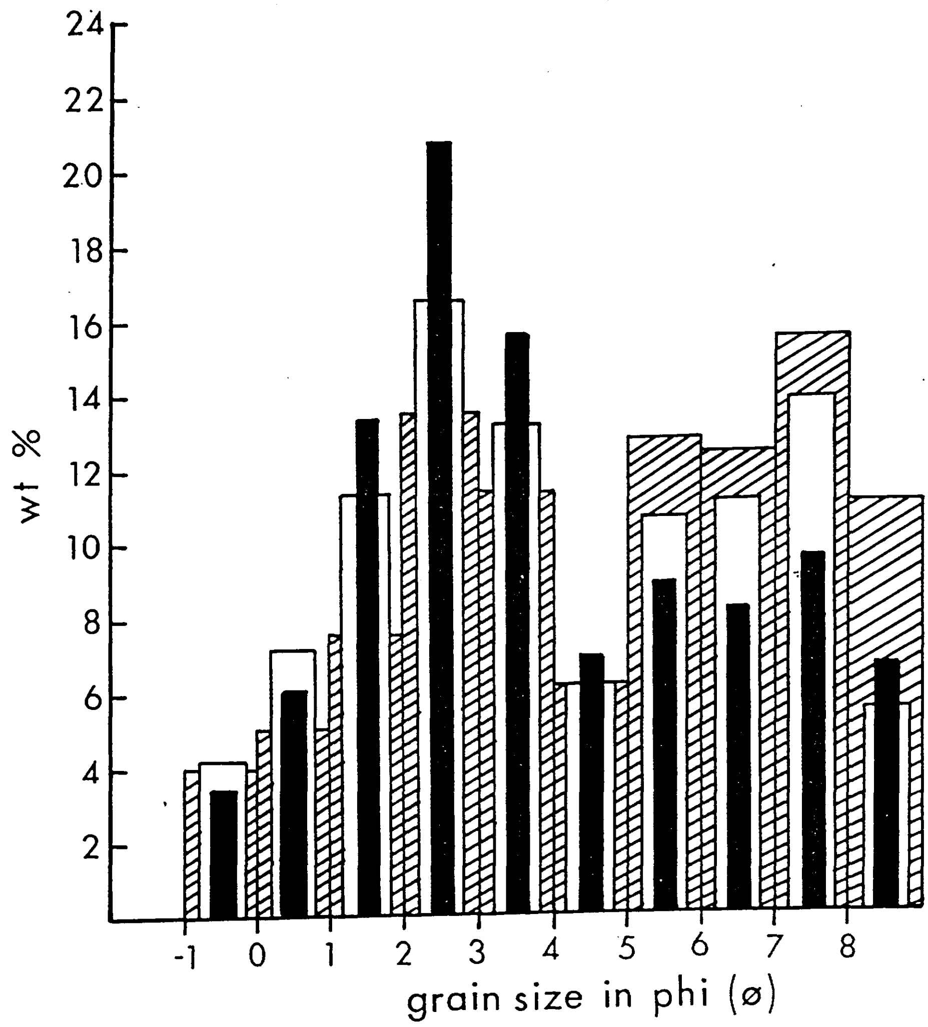


Figure 5.7 Histogram showing average grain-size distribution of 20 Red till samples (black bars), 10 Weathered Grey till samples (clear bars) and 19 Grey till samples (diagonal bars) from the NW Glasgow area.

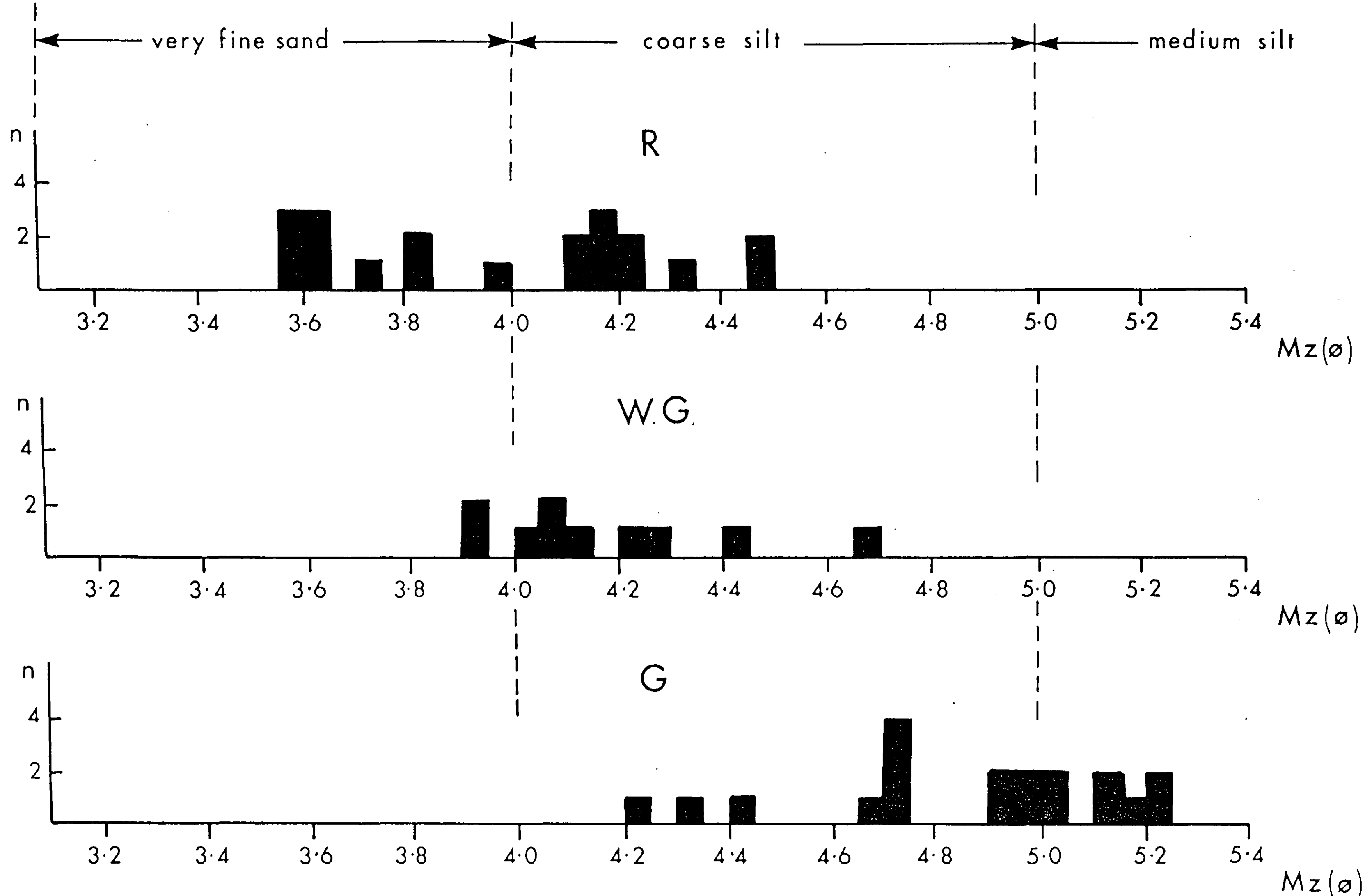


Figure 5.8 Histograms showing the distribution of Mz values (mean size) for the three categories of till in the NW Glasgow area.

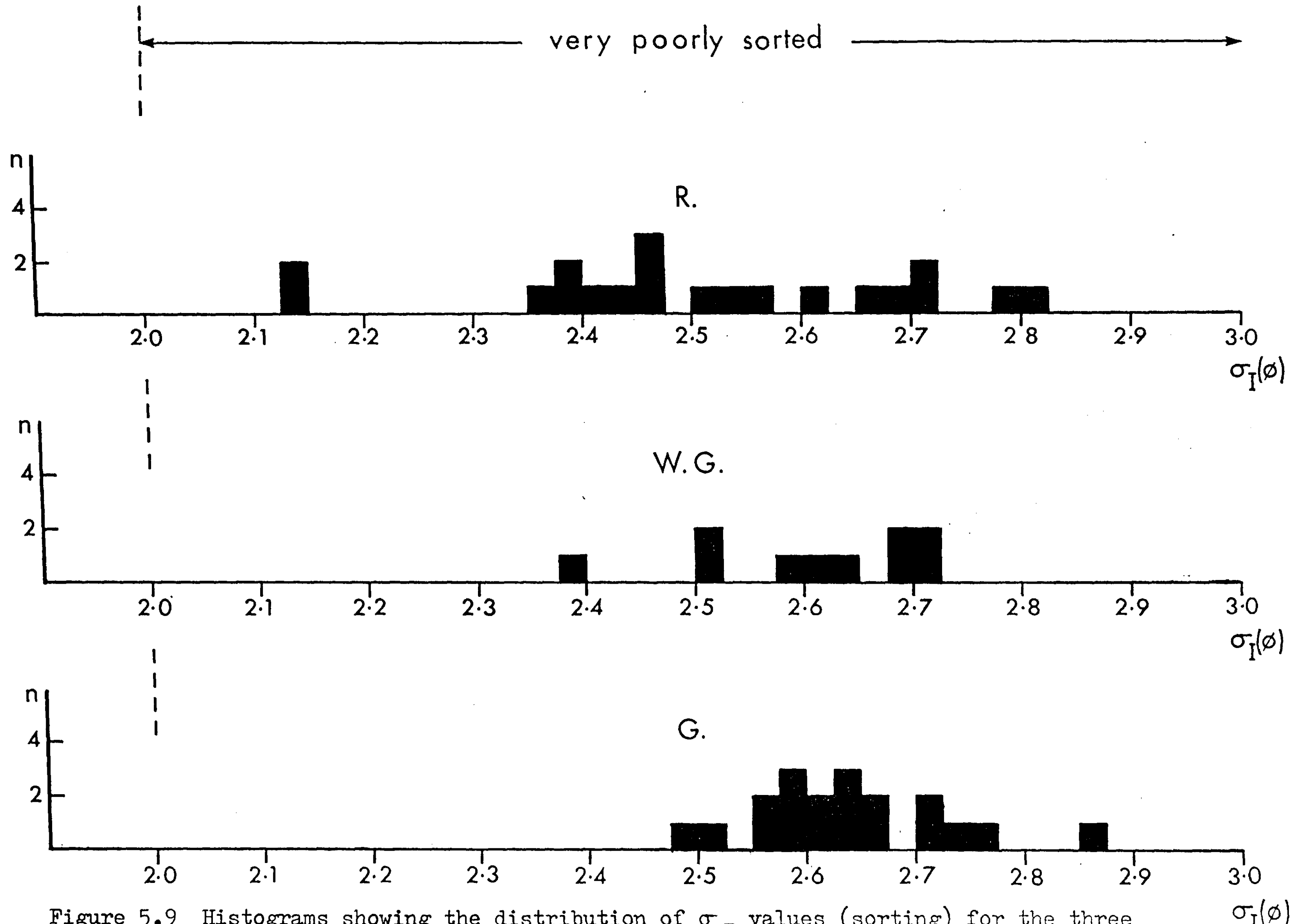


Figure 5.9 Histograms showing the distribution of σ_I values (sorting) for the three categories of till in the NW Glasgow area.

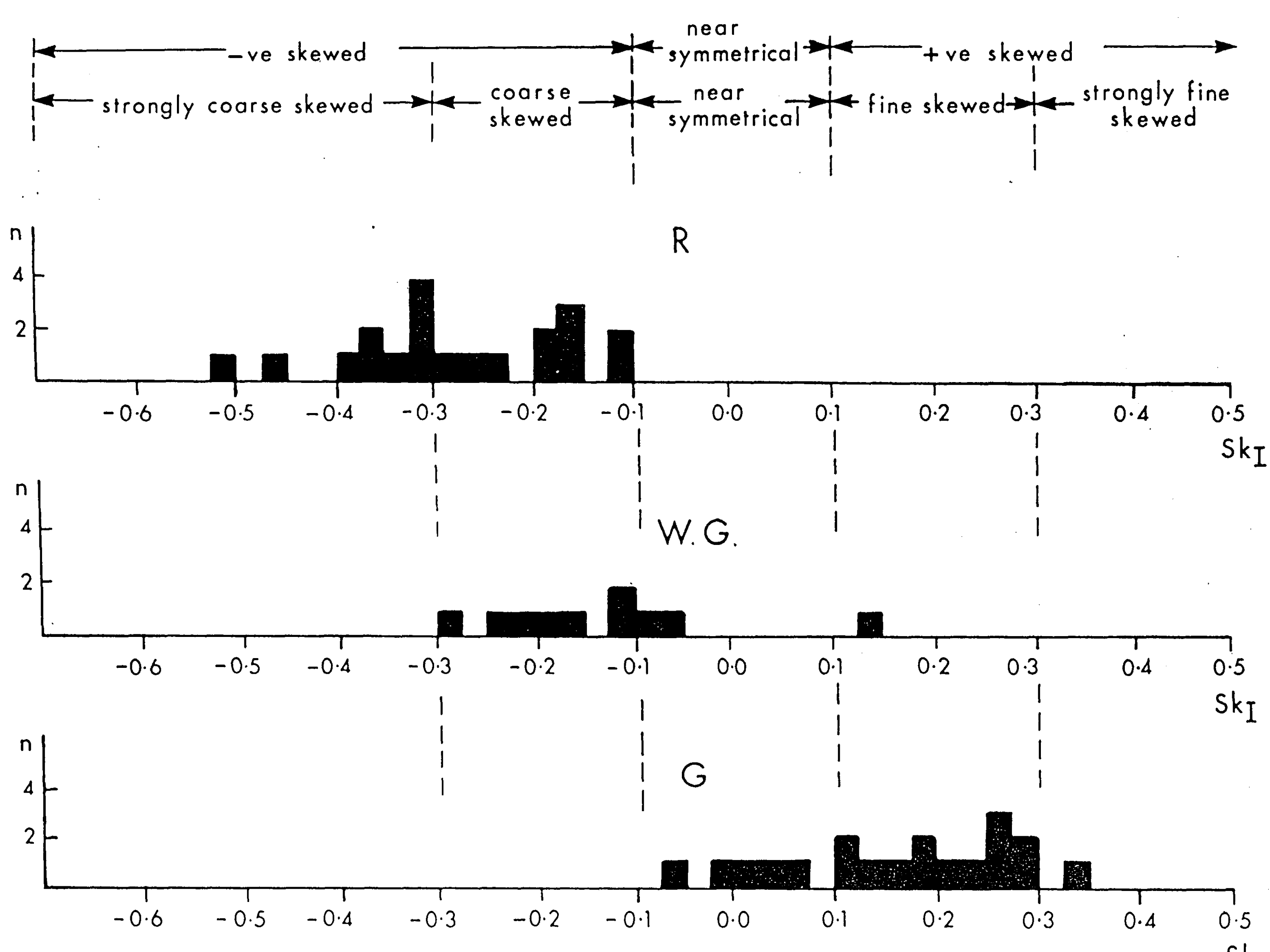


Figure 5.10 Histograms showing the distribution of Sk_I values (skewness) for the three categories of till in the NW Glasgow area.

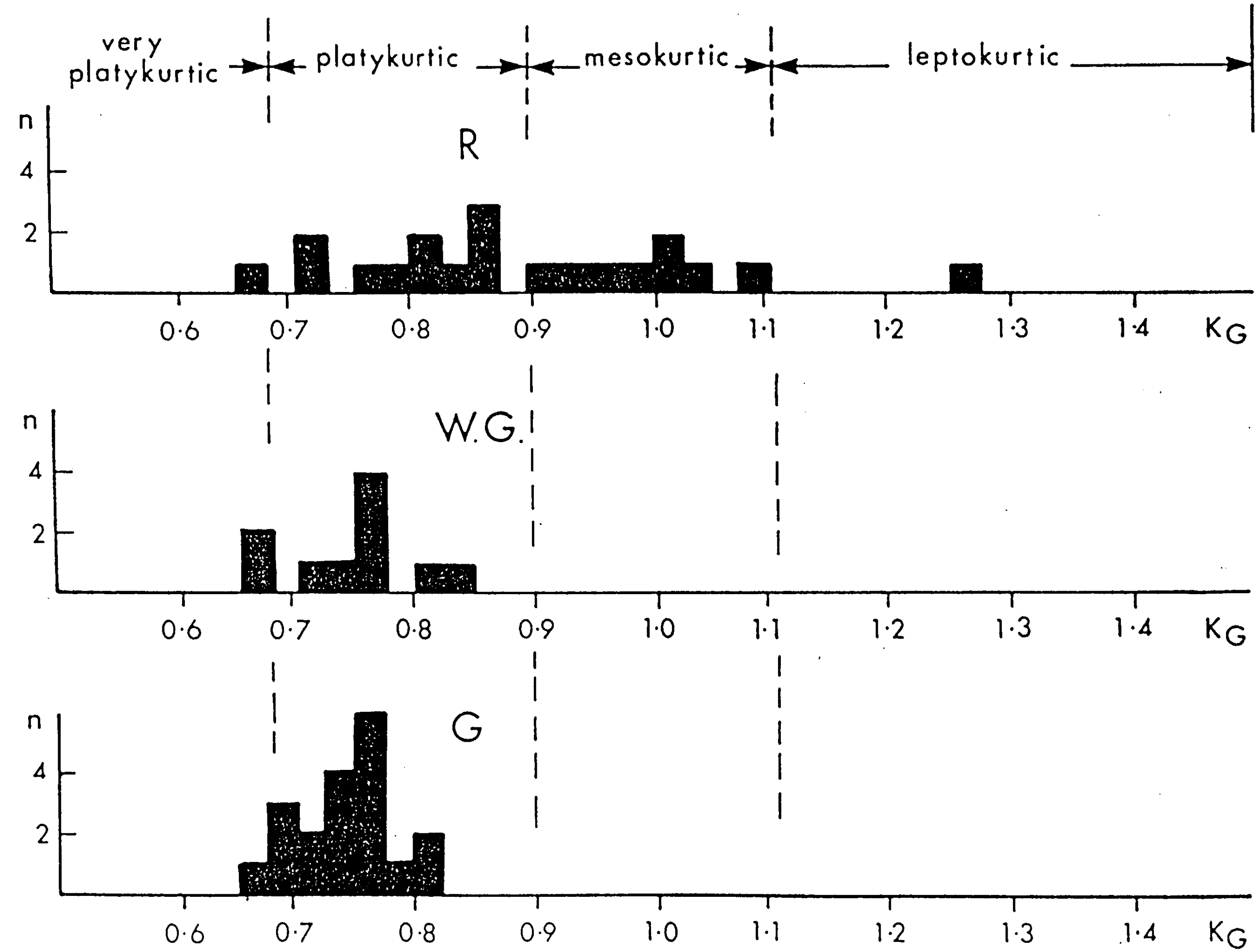


Figure 5.11 Histograms showing the distribution of K_G values for the three categories of till in the NW Glasgow area.

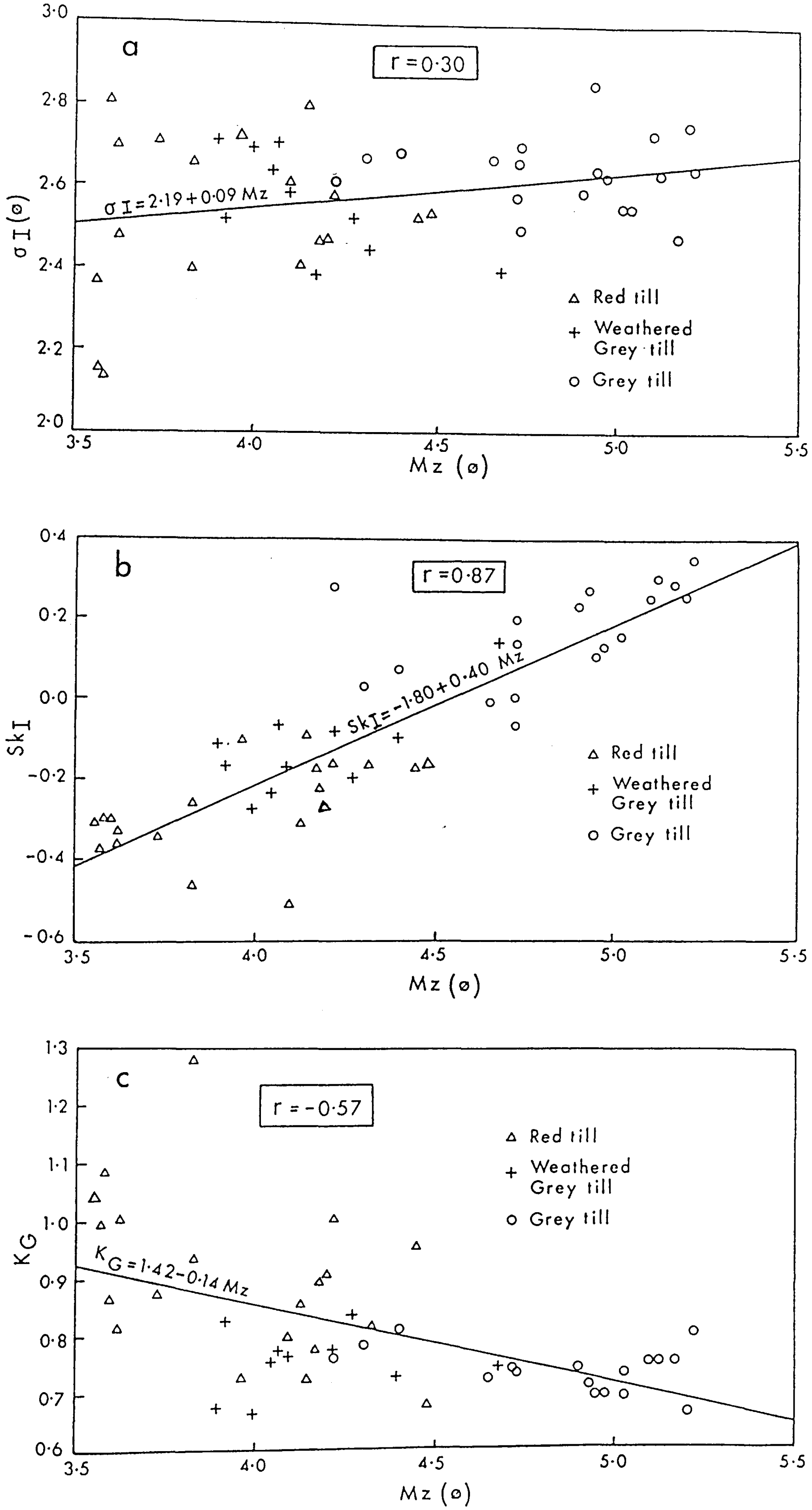


Figure 5.12 Till samples from the NW Glasgow area; scatter plots:
a: mean size (Mz) versus sorting (σ_I)
b: mean size (Mz) versus skewness (Sk_I)
c: mean size (Mz) versus kurtosis (K_G).

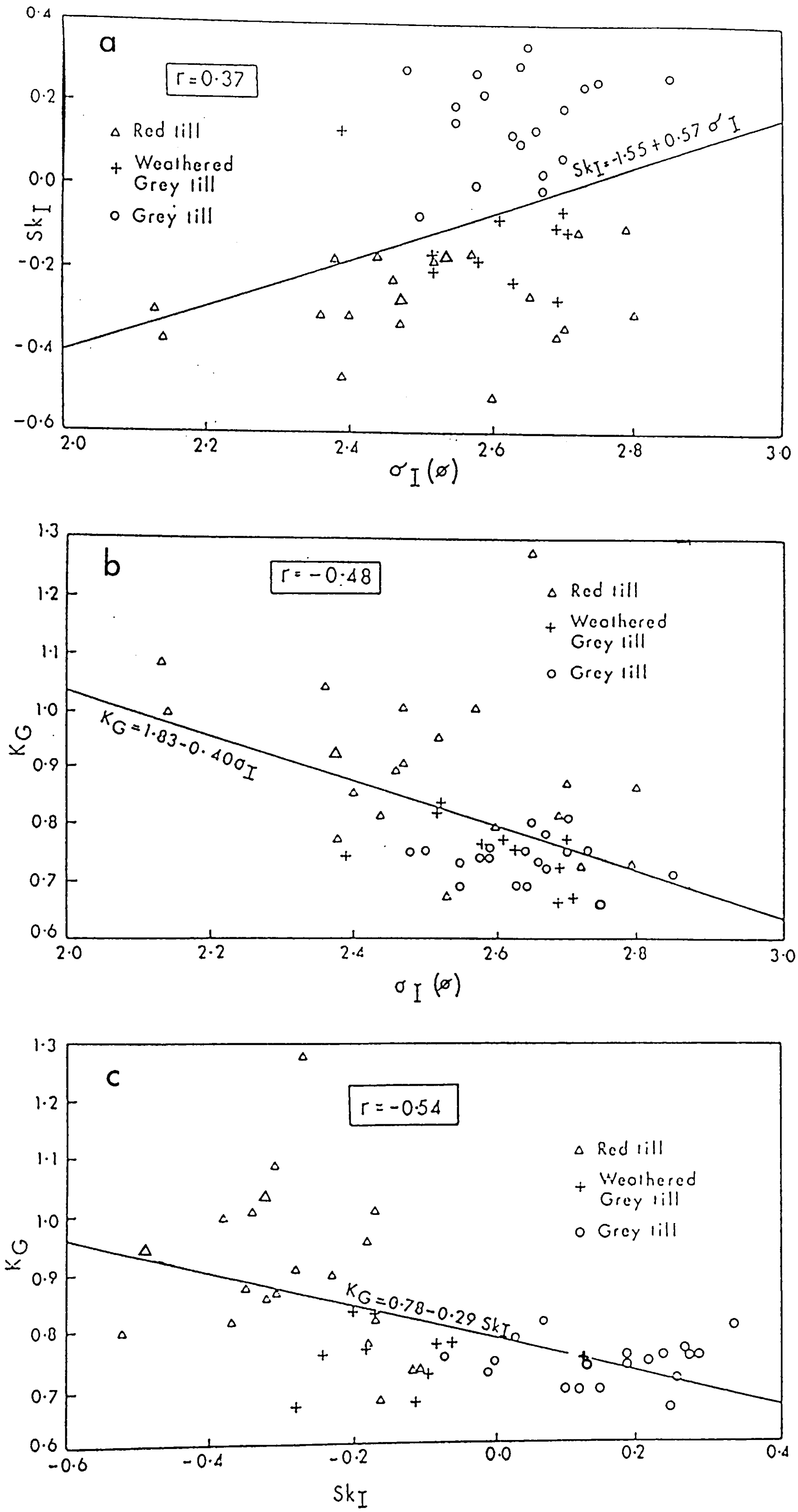


Figure 5.13 Till samples from the NW Glasgow area; scatter plots:
a: sorting (σ_I) versus skewness (Sk_I)
b: sorting (σ_I) versus kurtosis (K_G)
c: skewness (Sk_I) versus kurtosis (K_G).

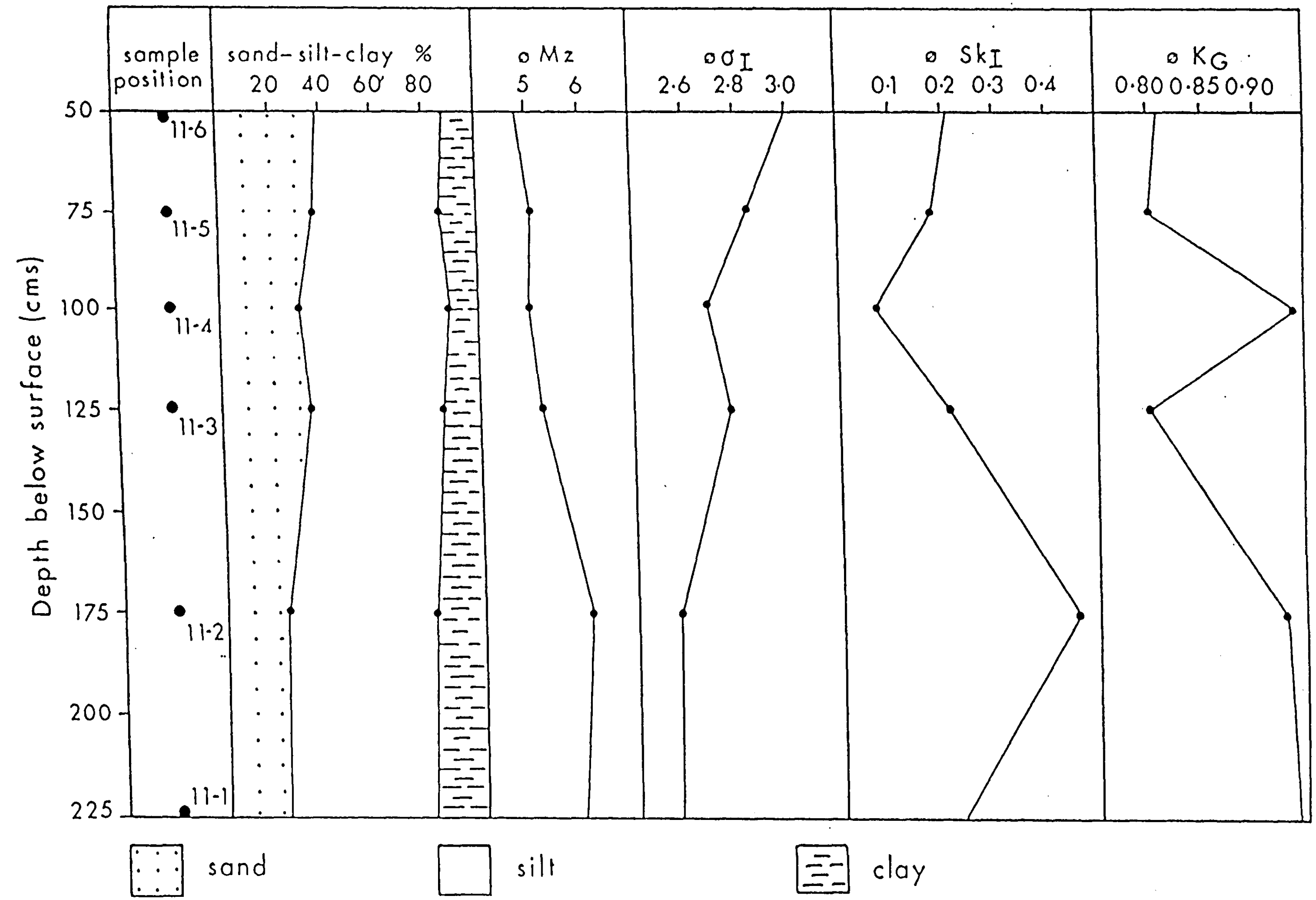


Figure 5.14 Vertical variation of sand-silt-clay percentages and grain-size parameters, Mz, σ_I, Sk_I and K_G, in Grey till profile at Queen Margaret Hall (NS 5633 6817).

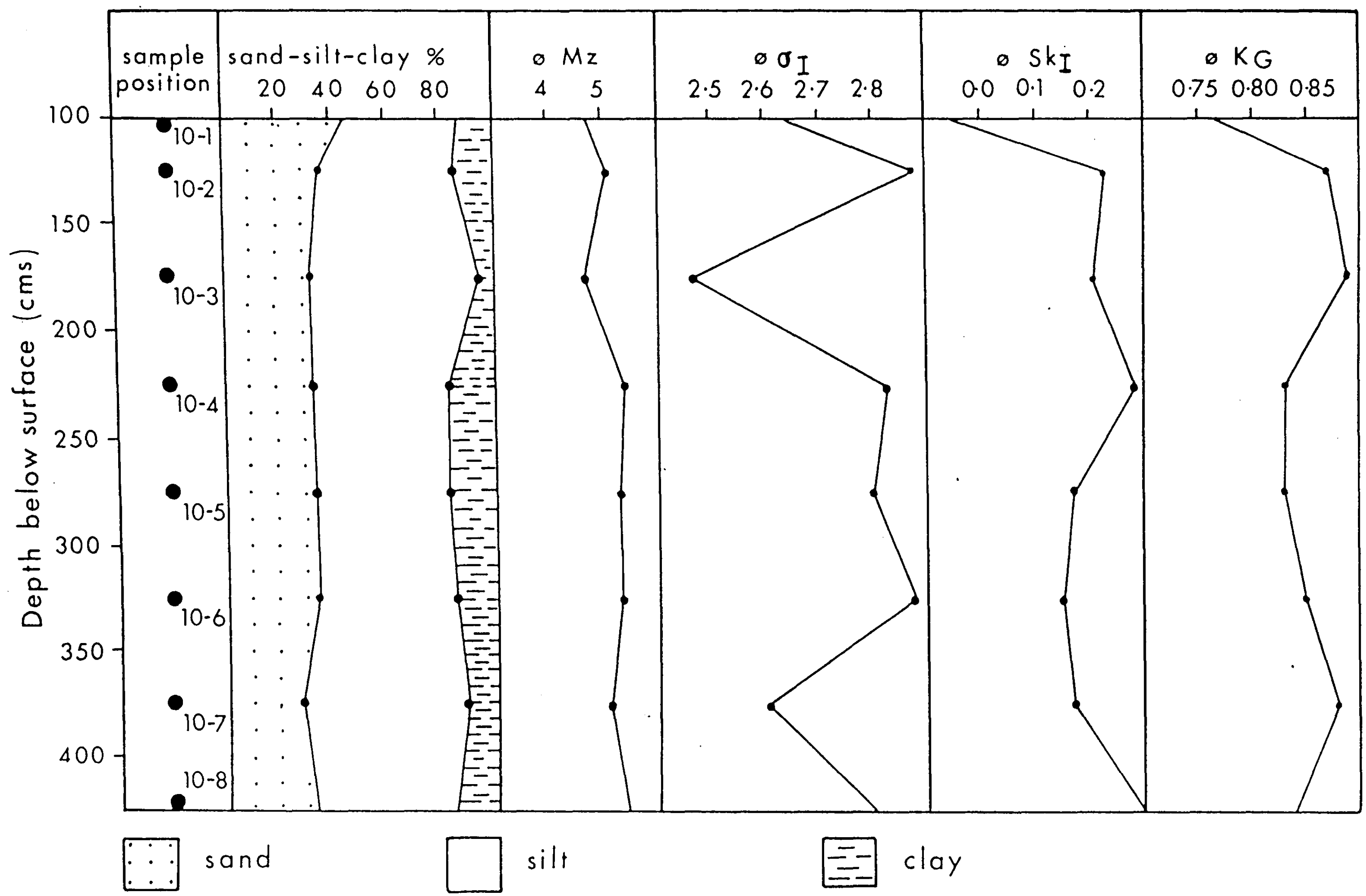


Figure 5.15 Vertical variation of sand-silt-clay percentages and grain-size parameters, Mz, σ_I, Sk_I and K_G, in Grey till profile at Kelvinside (NS 5581 6807).

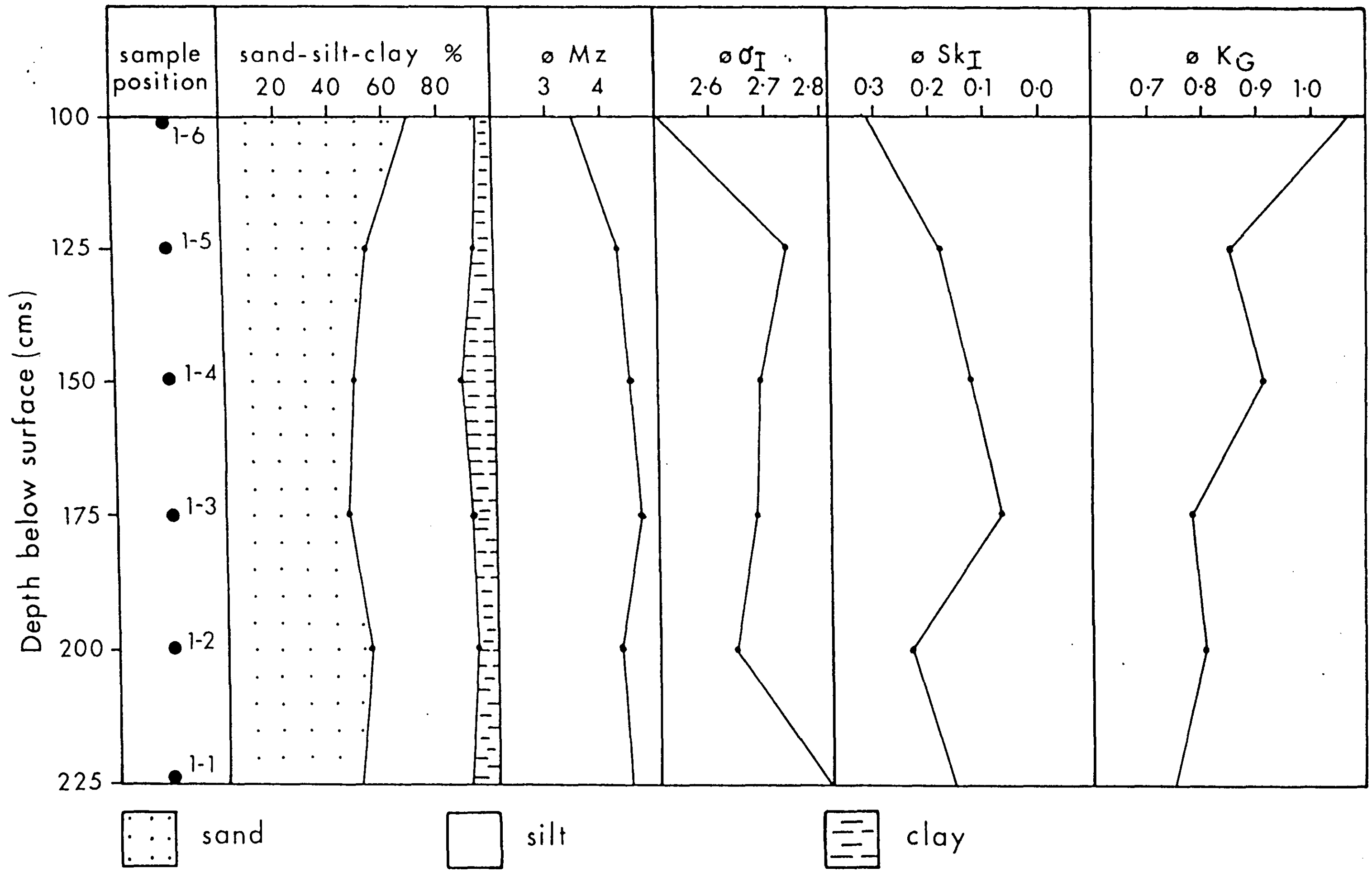


Figure 5.16 Vertical variation of sand-silt-clay percentages and grain-size parameters, Mz, σ_I, Sk_I and K_G, in Red till profile at Laighpark (NS 5360 7615).

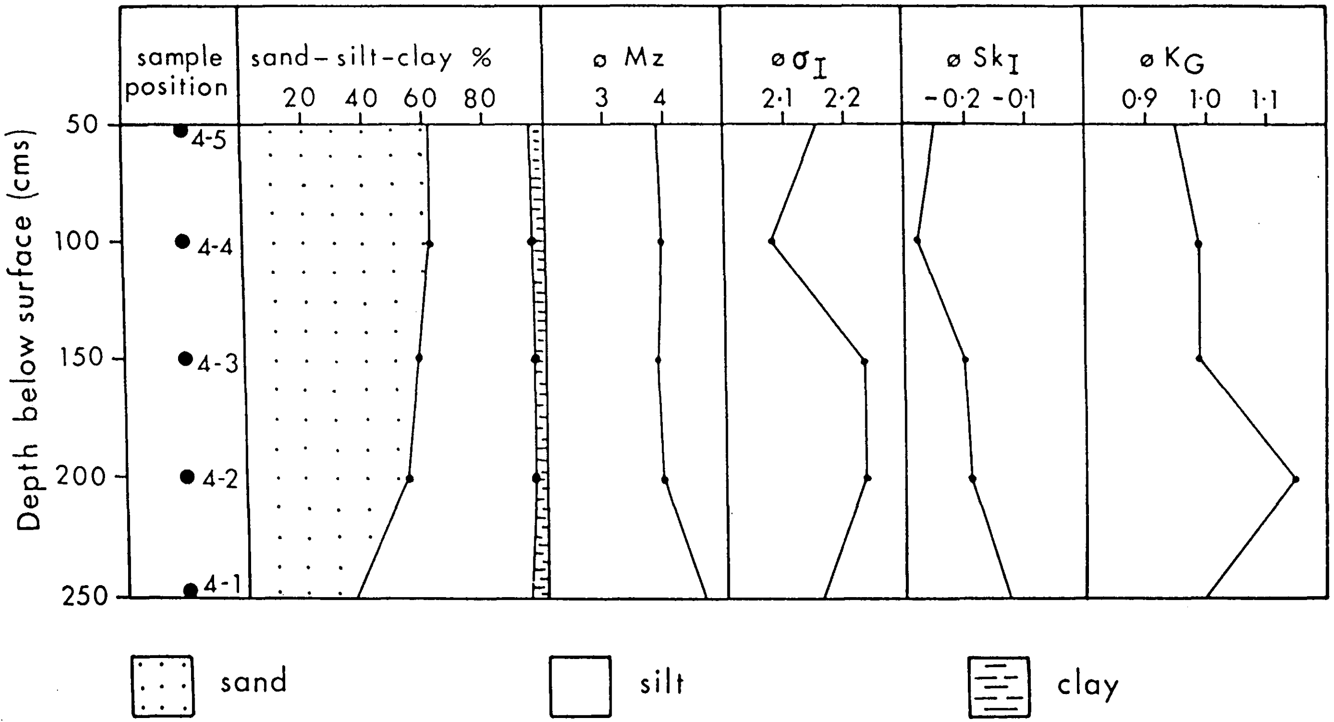


Figure 5.17 Vertical variation of sand-silt-clay percentages and grain-size parameters, Mz, σ_I, Sk_I and K_G, in Red till profile at Clober (NS 5460 7590).

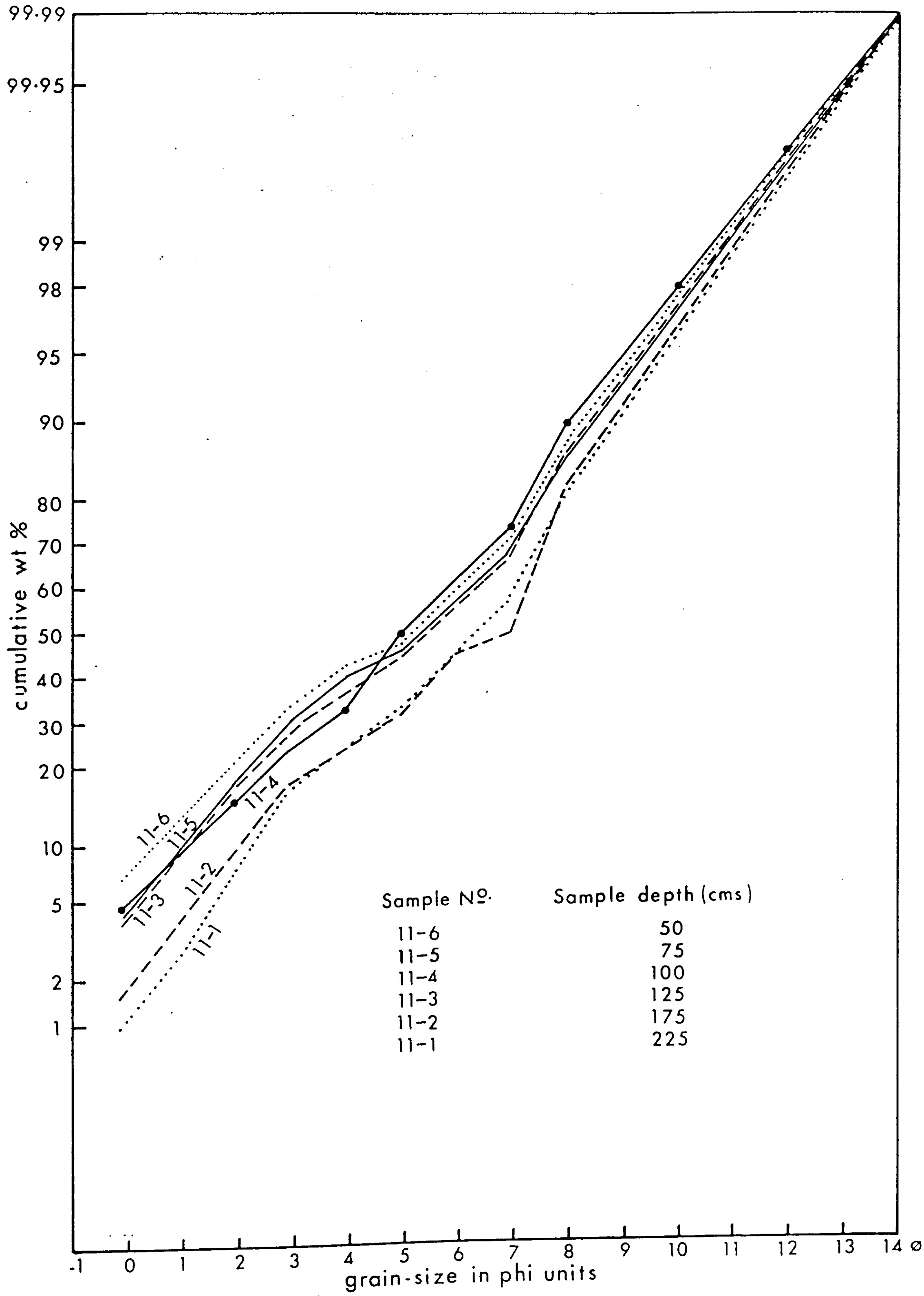


Figure 5.18 Cumulative frequency curves for till matrix (<2mm) through Grey till profile at Queen Margaret Hall (NS 5633 6817).

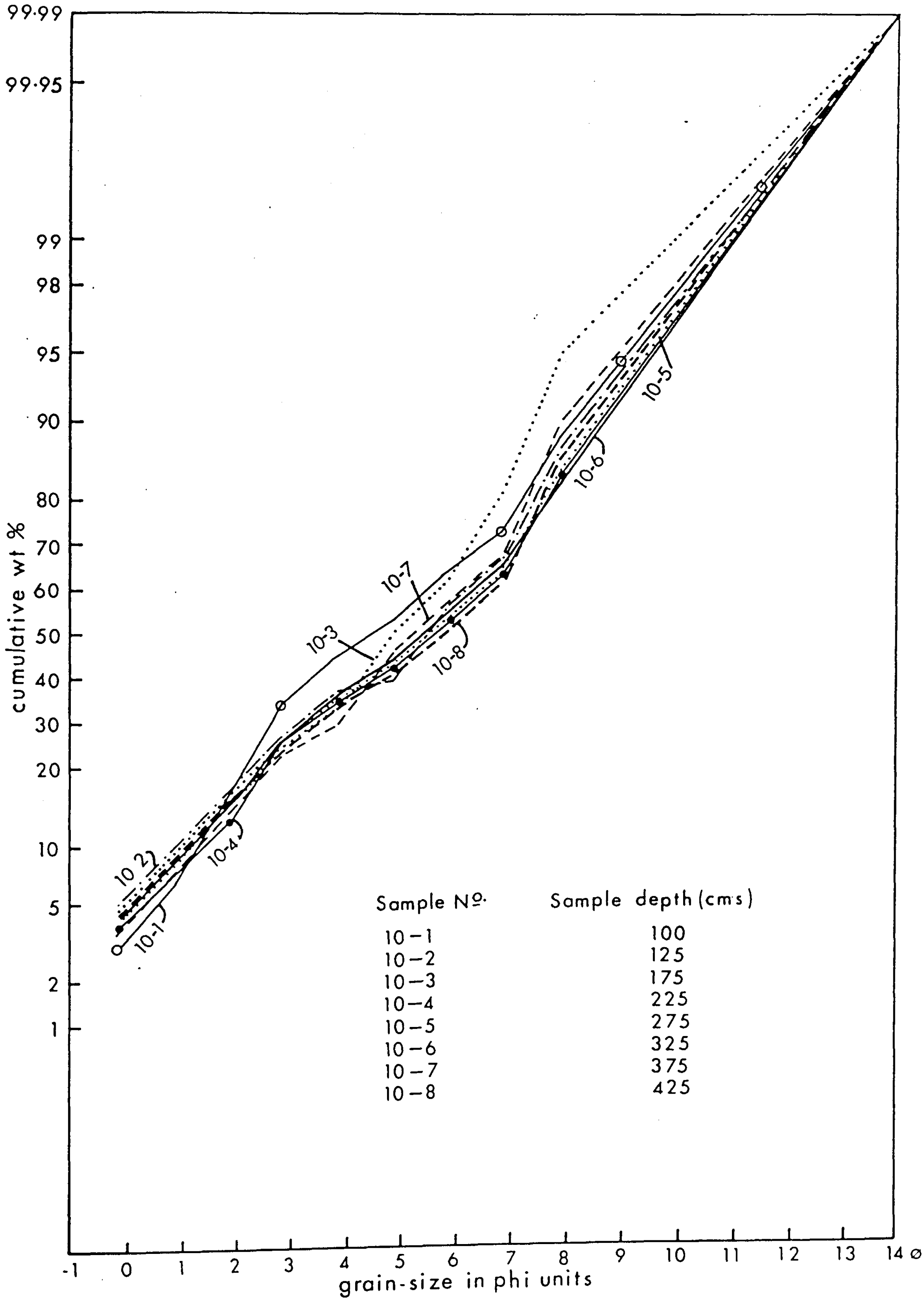


Figure 5.19 Cumulative frequency curves for till matrix (<2mm) through Grey till profile at Kelvinside (NS 5581 6807).

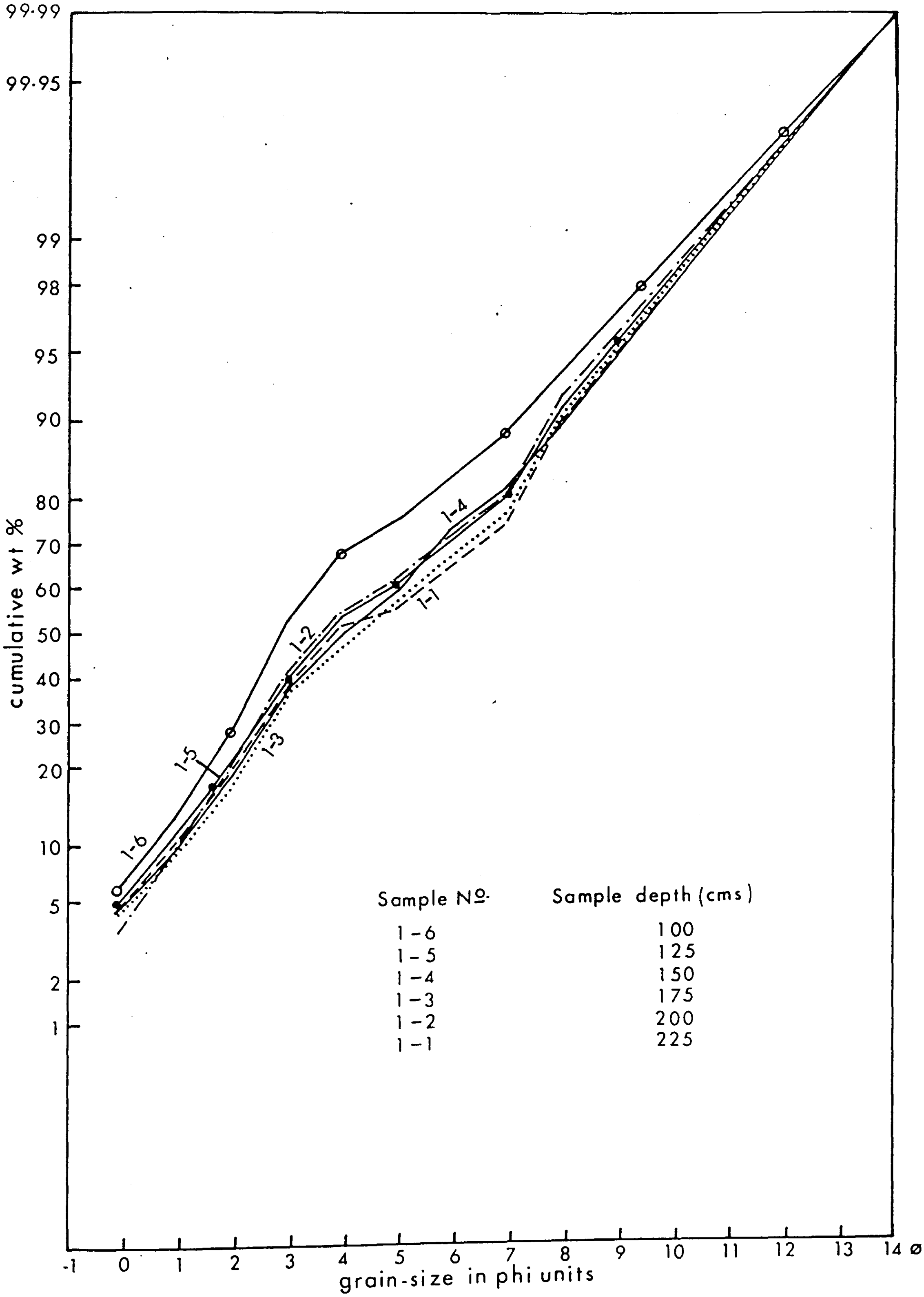


Figure 5.20 Cumulative frequency curves for till matrix (<2mm) through Red till profile at Laighpark (NS 5360 7615).

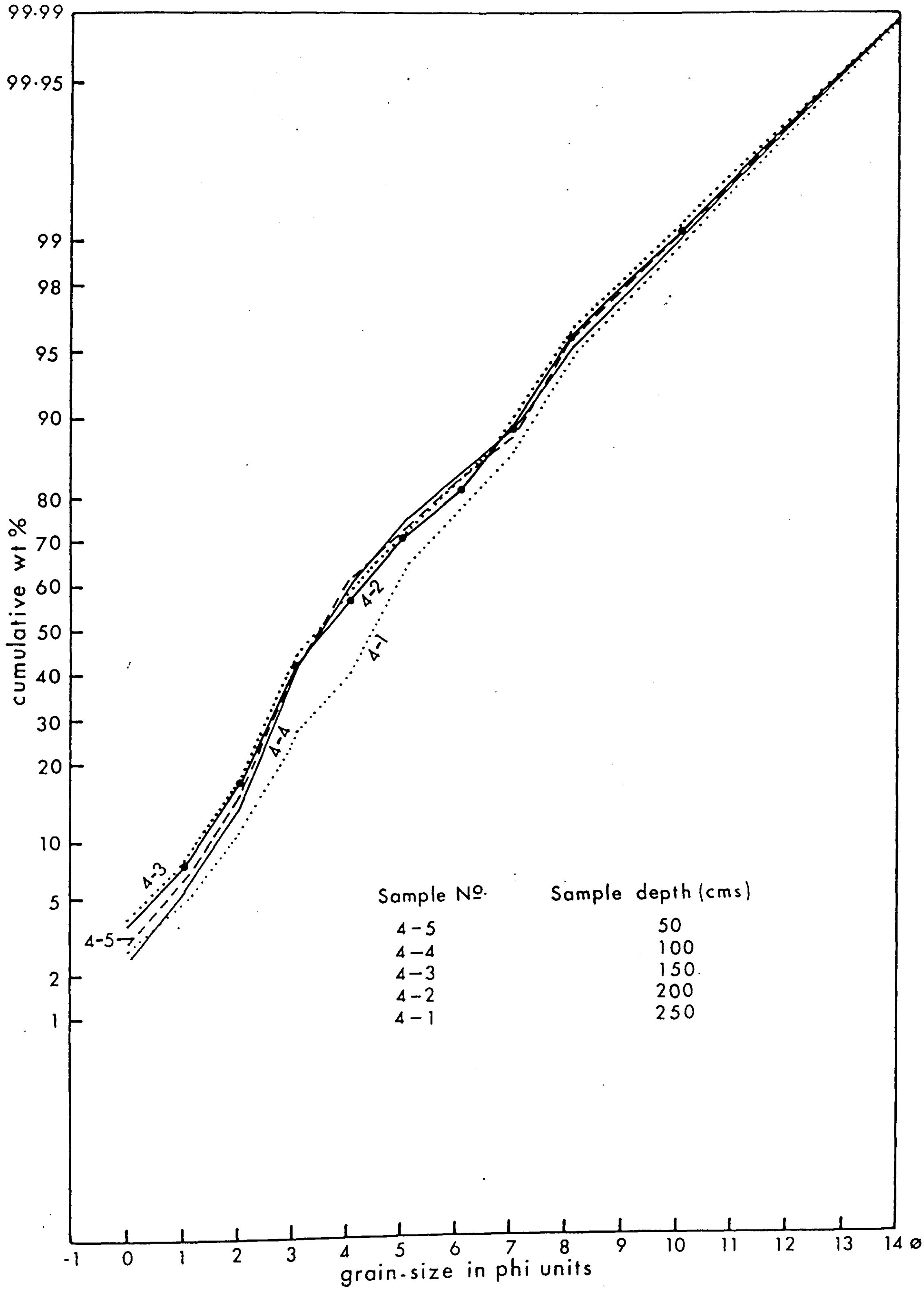


Figure 5.21 Cumulative frequency curves for till matrix (<2mm) through Red till profile at Clober (NS 5460 7590).

Table 5.1 Till samples from NW Glasgow area. Percentage by weight in each grade size. Grade sizes in phi units.

No.	Field No.	sand					silt				clay
		-1 – 0ϕ	0 – 1ϕ	1 – 2ϕ	2 – 3ϕ	3 – 4ϕ	4 – 5ϕ	5 – 6ϕ	6 – 7ϕ	7 – 8ϕ	>8ϕ
	Red till										
1	R 1	6.77	9.49	13.89	23.17	16.77	0.92	5.96	6.34	11.19	5.50
2	2	5.02	9.41	14.75	22.94	17.48	1.84	5.54	6.00	11.02	6.00
3	4	4.88	11.10	16.17	23.63	12.82	1.65	7.72	6.12	10.56	5.34
4	8	4.93	9.59	10.63	15.92	10.87	8.03	9.26	9.07	12.21	9.48
5	16	2.39	3.95	13.10	18.21	16.75	6.96	10.31	12.86	10.21	5.26
6	30	5.17	7.67	13.52	20.64	15.50	4.12	9.77	7.82	8.82	6.97
7	31	1.93	5.14	13.24	26.82	22.61	5.51	9.07	5.21	6.01	4.46
8	32	4.08	5.69	14.55	26.25	17.44	5.86	9.01	5.32	6.62	5.18
9	34	2.69	4.18	10.55	18.77	14.12	7.32	10.06	8.89	13.96	9.45
10	35	3.80	4.92	12.65	16.65	15.11	7.79	10.70	9.46	10.86	8.06
11	37	2.73	4.01	10.05	17.27	16.76	9.68	11.11	10.34	10.46	7.59
12	39	3.53	4.76	10.29	18.06	16.15	12.47	10.37	7.61	9.74	7.01
13	41	2.29	3.58	13.04	14.41	16.16	8.63	5.36	10.43	16.62	9.48
14	42	2.85	4.14	10.84	20.98	16.25	10.75	10.36	6.73	9.57	7.53
15	43	2.74	13.99	13.09	11.66	12.51	8.31	9.93	11.81	8.82	7.14
16	44	3.20	8.82	13.00	13.18	13.80	6.77	14.86	10.80	8.57	8.00
17	45	1.65	3.83	16.82	28.61	15.81	5.41	7.37	4.83	8.36	7.31

Table 5.1 (continued)

No.	Field No.	sand					silt				clay
		-1 - 0ϕ	0 - 1ϕ	1 - 2ϕ	2 - 3ϕ	3 - 4ϕ	4 - 5ϕ	5 - 6ϕ	6 - 7ϕ	7 - 8ϕ	>8ϕ
	Red till										
18	R 47	1.68	3.46	13.71	24.10	14.61	9.69	10.14	6.50	7.92	8.18
19	48	4.95	7.53	16.13	25.13	14.00	7.48	5.43	7.78	7.26	4.30
20	49	2.60	2.39	16.38	27.35	14.47	10.33	8.43	7.73	5.14	3.99
	Weathered Grey till										
21	WG 6	4.87	8.61	13.31	21.64	5.09	3.09	9.98	9.15	17.39	6.83
22	7	4.96	7.61	9.84	15.63	12.76	4.69	11.66	14.27	13.24	5.34
23	12	4.95	11.53	10.26	15.05	12.43	5.29	8.58	12.71	16.34	2.86
24	13	3.49	9.53	11.98	15.03	15.01	8.00	10.16	12.54	8.58	4.68
25	14	4.02	7.21	11.71	15.14	12.60	9.47	11.03	10.08	13.89	5.85
26	15	4.10	5.41	14.32	15.99	16.03	6.20	8.45	10.11	11.98	6.41
27	17	2.41	4.45	8.56	15.58	13.04	7.49	14.14	13.51	15.43	5.38
28	28	4.67	6.45	11.60	21.02	15.08	2.52	8.43	9.45	15.09	5.68
29	29	3.80	6.92	11.36	15.72	11.56	7.09	11.88	8.01	16.99	6.67
30	33	3.39	4.20	11.74	15.59	19.82	7.23	10.57	9.76	10.60	7.10
	Grey till										
31	G 3	4.95	7.49	9.74	10.56	11.12	12.92	14.20	10.56	9.15	9.31
32	5	5.07	9.19	5.31	17.38	12.40	1.02	12.53	19.95	9.79	8.36

Table 5.1 (continued)

No.	Field No.	sand					silt				clay
		-1 - 0ϕ	0 - 1ϕ	1 - 2ϕ	2 - 3ϕ	3 - 4ϕ	4 - 5ϕ	5 - 6ϕ	6 - 7ϕ	7 - 8ϕ	>8ϕ
	Grey till										
33	G 9	4.42	5.56	10.61	10.35	9.99	8.53	11.18	16.56	11.14	11.66
34	10	4.34	4.37	7.61	13.63	9.49	4.48	12.21	10.00	19.67	13.99
35	11	4.25	4.84	8.13	15.70	14.23	5.40	10.86	12.12	14.36	10.11
36	18	3.55	4.22	8.56	14.28	11.26	6.90	11.23	10.31	16.52	13.17
37	19	3.12	4.35	6.82	15.03	12.33	4.89	13.22	11.69	16.83	11.72
38	20	4.20	4.67	8.95	15.78	10.62	10.48	8.67	11.44	14.16	11.03
39	21	3.70	3.62	6.52	11.89	9.24	5.91	15.65	15.44	16.13	11.89
40	22	4.32	4.09	6.76	11.97	10.70	3.71	15.25	13.61	17.53	12.06
41	23	3.40	4.45	8.12	15.26	12.53	3.44	12.03	10.37	18.55	12.05
42	24	3.20	3.48	6.37	11.54	10.83	3.02	18.80	12.60	19.30	10.86
43	25	4.73	4.89	6.24	15.46	11.88	4.04	15.12	11.92	16.48	9.24
44	26	2.40	3.75	8.28	17.55	14.93	6.32	10.50	13.60	10.52	12.15
45	27	4.34	4.22	6.35	10.27	8.60	4.22	14.62	20.53	14.72	12.13
46	36	4.20	5.18	9.38	10.69	13.86	7.21	13.05	10.17	16.81	9.45
47	38	3.83	3.73	8.48	15.38	12.65	8.94	11.77	8.90	16.23	10.09
48	40	3.22	4.05	7.65	12.73	11.19	8.82	10.56	8.50	22.49	10.79
49	50	4.86	7.54	7.50	10.17	8.10	7.47	12.22	11.65	17.03	13.57

Table 5.1 (continued)

No.	Field No.	sand					silt				clay
		-1 – 0ø	0 – 1ø	1 – 2ø	2 – 3ø	3 – 4ø	4 – 5ø	5 – 6ø	6 – 7ø	7 – 8ø	>8ø
	Queen Margaret Hall, Grey till profile										
50	11 – 6	6.82	5.93	7.73	11.16	8.24	5.93	12.51	12.17	16.96	12.55
51	11 – 5	4.33	4.44	8.50	11.75	9.25	5.71	11.25	12.72	18.04	14.01
52	11 – 4	4.24	4.47	5.62	8.87	7.68	17.15	12.96	11.80	16.32	10.89
53	11 – 3	3.59	4.97	7.49	10.35	7.84	8.50	11.65	12.21	19.42	13.98
54	11 – 2	1.37	2.06	4.96	8.56	6.79	5.91	13.94	5.24	32.10	19.07
55	11 – 1	0.83	1.48	4.18	9.52	7.84	6.71	13.26	13.30	22.52	20.36
	Kelvinside, Grey till profile										
56	10 – 1	2.87	3.52	8.82	17.19	11.74	8.76	11.02	8.32	16.14	11.62
57	10 – 2	5.00	4.96	6.78	10.37	8.55	2.23	18.58	11.45	18.29	13.79
58	10 – 3	4.71	4.63	6.06	9.09	7.55	17.51	13.17	18.19	14.34	4.75
59	10 – 4	3.86	3.97	4.68	10.27	10.31	7.59	12.01	11.43	19.17	16.71
60	10 – 5	3.87	3.93	5.06	11.45	10.79	7.12	11.65	10.45	18.80	16.88
61	10 – 6	4.08	3.84	6.40	11.37	9.19	8.12	10.53	11.46	18.20	16.81
62	10 – 7	3.83	4.02	5.48	8.33	7.14	18.56	9.66	10.87	21.64	10.47
63	10 – 8	4.41	4.03	5.90	9.55	8.66	5.87	11.68	13.04	21.78	15.08

Table 5.1 (continued)

No.	Field No.	sand					silt				clay
		-1 - 0ϕ	0 - 1ϕ	1 - 2ϕ	2 - 3ϕ	3 - 4ϕ	4 - 5ϕ	5 - 6ϕ	6 - 7ϕ	7 - 8ϕ	>8ϕ
	Laighpark, Red till profile										
64	1 - 6	5.96	6.93	13.34	25.64	17.03	5.24	7.89	6.18	5.91	5.88
65	1 - 5	4.76	5.62	9.62	18.76	14.97	6.81	10.21	8.21	13.31	7.73
66	1 - 4	4.43	5.09	8.99	16.69	13.04	10.54	12.61	7.98	9.95	10.68
67	1 - 3	4.24	4.52	8.09	15.78	13.12	10.62	10.31	8.31	15.31	9.70
68	1 - 2	3.31	5.02	11.35	19.82	14.36	8.17	9.15	7.52	13.17	8.13
69	1 - 1	4.66	5.27	19.54	17.37	13.48	4.32	10.91	8.00	16.29	10.16
	Clober, Red till profile										
70	4 - 5	2.70	3.41	8.98	25.94	20.49	12.29	8.27	5.92	7.94	4.06
71	4 - 4	2.08	3.06	8.45	27.35	20.16	13.09	8.40	5.85	7.42	4.14
72	4 - 3	3.73	4.05	9.85	24.37	16.80	12.95	8.63	6.61	9.27	3.74
73	4 - 2	3.55	3.72	9.53	24.05	16.61	12.75	9.65	7.11	9.11	3.91
74	4 - 1	2.44	2.28	5.55	15.55	12.57	26.01	11.15	8.94	10.27	5.24

Table 5.2 Till samples from NW Glasgow area. Values of range, mean ($\overline{X}$) and standard deviation (S) of sand-silt-clay percentages in the three till categories, Red, Weathered Grey and Grey.

Till category		sand	silt	clay
Red till	range	49.48 - 70.09	24.40 - 43.26	3.99 - 9.48
	$\overline{X}$	59.38	34.24	6.81
N = 20	S	7.67	6.79	1.69
Weathered Grey till	range	49.36 - 58.82	35.50 - 45.58	2.86 - 7.10
	$\overline{X}$	53.31	41.11	5.68
N = 10	S	3.24	3.28	1.18
Grey till	range	33.78 - 49.35	42.29 - 54.09	8.36 - 13.99
	$\overline{X}$	41.50	47.26	11.24
N = 19	S	4.16	3.62	1.49

Table 5.3 Till samples from NW Glasgow area. Sand-silt-clay percentages and grain-size parameters of matrix.

No.	Field No.	% sand	% silt	% clay	Mz	σ_I	Sk_I	K_G
	Red till							
1	R 1	70.09	24.41	5.50	3.60	2.80	-0.31	0.86
2	2	69.60	24.40	6.00	3.73	2.70	-0.35	0.87
3	4	68.60	26.06	5.34	3.62	2.69	-0.37	0.81
4	8	51.94	38.58	9.48	4.15	2.79	-0.10	0.72
5	16	54.40	40.34	5.26	4.17	2.38	-0.18	0.77
6	30	62.50	30.53	6.97	3.83	2.65	-0.27	1.27
7	31	69.74	25.80	4.46	3.58	2.13	-0.31	1.08
8	32	68.01	26.81	5.18	3.56	2.36	-0.32	1.04
9	34	50.31	40.24	9.45	4.45	2.52	-0.18	0.95
10	35	53.13	38.81	8.06	4.22	2.57	-0.17	1.00
11	37	50.82	41.59	7.59	4.32	2.44	-0.17	0.81
12	39	52.79	40.20	7.01	4.20	2.47	-0.28	0.90
13	41	49.48	41.04	9.48	4.48	2.53	-0.16	0.67
14	42	55.06	37.41	7.53	4.18	2.46	-0.23	0.89
15	43	53.99	38.87	7.14	3.97	2.72	-0.11	0.72
16	44	51.00	41.00	8.00	4.10	2.60	-0.52	0.79
17	45	66.72	25.97	7.31	3.83	2.39	-0.47	0.93
18	47	57.56	43.26	8.18	4.13	2.40	-0.32	0.85
19	48	67.47	27.95	4.30	3.62	2.47	-0.34	1.00
20	49	64.38	31.63	3.99	3.57	2.14	-0.38	0.99
	Weathered Grey till							
21	WG 6	53.52	39.65	6.83	4.00	2.69	-0.28	0.66
22	7	50.80	43.86	5.34	4.07	2.70	-0.06	0.77
23	12	54.22	42.92	2.86	3.90	2.71	-0.11	0.67
24	13	56.04	39.28	4.68	3.92	2.52	-0.17	0.82
25	14	50.68	44.47	5.85	4.22	2.61	-0.08	0.77
26	15	55.85	37.74	6.41	4.10	2.58	-0.18	0.76
27	17	49.04	45.58	5.38	4.68	2.39	0.13	0.74
28	28	58.82	35.50	5.68	4.05	2.63	-0.24	0.75
29	29	49.36	43.97	6.97	4.40	2.69	-0.10	0.72
30	33	54.74	38.16	7.10	4.27	2.52	-0.20	0.83
	Grey till							
31	G 3	43.86	46.83	9.31	4.40	2.70	0.07	0.81
32	5	49.35	42.29	8.36	4.30	2.67	0.03	0.78

Table 5.3 (continued)

No.	Field No.	% sand	% silt	% clay	Mz	σ_I	Sk_I	K_G
	Grey till							
33	G 9	40.93	47.41	11.66	4.73	2.70	0.19	0.75
34	10	39.44	46.75	13.99	5.10	2.73	0.24	0.75
35	11	47.15	42.71	10.11	5.20	2.75	0.25	0.66
36	18	41.87	44.96	13.17	4.95	2.64	0.10	0.69
37	19	41.65	46.63	11.72	5.03	2.55	0.19	0.73
38	20	44.22	44.75	11.03	4.65	2.67	-0.01	0.72
39	21	34.97	53.11	11.89	4.22	2.58	0.27	0.76
40	22	37.84	50.10	12.06	5.12	2.64	0.29	0.75
41	23	43.56	44.39	12.05	4.97	2.63	0.12	0.69
42	24	35.42	53.72	10.86	5.17	2.48	0.28	0.75
43	25	43.20	47.56	9.24	4.90	2.59	0.22	0.74
44	26	46.91	40.94	12.15	4.73	2.50	-0.07	0.75
45	27	33.78	54.09	12.13	5.22	2.65	0.34	0.80
46	36	43.31	47.24	9.45	4.73	2.66	0.13	0.73
47	38	44.04	45.84	10.09	4.72	2.58	0.00	0.74
48	40	38.84	50.37	10.79	5.02	2.55	0.15	0.69
49	50	38.17	48.26	13.57	4.93	2.85	0.26	0.71
	Queen Margaret Hall, Grey till profile							
50	11 - 6	39.88	47.57	12.55	4.80	3.00	0.21	0.81
51	11 - 5	38.27	47.72	14.01	5.00	2.86	0.18	0.80
52	11 - 4	30.88	58.23	10.89	4.96	2.68	0.07	0.94
53	11 - 3	34.24	51.78	13.98	5.13	2.78	0.21	0.80
54	11 - 2	23.74	57.19	19.07	6.03	2.57	0.46	0.93
55	11 - 1	23.85	55.79	20.36	5.87	2.56	0.23	0.94
	Kelvinside, Grey till profile							
56	10 - 1	44.14	44.24	11.62	4.80	2.65	-0.05	0.77
57	10 - 2	35.66	50.55	13.79	5.10	2.88	0.23	0.87
58	10 - 3	32.04	63.21	4.75	4.70	2.47	0.21	0.89
59	10 - 4	33.09	50.02	16.71	5.40	2.83	0.29	0.83
60	10 - 5	35.10	48.02	16.88	5.33	2.80	0.17	0.83
61	10 - 6	34.88	48.23	16.81	5.30	2.88	0.15	0.85
62	10 - 7	28.80	60.73	10.47	5.10	2.60	0.17	0.88
63	10 - 8	32.55	52.37	15.08	5.37	2.80	0.30	0.84

Table 5.3 (continued)

No.	Field No.	% sand	% silt	% clay	Mz	σ_I	Sk_I	K_G
	Laighpark, Red till profile							
64	1 - 6	68.90	25.22	5.88	3.50	2.50	-0.31	1.06
65	1 - 5	53.73	38.54	7.73	4.23	2.74	-0.18	0.85
66	1 - 4	48.24	41.08	10.68	4.40	2.69	-0.13	0.91
67	1 - 3	45.75	44.55	9.70	4.63	2.68	-0.07	0.78
68	1 - 2	53.86	38.01	8.13	4.23	2.64	-0.23	0.80
69	1 - 1	50.32	39.52	10.16	4.43	2.81	-0.16	0.75
	Clober, Red till profile							
70	4 - 5	61.52	34.42	4.06	3.93	2.15	-0.25	0.95
71	4 - 4	61.10	34.76	4.14	3.93	2.08	-0.28	0.99
72	4 - 3	58.80	37.46	3.74	3.86	2.23	-0.20	0.99
73	4 - 2	57.46	38.63	3.91	3.97	2.23	-0.19	1.15
74	4 - 1	38.39	56.37	5.24	4.57	2.16	-0.13	1.00

Table 5.4 Till samples from NW Glasgow area. The seven phi percentiles derived from grain-size analysis.

No.	Field No.	ϕ 5	ϕ 16	ϕ 25	ϕ 50	ϕ 75	ϕ 84	ϕ 95
	Red till							
1	R 1	-0.30	0.90	1.60	2.85	5.60	7.05	8.05
2	2	0.00	1.20	1.80	2.90	5.60	7.10	8.10
3	4	0.10	1.05	1.60	2.80	5.60	7.00	8.05
4	8	0.00	1.20	1.95	3.85	6.65	7.40	8.20
5	16	0.70	1.80	2.30	3.80	6.20	6.90	8.00
6	30	0.00	1.30	1.90	3.20	4.50	7.00	8.10
7	31	0.70	1.70	2.20	3.15	4.90	5.90	7.80
8	32	0.20	1.50	2.00	3.00	5.10	6.20	8.05
9	34	0.70	1.90	2.45	4.00	5.70	7.45	8.20
10	35	0.35	1.65	2.20	3.80	5.40	7.20	8.15
11	37	0.70	1.90	2.50	3.95	6.30	7.10	8.20
12	39	0.40	1.80	2.40	3.80	5.90	7.00	8.10
13	41	0.85	1.85	2.50	4.10	7.05	7.50	8.25
14	42	0.60	1.80	2.35	3.70	5.80	7.05	8.15
15	43	0.30	1.00	1.70	3.80	6.20	7.10	8.20
16	44	0.30	1.40	2.10	3.90	6.20	7.00	8.20
17	45	0.90	1.70	2.10	2.95	5.30	6.85	8.15
18	47	1.00	1.85	2.30	3.50	5.80	7.05	8.25
19	48	0.05	1.30	1.80	2.85	5.00	6.40	7.85
20	49	0.75	1.70	2.10	3.00	5.00	6.00	7.75
	Weathered Grey till							
21	WG 6	0.10	1.40	1.90	3.30	6.90	7.30	8.10
22	7	0.00	1.20	2.20	3.90	6.50	7.10	8.05
23	12	0.05	0.95	1.80	3.60	6.50	7.15	7.70
24	13	0.25	1.40	2.20	3.55	6.05	6.80	7.95
25	14	0.20	1.50	2.20	4.00	6.40	7.15	8.10
26	15	0.20	1.55	2.05	3.65	6.30	7.10	8.10
27	17	0.70	2.05	2.65	4.80	6.70	7.20	8.00
28	28	0.10	1.50	2.15	3.45	6.50	7.20	8.05
29	29	0.30	1.60	2.25	4.16	6.80	7.50	8.30
30	33	0.50	1.80	2.40	3.80	6.20	7.20	8.20

Table 5.4 (continued)

No.	Field No.	ø 5	ø 16	ø 25	ø 50	ø 75	ø 84	ø 95
	Grey till							
31	G 3	0.10	1.40	2.30	4.50	6.40	7.30	8.20
32	5	0.00	1.40	2.35	4.30	6.60	7.20	8.10
33	9	0.20	1.60	2.40	5.10	6.80	7.50	8.30
34	10	0.30	1.90	2.70	5.50	7.40	7.90	8.40
35	11	0.40	1.80	2.50	5.50	7.50	7.90	8.30
36	18	0.45	2.00	2.60	5.00	7.25	7.85	8.20
37	19	0.55	2.15	2.80	5.30	7.15	7.65	8.30
38	20	0.25	1.80	2.50	4.50	7.00	7.65	8.20
39	21	0.35	2.25	2.95	5.60	7.20	7.80	8.20
40	22	0.20	2.05	2.85	5.60	7.30	7.70	8.30
41	23	0.50	2.00	2.65	5.10	7.30	7.80	8.30
42	24	0.60	2.30	3.05	5.60	7.20	7.60	8.20
43	25	0.10	2.00	2.65	5.20	7.10	7.50	8.15
44	26	0.80	2.10	2.75	4.50	6.80	7.60	8.25
45	27	0.25	2.10	3.00	5.80	7.20	7.75	8.40
46	36	0.20	1.75	2.60	4.90	7.10	7.55	8.20
47	38	0.40	2.00	2.60	4.60	7.00	7.55	8.30
48	40	0.55	2.15	2.80	5.20	7.35	7.70	8.25
49	50	0.10	1.50	2.45	5.45	7.30	7.85	8.45
	Queen Margaret Hall, Grey till profile							
50	11 - 6	1.70	2.90	4.20	6.40	7.70	8.30	9.70
51	11 - 5	1.40	2.90	4.20	7.00	7.80	8.20	9.60
52	11 - 4	0.40	2.00	2.80	5.60	7.30	7.80	9.20
53	11 - 3	0.20	2.20	3.30	5.10	7.10	7.60	9.00
54	11 - 2	0.30	1.90	2.70	5.50	7.30	7.90	9.30
55	11 - 1	0.30	1.40	2.40	5.30	7.20	7.70	9.20
	Kelvinside, Grey till profile							
56	10 - 1	0.70	2.10	2.60	4.70	7.10	7.60	9.10
57	10 - 2	0.00	1.90	2.90	5.60	7.30	7.80	9.30
58	10 - 3	0.10	2.00	3.00	5.00	6.60	7.10	8.00
59	10 - 4	0.40	2.30	3.00	5.80	7.50	8.10	9.50
60	10 - 5	0.40	2.30	3.00	5.70	7.50	8.00	9.50
61	10 - 6	0.30	2.20	3.00	5.60	7.50	8.10	9.60
62	10 - 7	0.50	2.30	3.30	5.40	7.20	7.60	8.90
63	10 - 8	0.20	2.20	3.10	6.00	7.50	7.90	9.30

Table 5.4 (continued)

No.	Field No.	ø 5	ø 16	ø 25	ø 50	ø 75	ø 84	ø 95
	Laighpark, Red till profile							
64	1 - 6	0.10	1.70	2.30	4.00	7.10	7.60	8.90
65	1 - 5	0.40	1.70	2.30	3.70	6.50	7.30	8.60
66	1 - 4	0.20	2.00	2.50	4.40	7.00	7.50	8.80
67	1 - 3	0.20	1.80	2.40	4.10	6.30	7.30	8.90
68	1 - 2	0.10	1.60	2.30	3.80	6.50	7.30	8.80
69	1 - 1	-0.10	1.30	1.90	2.90	5.10	6.30	8.20
	Clober, Red till profile							
70	4 - 5	1.10	2.40	2.90	4.50	5.90	6.80	8.10
71	4 - 4	0.50	1.90	2.40	3.60	5.40	6.40	7.80
72	4 - 3	0.40	1.80	2.30	3.50	5.30	6.30	7.70
73	4 - 2	0.90	2.10	2.50	3.50	5.00	6.20	7.90
74	4 - 1	0.70	2.00	2.40	3.50	5.30	6.30	7.80

Table 5.5 Till samples from NW Glasgow area. Values of maximum (X max), minimum (X min), mean ($\overline{X}$) and standard deviation (S) of grain-size parameters for Red till (R), Weathered Grey till (WG) and Grey till (G) samples. N gives number of samples.

Till category	Parameter	X max	X min	$\overline{X}$	S	N
R	Mz	4.48	3.56	3.96	0.30	20
WG	Mz	4.68	3.90	4.16	0.23	10
G	Mz	5.22	4.22	4.85	0.29	19
R	σ_I	2.80	2.43	2.51	0.18	20
WG	σ_I	2.71	2.39	2.60	0.10	10
G	σ_I	2.85	2.48	2.64	0.09	19
R	Sk_I	-0.10	-0.52	-0.28	0.11	20
WG	Sk_I	+0.13	-0.28	-0.13	0.11	10
G	Sk_I	+0.34	-0.07	+0.16	0.11	19
R	K_G	1.27	0.67	0.85	0.22	20
WG	K_G	0.83	0.66	0.75	0.05	10
G	K_G	0.81	0.66	0.74	0.04	19

CHAPTER 6

CLAY MINERALOGY OF TILLS OF THE NW GLASGOW AREA

6.1 Introduction

Although clay mineralogy is of prime importance in the study of tills, knowledge of the clay mineralogy of tills in the U.K., especially in Scotland, is poor. This is particularly unfortunate in view of the widespread occurrence of Quaternary glacial deposits within the country. Part of the overall purpose of the research project discussed in this thesis is to partially fill this gap and thus provide indicators of the extent of weathering in tills in south-western Scotland. Certain clay minerals that occur in tills are indicative of specific weathering processes.

The purpose of the part of the research project discussed in this chapter is to determine the types, abundance and significance of the clay minerals in the Quaternary tills in the north-western part of the Glasgow area. The study attempts to answer the following questions:

1) What is the general clay mineral composition of the tills?
2) Can clay mineral composition and distribution be used as a tool in the correlation of the tills?
3) Does the clay mineralogy change laterally in a single till?
4) Does the clay mineralogy change vertically in till profiles?
5) How does weathering alter the clay minerals in the tills?
6) What are the probable modes of origin of the clay minerals in the tills?

6.2 Previous work

For many years soil investigators have studied the clay mineral composition of soils. These studies have been summarised, generalised and probably over-simplified by Jackson & Sherman (1953). From their own studies and from an extensive review of the literature, these authors state that soil development may go through thirteen stages of weathering, the end product being a laterite.

Within the huge volume of literature on soils, many papers deal with soil development on glacial till. Many of these papers do not concern themselves with clay mineral content and, unfortunately, most of the papers containing clay mineral information were written before the introduction of recent improvements both in X-ray diffraction instrumentation and in other techniques of clay mineral identification. Moreover, there is now an increased understanding of the effects of pedogenesis and of mineral weathering transformation in determining the nature of the clay mineralogy of soils.

The mineralogy of the soil clays of Scotland was reviewed twenty to thirty years ago by Mitchell (1955) and Mackenzie (1965). It was concluded, from data obtained by X-ray powder cameras and differential thermal analysis, that the types of clay minerals found in soils depend largely on the parent material of the soil and on the drainage class of the soil. McCaleb (1953) reported on the clay mineral composition of six soils in New York State that had developed on glacial till. He found that illite was the dominant clay mineral in these soils. The most alkaline profile also contained vermiculite and montmorillonite, and the most acidic soils contained some kaolinite. Mitchell (1955) reported that the clay minerals in Scottish clay soils developed on a glacial till are illite, kaolinite, montmorillonite, vermiculite and, rarely, chlorite. He found that the tills containing granitic and sedimentary rocks had more illite in the soils developed on them, whereas the soils developed on tills containing basic rocks were characterised by vermiculite.

Recently, Wilson et al. (1984) reported on the clay mineral composition of eight soils in Scotland. These were developed on drifts which were derived from: granite and granitic gneiss; gabbro, basalt and andesite; mica-schist and related metamorphic rock types; Lower Palaeozoic greywackes and shales; Old Red Sandstone sediments; Carboniferous sediments; fluvioglacial sands and gravels; estuarine silts and clays. They concluded that the influence of inheritance is predominant, but the effects of pre-glacial weathering and Holocene pedogenesis can also be discerned. Murray et al. (1954) reported, from a study of a till weathering profile of Illinoian age in Indiana, that the un-oxidised till contained kaolinite, illite, chlorite and a small amount of montmorillonite. They stated that the kaolinite, illite and chlorite decreased in abundance and montmorillonite increased in abundance in the oxidised zone of the till.

Studies of the clay mineralogy of tills have concentrated mainly on the upper soil-forming horizons. Wiklander & Lotse (1966) and Wiklander & Aleksandrovic (1969) determined the clay mineral distribution in both agricultural soils and in podsol and brown earth profiles in tills from a number of localities in Sweden. Björnbom (1979) provided mineralogical data on various clay-dominated till samples collected from the C horizon. In addition, Melkerud (1983; 1984) determined the mineral distribution and chemical changes in till profiles down to a depth of 1m in the Lake Gardsjön area of south-western Sweden. More recently, Snäll (1986) provided clay mineralogical data on the effects of weathering on Quaternary till samples from two regions in east-central Sweden and from the bed of the Baltic Sea near the island of Götland.

The writer is not aware of any study of the clay mineralogy of fresh till over a large area. In this investigation the clay mineralogy of fresh till was determined first and then the alteration of clay minerals by weathering of fresh till was examined.

6.3 Mineral identification criteria

All clay minerals can be identified most accurately and most easily by examination of their basal (001) diffraction lines, so oriented aggregates were used in this clay mineral study in order to obtain the best possible basal diffraction data. The identification of each clay mineral type discussed in this thesis is based almost entirely on diffraction data obtained from basal planes in each sample. Table 6.1 is included to give the reader a means of rapidly converting Ångstrom measurements, given in the interpretation of data, into 2θ values.

The mineral identification criteria were taken from the publication Crystal structures of clay minerals and their X-ray identification, edited by Brindley & Brown (1980), and were supplemented by methods outlined by Weiss & Rowland (1956), Warshaw & Roy (1961), Jørgensen (1965), Dumbleton & West (1966), Weaver (1967), Gjems (1967), Pierce & Siegel (1969) and Carroll (1970a).

The diagnostic criteria for the clay minerals are summarised in Table 6.2.

Illite is recognised by a strong first order basal reflection at 10 Å, which remains unchanged by thermal treatment (Molloy & Kerr 1961). If the intensity ratio $I_{(001)}/I_{(002)}$ is less than 4, the illite is assumed to be of dioctahedral type (Graff-Peterson 1961). Trioctahedral illite and biotite, studied by Bradley & Grim (1961), have intensity ratios $I_{(001)}/I_{(002)}$ in the range 5-10. The asymmetrical shape of the illite reflection is interpreted as being due to degradation of illite (Gaudette et al. 1966).

Chlorite is identified by strong first and second order basal reflections at 14 Å and 7 Å respectively, and the mineral is non-expandable. Thermal treatment will cause a small shift in position to 13.8 Å and an increase in the intensity of the 14 Å reflection (Brindley & Ali 1950; Weiss & Rowland 1956), and the other basal reflections generally disappear.

Vermiculite is identified by a strong 14 Å reflection that remains unchanged upon glycolation and collapses to about 10 Å upon heating to 450°C, the intensity decreasing to about one-half upon thermal heating (Weiss & Rowland 1956).

Kaolinite is identified by its series of basal diffraction peaks at about 7 Å and 3.5 Å that remain unchanged by glycolation or thermal heating to 450°C; but kaolinite shows collapse of structure to an X-ray amorphous mineral on heating to 550°C.

Montmorillonite is identified by the expansion of the mineral to about 17 Å on treatment with ethylene glycol (MacEwan 1944). Upon heating, the basal reflection shifts to 10 Å.

Swelling chlorite is identified by the expansion of the mineral to about 17 Å on treatment with ethylene glycol (Brown 1961). It collapses to about 14 Å upon heating to 450°C.

6.4 Semi-quantitative determination of the clay mineral composition

Various methods have been used for quantitative work on clays. X-ray methods are usually based on comparisons of reflection intensities from different minerals in the sample. Since there are large variations in crystallinity, chemical composition, etc. of different minerals, there are possibilities of large errors in the absolute values, but the methods can be used to show how the composition varies in the different types of till.

Semi-quantitative determinations, Table 6.3, were performed along the lines suggested by Johns _et al_. (1954), and modified by Jørgensen (1965). The relative proportions of the clay mineral species were estimated by using the intensities (peak areas) in the X-ray diffractograms. The integrated intensities (peak areas) used in this work were estimated by taking the product of the maximum peak height and the peak width at half maximum height (Norrish & Taylor 1962). The relative clay mineral content was determined as follows:

1) The peak area of the 17 Å glycolated peak for montmorillonite was compared with four times the peak area of the 10 Å glycolated peak area of illite, to give the relative amounts of montmorillite and illite.
2) The peak area of the 10 Å untreated peak of illite was compared with the peak area of the 14 Å untreated peak to give the relative amounts of illite and chlorite (Oinuma & Kobayashi 1960; Weaver 1968) or illite and vermiculite (Johns _et al_. 1954).
3) The peak area of the 3.3 Å untreated peak for illite was compared with that at 3.5 Å after heating to 450°C, to give the relative amounts of illite and kaolinite (Johns _et al_. 1954).
4) To cover the possibility of the presence of both chlorite and vermiculite in the same sample, the peak area of the 10 Å untreated reflection of illite was compared with the peak area of the 14 Å reflection after heating to 450°C, to give the relative amounts of illite and chlorite. After heating to

450°C, the intensity of the 14 Å reflection decreases, since at this temperature the vermiculite reflections disappear (the remaining 14 Å reflection is due to chlorite only). Thus, the difference between the peak areas of the 14 Å reflection before and after heating gives the peak area for vermiculite, and this difference was compared with the peak area of the 10 Å untreated reflection to give the relative amounts of vermiculite and illite.

6.5 Data and interpretation

14 Å peak

In all samples, a peak due either to vermiculite only or to both vermiculite and chlorite occurs between 13.8 Å and 14.2 Å. The position, intensity and sharpness of this peak are quite variable and react similarly to ethylene glycol and differently with heat treatment. While in some samples the peak is sharp and has only a moderate intensity, in others it is broad and more intense. The more intense and broad the peak is in the air dried sample, the more the peak is lost after heating to 450°C. After heating to 450°C, the peak will be decreased in its intensity in some samples, completely lost in others.

From the outset of the investigation it was evident that, in the till samples showing peaks in the 13.8 Å - 14.2 Å position, the component causing the peak was not the same in all samples. Some samples contained chlorite as part of the clay mineral component. This chlorite was not affected by glycolation or by heat treatment at 450°C. In other samples it appeared, from the changes caused by heat treatment, that chlorite was not present. On the other hand, it appeared, from the changes caused by heat treatment, that vermiculite was present in all samples.

Chlorite was found only in the Grey till samples. It may be expected that chlorite would change to vermiculite upon weathering (see below, Chapter 6.10) and, therefore, chlorite would disappear in the Weathered Grey till samples. Since each of the Weathered Grey till samples had not necessarily been taken in exactly the same place within the zone of weathering, they may have been subjected to different amounts of alteration by weathering, and hence the Weathered Grey till samples would show varying amounts of vermiculite, depending upon where the sample was taken within the zone of weathering. The details of alteration of chlorite to vermiculite are discussed later when alteration by weathering is considered (Chapter 6.9).

10 Å peak

A 10 Å peak with appropriate moderate orders is present in every sample, indicating the presence of illite. In all the Weathered Grey till samples, and in many of the Grey and Red till samples, the 10 Å peak of the air dried sample is slightly asymmetrical, on the 'high' side of the peak. The loss of this asymmetry after heating to 450°C indicates that some of the illite is hydrated. Some of the potassium is probably removed from between the mica layers and is decreased by water. Thus, it is clear that the illite of the Weathered Grey till samples compared with that of the Grey till samples shows a slight amount of alteration to vermiculite.

7 Å peak

A sharp, intense 7 Å peak with appropriate higher orders is recorded in all samples, indicating the presence of kaolinite. The problem of the identification of kaolinite in the presence of chlorite arises here only in the case of the Grey till samples because chlorite is present only in this till category (and never appears in either the Red till or Weathered Grey till samples). The (002)-reflections of chlorite and (001)-reflections of kaolinite occur at almost the same positions. To establish the presence of chlorite is not very difficult for the odd reflection orders (001, 003, 005, etc.) of chlorite do not occur in a kaolinite diffraction pattern. Because the even reflection orders (002, 004, 006, etc.) of chlorite correspond almost exactly with the successive odd orders (001, 003, 005, etc.) of kaolinite, it is often difficult to demonstrate the presence of kaolinite when chlorite is present. The 7 Å/14 Å intensity ratio of chlorite is about 1/1 for the magnesium-rich varieties and 3/1 for the iron-rich varieties (Brindley 1951, Table 14). In most of the Grey till samples, the 7 Å/14 Å intensity ratio is between 5/1 and 8/1. In all the Grey till samples, following ignition to 450°C, the intensity of the 14 Å peak remains after heating and is related to chlorite, and any diffraction effects noted at the 7 Å and 3.5 Å peaks can be attributed to kaolinite, since the higher orders of chlorite are lost upon heating to 450°C (Johns et al. 1954). In both the Weathered Grey till and the Red till samples, the 7 Å and 3.5 Å peaks remain almost unchanged, whilst the 14 Å peak disappears after heating to 450°C. This indicates that kaolinite is present in all the samples, whilst chlorite is present only in the Grey till samples. The abundance of kaolinite in each sample is computed by the method suggested by Johns et al. (1954).

6.6 Description of the X-ray diffractograms

X-ray curves of representative samples were drawn to display the characteristic features of the various categories of till in the NW Glasgow area. The Red, Weathered Grey and Grey till samples are grouped separately and the clay mineral content of the three categories of till are discussed as follows.

6.6.1 Red tills

All the Red till samples have almost identical X-ray diffractograms (see samples R1, R31, R39 and R45 in Figs. 6.1 and 6.2). The glycolation treatment did not cause any shift in the position of the 14 Å reflection. After heating, the 14 Å reflection disappeared, and the intensity of the 10 Å reflection increased due to the shifting of the 14 Å reflection upon heating. A decrease in the intensities of the 7 Å and 3.5 Å reflections was noticed after heating. This was due to the disappearance of the other basal reflections of the 14 Å mineral. According to the diagnostic criteria, all the Red till samples contain kaolinite, illite and vermiculite. The values of the illite intensity ratio, $I_{(001)}/I_{(002)}$ = 3-5, are suggestive of a mixture of di- and trioctahedral illite. The greater part is dioctahedral.

6.6.2 Weathered Grey tills

All the Weathered Grey till samples have almost identical X-ray diffractograms (see samples WG6 and WG29 in Fig. 6.3). The glycolation treatment did not cause any shift in the position of the 14 Å reflection. After heating, the 14 Å reflection disappeared and an increase in the intensity of the 10 Å reflection was noticed clearly. The interpretation of these effects is that all the Weathered Grey till samples contain kaolinite with illite and vermiculite. The values of the illite intensity ratio, $I_{(001)}/I_{(002)}$ = 2-5, indicate the presence of a mixture of trioctahedral and dioctahedral illite. The greater part is dioctahedral.

6.6.3 Grey tills

All the Grey till samples have almost identical X-ray diffractograms (see samples G5, G10, G20 and G27 in Figs. 6.4 and 6.5). The clay material is unweathered and gives distinct X-ray diffraction peaks. The glycolation treatment did not change the 14 Å reflection. Upon heating to 450°C, the intensity of the 10 Å reflection increased and that of the 14 Å reflection decreased. A decrease in the intensities of the 7 Å and 3.5 Å reflections was noticed after heating. This was due to the disappearance of the other basal reflections of the 14 Å mineral. Thus, according to the diagnostic criteria, the interpretation of these effects is that the clay material of the Grey till samples consists mainly of kaolinite and illite, with minor amounts of chlorite and vermiculite. The values of the illite intensity ratio, $I_{(001)}/I_{(002)}$ = 3-6, are suggestive of a mixture of tri- and dioctahedral illite. The greater part is trioctahedral.

6.7 Semi-quantitative mineralogy

Table 6.4 shows the average clay mineral composition of the three different categories of till in the NW Glasgow area. The clay minerals identified include kaolinite, illite, vermiculite and chlorite. Their average distribution in the studied tills is illustrated in Figure 6.6.

Kaolinite is recorded in all the samples that were analysed. In the Grey till kaolinite amounts to 41.4 - 71.7%, in the Weathered Grey till to 55.1 - 69.2% and in the Red till to 31.6 - 61.3% of the total clay mineral composition. The means of kaolinite are 58.67%, 59.88% and 42.01% in the Grey till, Weathered Grey till and Red till, respectively. Kaolinite is the dominant clay mineral wherever it is present in the three different categories of till in the NW Glasgow area, with a tendency towards enrichment in both the Grey and the Weathered Grey till. A high kaolinite content characterises the Quaternary deposits of certain parts of Scotland. The kaolinite is assumed to have been derived from pre-glacially kaolinitised local bedrock. Probably the kaolinite formed when kaolinite weathering was intense in Scotland during Tertiary times (Wilson et al. 1984).

All the samples analysed contain illite, which in the Grey till amounts to 15.2 - 34.5%, in the Weathered Grey till to 13.3 - 23.3% and in the Red till to 14.7 - 30.3% of the total clay mineral composition. The means of illite are 22.61%, 17.15% and 21.42% in the Grey till, Weathered Grey till and Red till, respectively. Illite is thus an essential clay mineral in the three different categories of till.

Vermiculite is recorded in all the samples analysed. In the Grey till vermiculite amounts to 3.2 - 16.9%, in the Weathered Grey till to 14.1 - 27.3% and in the Red till to 20.5 - 44.7% of the total clay mineral composition. The means of vermiculite are 9.81%, 21.96% and 33.90% in the Grey till, Weathered Grey till and Red till, respectively. In the Weathered Grey till samples, vermiculite is not found in association with chlorite. This may indicate that the vermiculite was developed in the Weathered Grey till at the expense of chlorite and illite, since the last two give way to the first by weathering (Droste 1956; Smeck et al. 1968; Wilding et al. 1971; Snäll 1986).

Chlorite is encountered only in the Grey till samples, and ranges from 5.1% to 15.5% of the total clay mineral composition, having a mean of 9.19%. It is not found in either the Weathered Grey till or the Red till samples.

An evaluation of the semi-quantitative data given in Table 6.4

and Figure 6.6 shows the following:

1) The Grey till and Weathered Grey till contain large amounts of kaolinite relative to amounts in the Red till.
2) The Red till contains a greater amount of vermiculite than that in both the Grey till and the Weathered Grey till.
3) The amount of illite in the Grey till is greater than that in the Weathered Grey till, and vice versa for the amount of vermiculite.
4) Chlorite is present only in the Grey till. Presumably, it has disappeared in the Weathered Grey till, and it does not seem to have been present in the Red till.

In general, the relative abundances of the clay minerals identified may lead to recognition of the following three associations:

1) The first association prevails in the Grey till and includes kaolinite as the dominant mineral, followed by illite. It contains chlorite as a characteristic clay mineral. It also contains minor amounts of vermiculite.
2) The second association is recorded in the Weathered Grey till, where kaolinite is the dominant clay mineral, followed by vermiculite and a subordinate amount of illite. There is no chlorite.
3) The third association is found in the Red till. This till is not so kaolinite-rich as the Grey till and the Weathered Grey till, although kaolinite can still be a dominant mineral. The Red till tends to contain vermiculite as a major clay mineral, with a subordinate amount of illite. This association contains no chlorite.

Generally, the clay mineralogy of the Grey till differs considerably from that of the Red till, both qualitatively and quantitatively. In each of these categories of till the clay mineralogy does not vary greatly from one site to another, and no regular distribution pattern of the individual minerals appears discernible, such as might suggest widespread derivation from one particular source or direction. This lack of pattern may suggest different sources for the Red and Grey tills.

Table 6.5 summarises the clay mineral characteristics of the three categories of till in the NW Glasgow area. The information included in the Table is not only interesting in relation to a study of weathering. It may also prove to be a valuable tool in Quaternary stratigraphy (see Chapter 14).

6.8 Samples showing weathering within vertical profiles

All four profiles studied showed substantially the same trend of clay mineral alteration and differed only in minor details. Only one profile from the Grey till and one from the Red till, therefore, is described in detail. The Kelvinside Grey till profile (Fig. 6.7) and the Laighpark Red till profile (Fig. 6.8) were selected and are included in the descriptions that follow. The Kelvinside section was selected in preference to the Queen Margaret Hall section, as representing a weathering profile in the Grey till, because the depth of the exposed profile at Kelvinside was much greater than at Queen Margaret Hall and, hence, changes in the Grey till at depth could be detected in the analytical results (see Table 6.3).

A detailed description of the clay minerals in each of the selected profiles follows, starting with the unaltered material, and changes due to weathering are pointed out from base to top. The clay minerals present are discussed with respect to their basal reflections recorded on the X-ray spectrometer traces. In estimating the effects of weathering, illite, kaolinite and chlorite are considered to be primary minerals, whereas vermiculite is regarded as secondary, that is, as a product of weathering.

6.8.1 Kelvinside Grey till profile

Figure 6.7 shows how weathering can be traced by XRD-analysis of the clay fraction in the Kelvinside Grey till profile. At the deepest levels of sampling, 250-425cm below the surface, the Grey till is very little influenced by weathering processes. Primary minerals with peaks at 7 Å (kaolinite and chlorite) and 10 Å (illite) are predominant. Only minor amounts of a secondary mineral (weathering product = vermiculite) at 14 Å can be identified. The peak at 14 Å is supplemented by chlorite. Passing upwards in the profile, the 10 Å peak (illite) decreases and the 14 Å peak (vermiculite) increases. In the uppermost levels (100-175cm below the surface), chlorite is not present in the samples and the peak found at 14 Å (001-peak of vermiculite) is broadened and more intense. It shifts to 10 Å and is completely lost after heating to 450°C. Figure 6.9 shows an almost continuous increase of vermiculite and decrease in chlorite and illite upwards through the profile.

6.8.2 Laighpark Red till profile

Figure 6.8 shows how weathering can be traced by XRD-analysis of the clay fraction in the Laighpark Red till profile. At the deepest levels of sampling (200-225cm below the surface), a broad, rather weak peak occurs at 14 Å. It is unaffected by glycolation and is completely lost upon heating to 450°C. This peak is attributed to vermiculite. A sharp, intense and symmetrical 10 Å peak is present. It is unchanged after glycolation and heating. This peak is attributed to illite. The 7 Å peak, which is unaffected by glycolation and heating to 450°C, is attributed to kaolinite.

Passing upwards in the profile, at the 150-175cm levels the 14 Å peak (vermiculite) is broader and more intense, and the intensity of the 10 Å peak (illite) has decreased. In the uppermost levels of the profile (100-125cm), the vermiculite peak at 14 Å has become more intense, whilst the illite peak at 10 Å is less intense, and is asymmetrical on the high side of the 10 Å peak. The loss of this asymmetry after glycolation and heating imply that some of the illite layers are hydrated. The illite is becoming degraded, probably by removal of potassium from between the mica sheets, and vermiculite is developing. This is the first indication of the alteration of illite in a series of samples from the base to the top of the profile. Figure 6.10 shows that the amount of vermiculite tends to increase upwards in the profile and vice versa the amount of illite.

6.9 Weathering

During the study of the clay mineralogy of 74 samples of the tills of the NW Glasgow area, weathering of the Grey till was noted. The Grey till is generally leached and oxidised to depths of about 2m (Fig. 6.7). The Red till is also leached and oxidised, but to a lesser extent than the Grey till, as appears from the results obtained from the study of vertical profiles (Fig. 6.8).

Accompanying the oxidation of the Grey till, there is breakdown of chlorite and illite to form vermiculite. Since the amounts of illite and chlorite in the unweathered Grey till are relatively consistent, the breakdown of chlorite and illite is often detected by the anomalously high vermiculite content and by the disappearance of chlorite in the Weathered Grey till. Willman et al. (1966) described chlorite alteration in till profiles in Illinois. They suggested that illite and chlorite both break down progressively upwards through the weathering profile. Willman et al. showed that illite began to decrease in the unaltered till at the depth that chlorite began progressively to decrease. More recently, Snäll (1986) has described illite alteration in till samples from two regions in east-central Sweden and from the bed of the Baltic Sea near Götland. He showed that illite breaks down progressively upwards through the weathering profile and changes to vermiculite.

Vermiculite is present in all the 74 analysed samples of tills from the NW Glasgow area. The content varies in the different categories of till (Table 6.4). As noted above (e.g. Chapter 6.7), the vermiculite content tends to be higher in the Weathered Grey till than in the Grey till. As may be expected, the increased vermiculite content in the Weathered Grey till can be correlated with the smaller amount of illite in the Weathered Grey till than in the Grey till, and also with the (presumed) disappearance of chlorite from the Weathered Grey till. These changes may be due to weathering at the sampled sites. Transformation of clay minerals by weathering in tills has been proposed as follows: chlorite to vermiculite (Droste 1956); illite to vermiculite (Smeck et al. 1968; Wilding et al. 1971; Melkerud 1984).

The alteration of both chlorite and illite, and the concomitant development of vermiculite should be useful in proving the presence of weathering in tills with significant contents of chlorite and illite.

6.10 Genesis of the clay minerals

As stated above (Chapter 6.7), the clay mineral assemblages of the tills of the NW Glasgow area are dominated by kaolinite. Kaolinite is described as being very stable in the hydrosphere, in soils and in sediments, and it is generally considered the most resistant clay mineral (Millot 1970). The occurrence of kaolinite is interesting genetically. The presence of kaolinite in tills is explained as being due to inheritance from kaolinitised bedrocks. The bedrocks concerned were comminuted by glacial action, and then transported and deposited as till in the down-glacier direction. Until now, in situ neoformation of kaolinite in the tills of the NW Glasgow area has not been established.

Illite present in the NW Glasgow tills exhibits a moderate to low degree of crystallinity (Fig. 6.11). This is normal for sedimentary illites. Figure 6.11 also indicates that the identified clay mineral is either a mica polymorph of phengite composition or is of muscovite and biotite composition. Because illite does not show any particular trend of distribution among the three different categories of NW Glasgow tills, it seems to be detrital in origin. Millot (1970) stated that most illites in soils and sediments are detrital. The accumulation of illite in such circumstances is accompanied by a slight degree of weathering.

The semi-quantitative data given in Table 6.5 show that the amount of vermiculite tends to increase as the amount of chlorite and/or illite decreases. This relationship is illustrated more clearly in Figures 6.9 and 6.10; the formation of vermiculite from illite and chlorite may have occurred. In laboratory experiments it has been shown that biotite, particularly phlogopite, is altered to vermiculite on the interlayer K^+ being substituted by Mg^{++} and vice versa (Barshad 1948). In biotites, the rate of K^+ release is influenced by oxidation of Fe^{++} in the octahedral sheet of the structure (Reichenbach & Rich 1969). In podsol profiles, biotite may be completely transformed via hydrous mica to vermiculite (Walker 1947; 1949; 1950). It is suggested that trioctahedral mica is unstable in the acid surface horizons of podsols (Mitchell 1955). The formation of vermiculite from chlorite was described by Jørgensen (1965). The process was assumed to be an exchange between Mg from the brucite layer and protons in exchangeable positions. Walker (1961) assumed that the vermiculite was always of secondary origin, formed by the alteration of rock-forming mica, pyroxene, amphibole, chlorite and feldspar.

Chlorite is a minor constituent in all the (unweathered) Grey till samples of the NW Glasgow area, and is considered to be detrital.

The X-ray investigation of the clay mineralogy suggests that the clay mineral assemblages of the various categories of till may be expected to differ substantially for the following reasons:

1) Variation in the composition of the source rock.
2) Variation in the environments of sedimentation.
3) Post-depositional changes.

In the NW Glasgow area, the clay mineral composition of the till deposits is controlled by:

1) The available sources of sediment.
2) Diagenetic development of clay minerals in response to particular environments.

Three possible modes of origin of the clay minerals in the tills of the NW Glasgow area are these:

1) By direct inheritance from a parent rock or rocks.
2) By pre-glacial weathering of bedrock.
3) By pedogenic processes since glacial deposition of the tills concerned.

Direct inheritance

Because of the relative youthfulness of the NW Glasgow tills, this mode of origin may be predominant, and it is generally prudent to assume that all the clay minerals in the tills originated in this way unless it can be proved otherwise.

Pre-glacial weathering

The weathering considered under this heading is regarded as having pre-dated the glaciation that deposited the Grey and Red tills of the NW Glasgow area, and may include both Quaternary interglacial and pre-Quaternary weathering episodes. There is no doubt, however, that the weight of evidence strongly suggests that pre-Pleistocene weathering is the more significant (Fitzpatrick 1963), although interglacial effects cannot be discounted entirely. On geophysical evidence, it appears that during Palaeogene or Neogene times most, if not all, of Scotland was an area of positive relief (Hall 1983). According to Wilson *et al.* (1984), during Tertiary times Scotland was subject to periods of intense weathering under a climate that often was hot and humid. This resulted in the formation of a deep weathering cover, the remnants of which are to be found in many parts of the country, particularly in the north-east. The remnants of the cover show profound weathering. The primary minerals have been altered to kaolinite (Wilson et al. 1984). Such weathering obviously influences till clay mineralogy where the tills concerned have been derived directly from the weathering cover. Thus, the part of the ancient weathering cover that was removed by glacier erosion must, to some extent, have been incorporated into the till. In general, the influence of pre-glacial weathering must be expected in areas where deeply weathered bedrock is common. The occurrence of kaolinite in tills, in situations where direct inheritance is excluded, is strong evidence for the mineral to be attributed to an earlier episode or episodes of weathering, although it may be impossible to say whether this weathering was pre-glacial or interglacial (or both) in age.

Pedogenesis since till deposition

In general, the influence of post-depositional pedogenesis on till clay mineralogy in the NW Glasgow area is relatively great. Through the study of till profiles, careful comparison of clay fractions separated from fresh till and those separated from weathered till shows that certain changes do occur. These changes relate to transformation of illite and chlorite to vermiculite. Such changes have also been widely reported from Canada and Scandinavia.

6.11 Conclusion

In the Introduction to this Chapter (6.1), six questions concerning the clay mineralogy of the tills of the NW Glasgow area were asked. A summary follows of the answers that have been given to these questions within the content of this chapter.

1) The general clay mineral composition of the tills is:

   Red till - dominated by kaolinite and vermiculite, with subordinate amounts of illite.

   Weathered Grey till - dominated by kaolinite, with major amounts of vermiculite and subordinate amounts of illite.

   Grey till - dominated by kaolinite, with subordinate amounts of illite and minor amounts of vermiculite and chlorite.

2) Clay mineral composition and distribution can be used as a tool in the correlation of the tills, as follows. Chlorite is present only in the Grey till. Although kaolinite is the dominant clay mineral in both the Red till and the Weathered Grey till, the percentage of kaolinite is much lower in the Red till than in the Weathered Grey till (and also in the Grey till).

3) The clay mineralogy shows little change laterally within a single till, i.e. there is little change in clay mineral composition throughout the Red till samples, the Weathered Grey till samples and the Grey till samples although in each case the samples were collected over a wide area.

4) The clay mineralogy changes vertically in till profiles. In the case of Grey/Weathered Grey till profiles, chlorite disappears up the profile, and the amount of vermiculite increases up the profile at the expense of chlorite and illite. Although it is difficult to distinguish between weathered Red till and non-weathered Red till in the same profile, it is obvious that the amount of vermiculite increases upwards at the expense of illite.

5) Weathering affects the clay minerals in the tills by the alteration of chlorite (and to a lesser extent) illite to vermiculite.

6) There are three probable modes of origin of the clay minerals in the tills:

a) Direct inheritance

b) Pre-glacial weathering

c) Pedogenesis since till deposition.

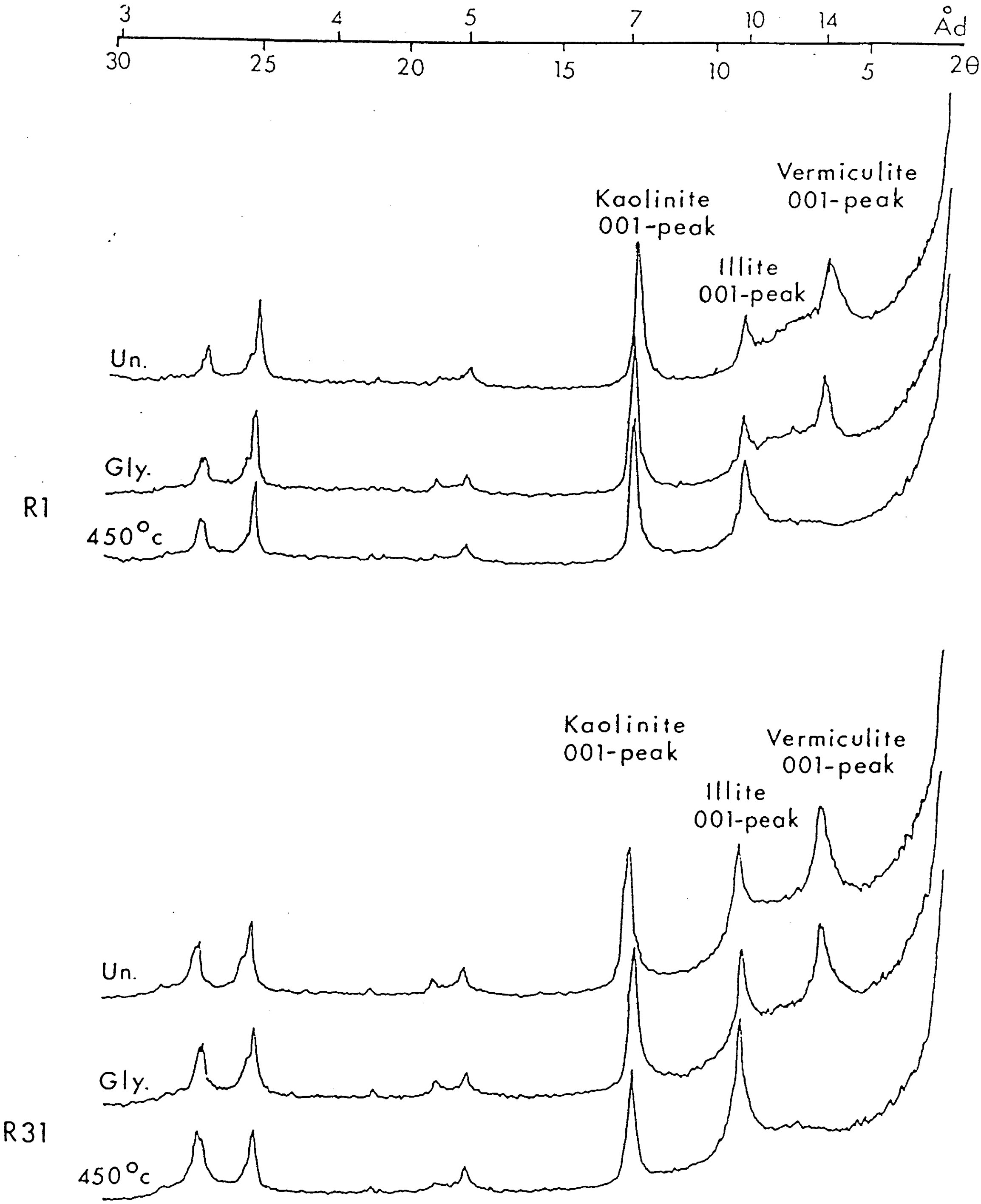


Figure 6.1 Selected X-ray diffractograms for oriented samples of the clay fraction (<2 μm) from the Red till of the NW Glasgow area.

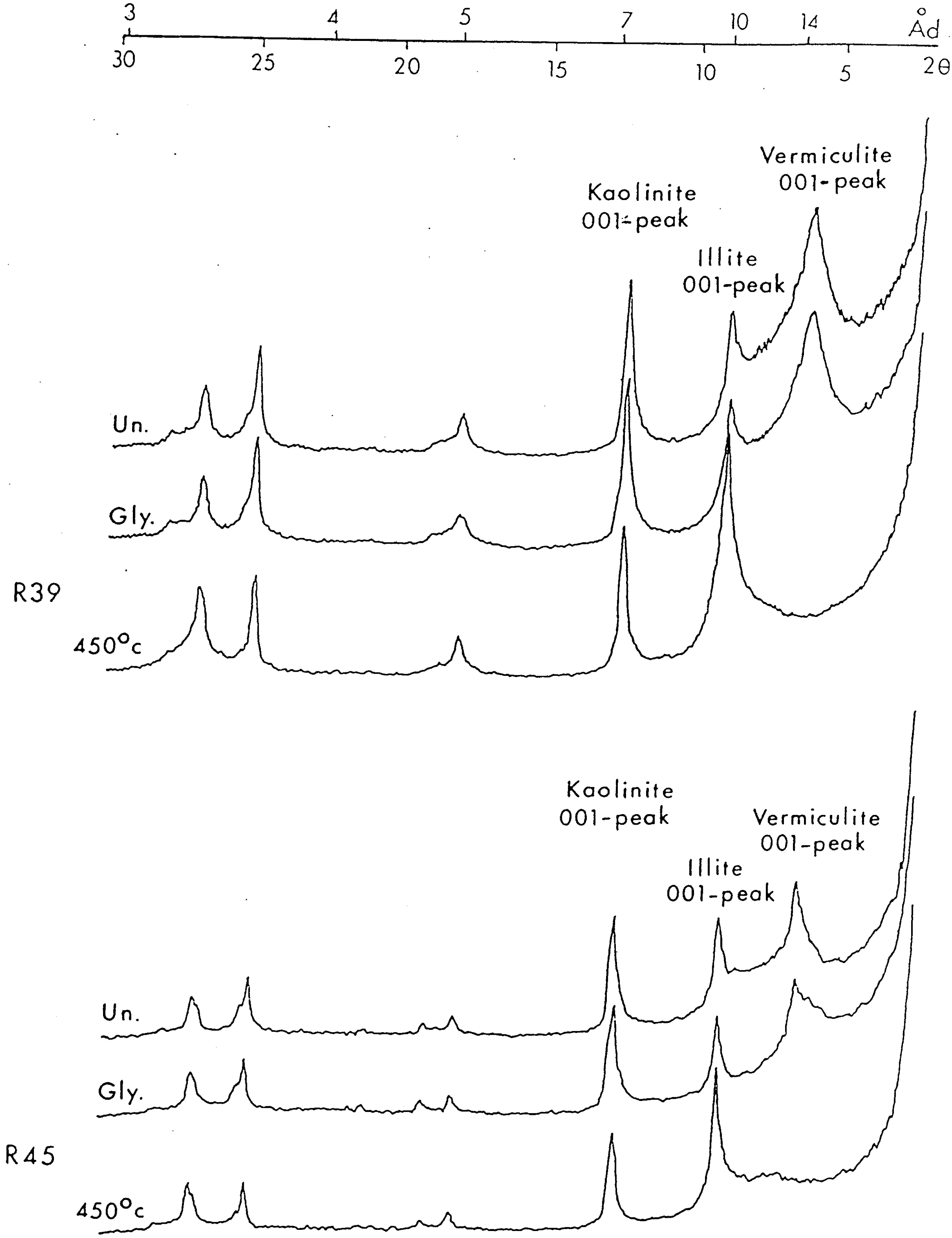


Figure 6.2 Selected X-ray diffractograms for oriented samples of the clay fraction (<2 μm) from the Red till of the NW Glasgow area.

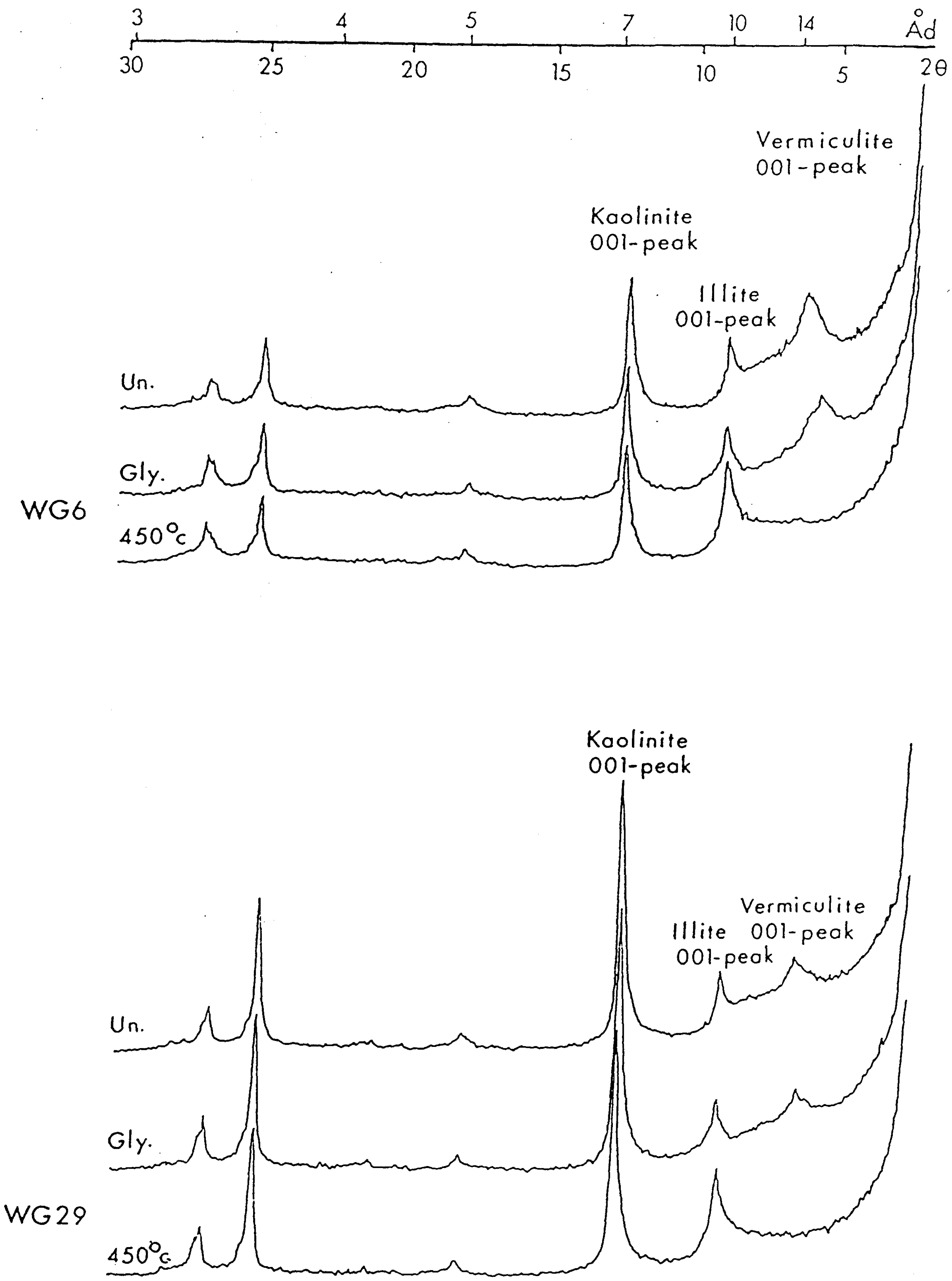


Figure 6.3 Selected X-ray diffractograms for oriented samples of the clay fraction (<2 µm) from the Weathered Grey till of the NW Glasgow area.

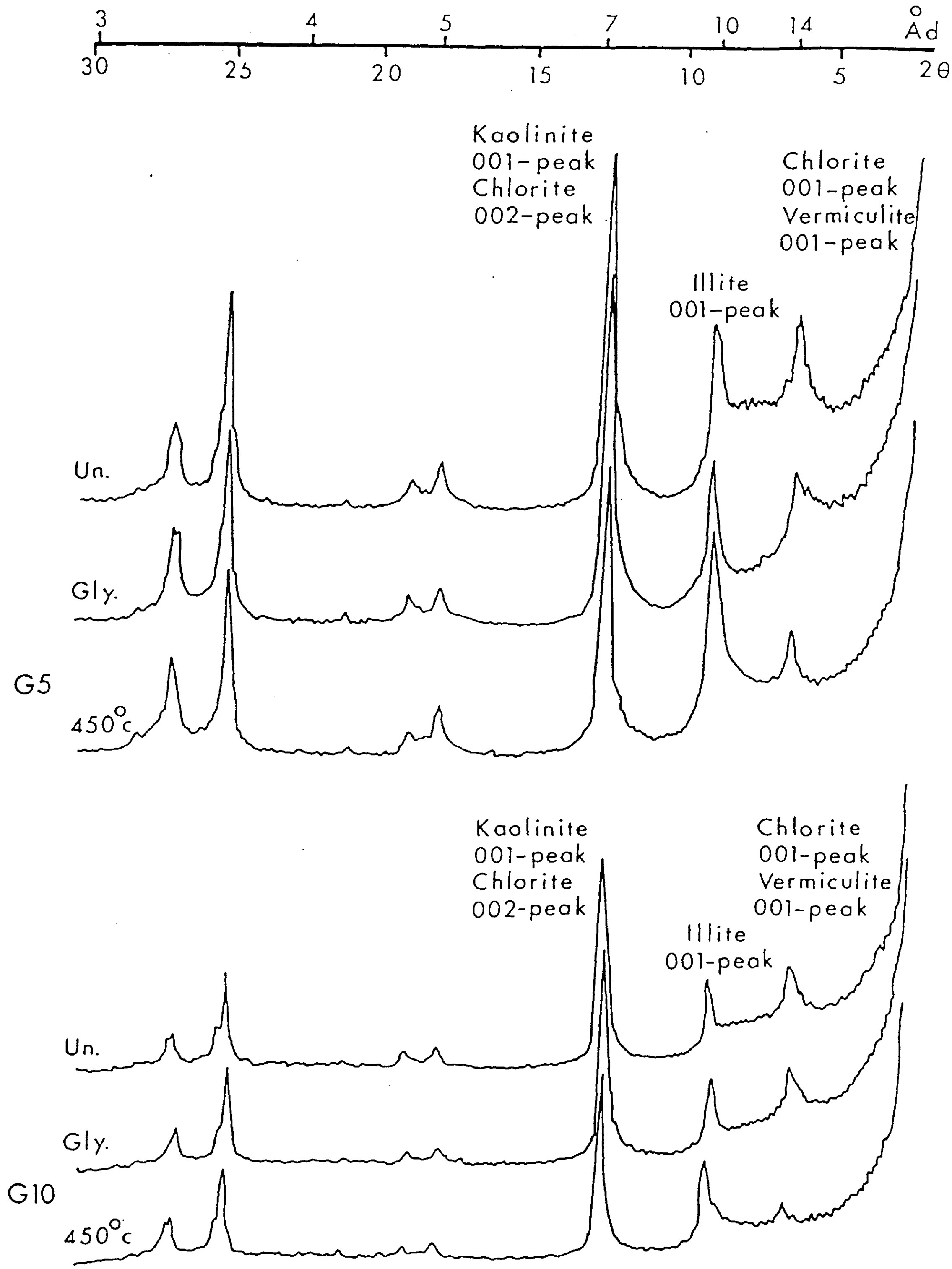


Figure 6.4 Selected X-ray diffractograms for oriented samples of the clay fraction (<2 μm) from the Grey till of the NW Glasgow area.

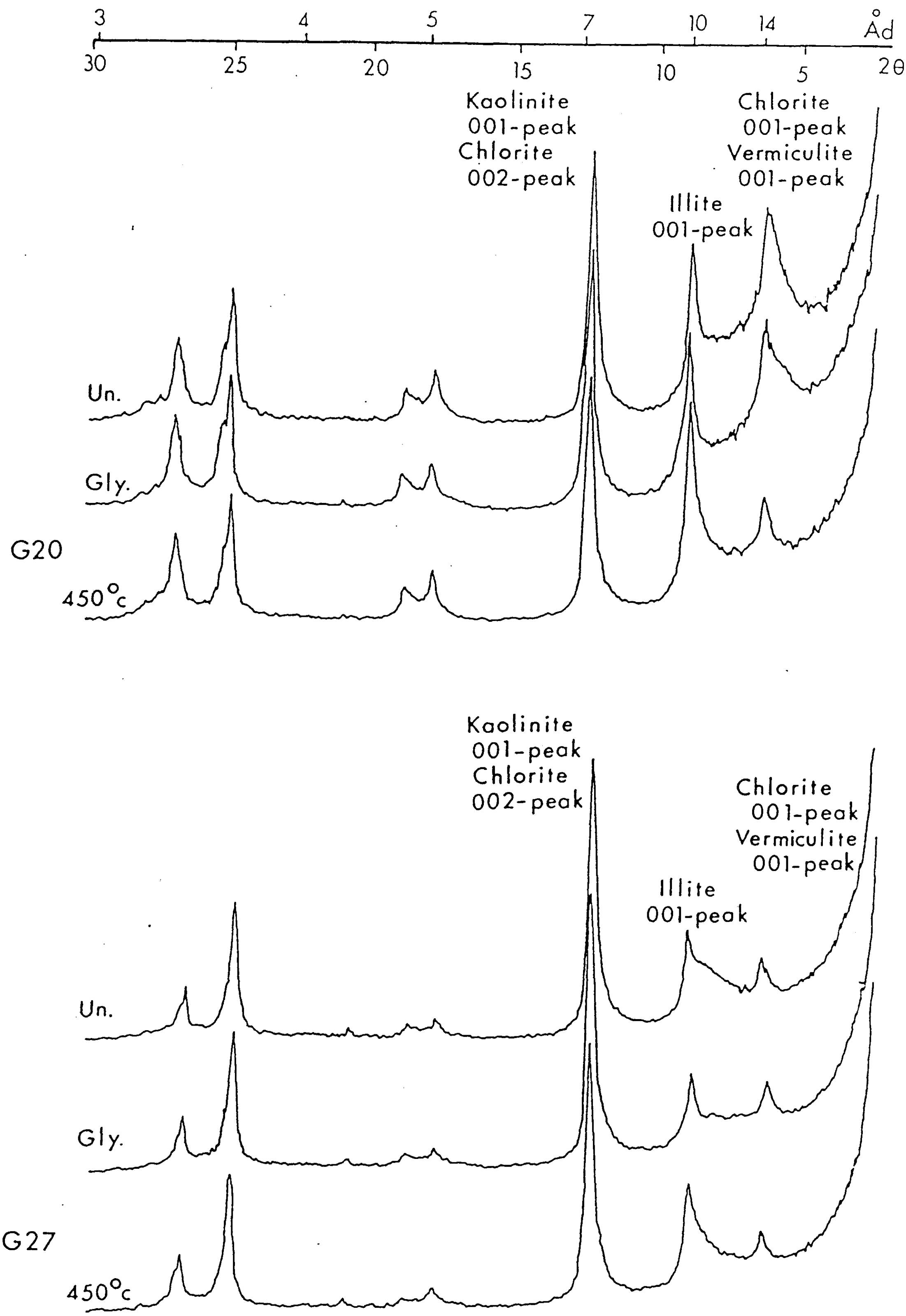


Figure 6.5 Selected X-ray diffractograms for oriented samples of the clay fraction (<2 μm) from the Grey till of the NW Glasgow area.

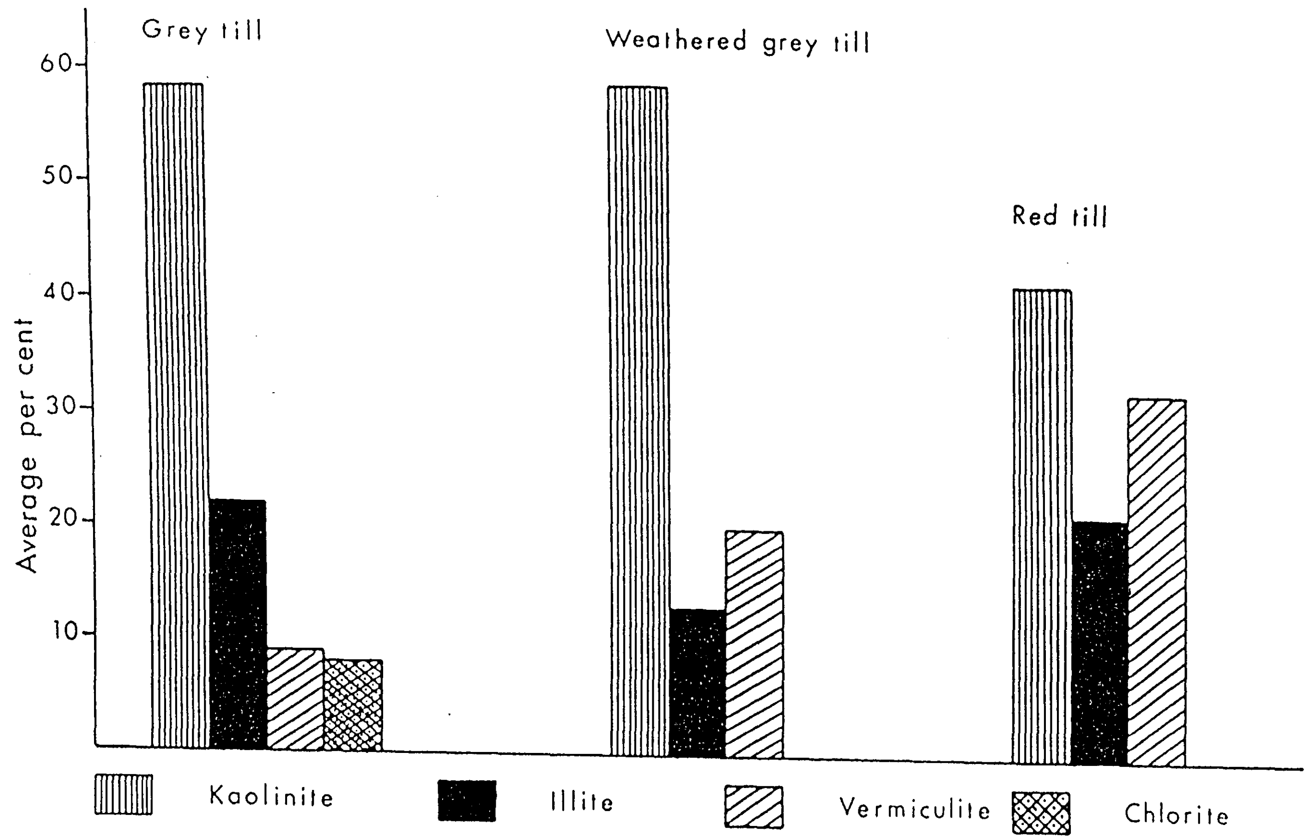


Figure 6.6 Average distribution of clay minerals in the clay fraction (<2 μm) of the three categories of till in the NW Glasgow area.

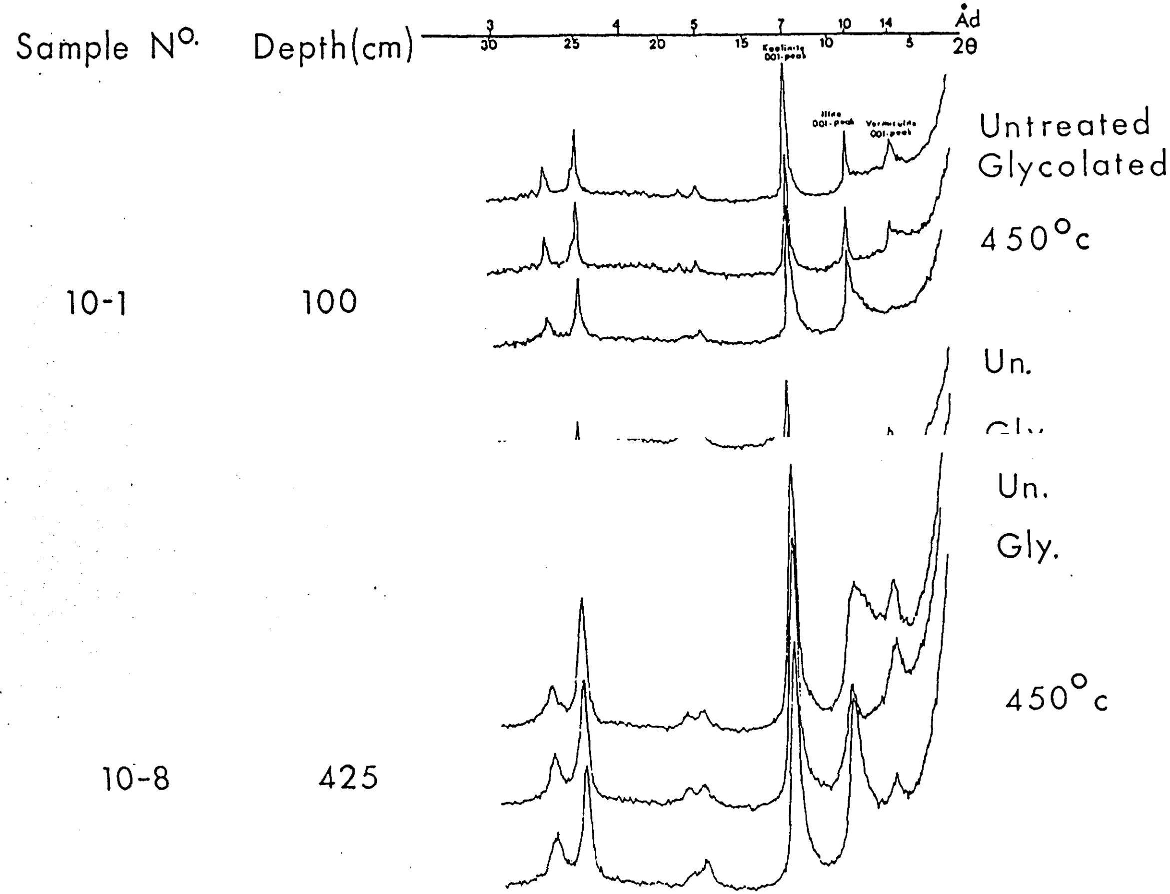


Figure 6.8 Till profile at Laighpark (NS 5360 7615): XRD diffractograms of the clay fraction (<2 μm) separated from the Red till at various depth levels below ground surface.

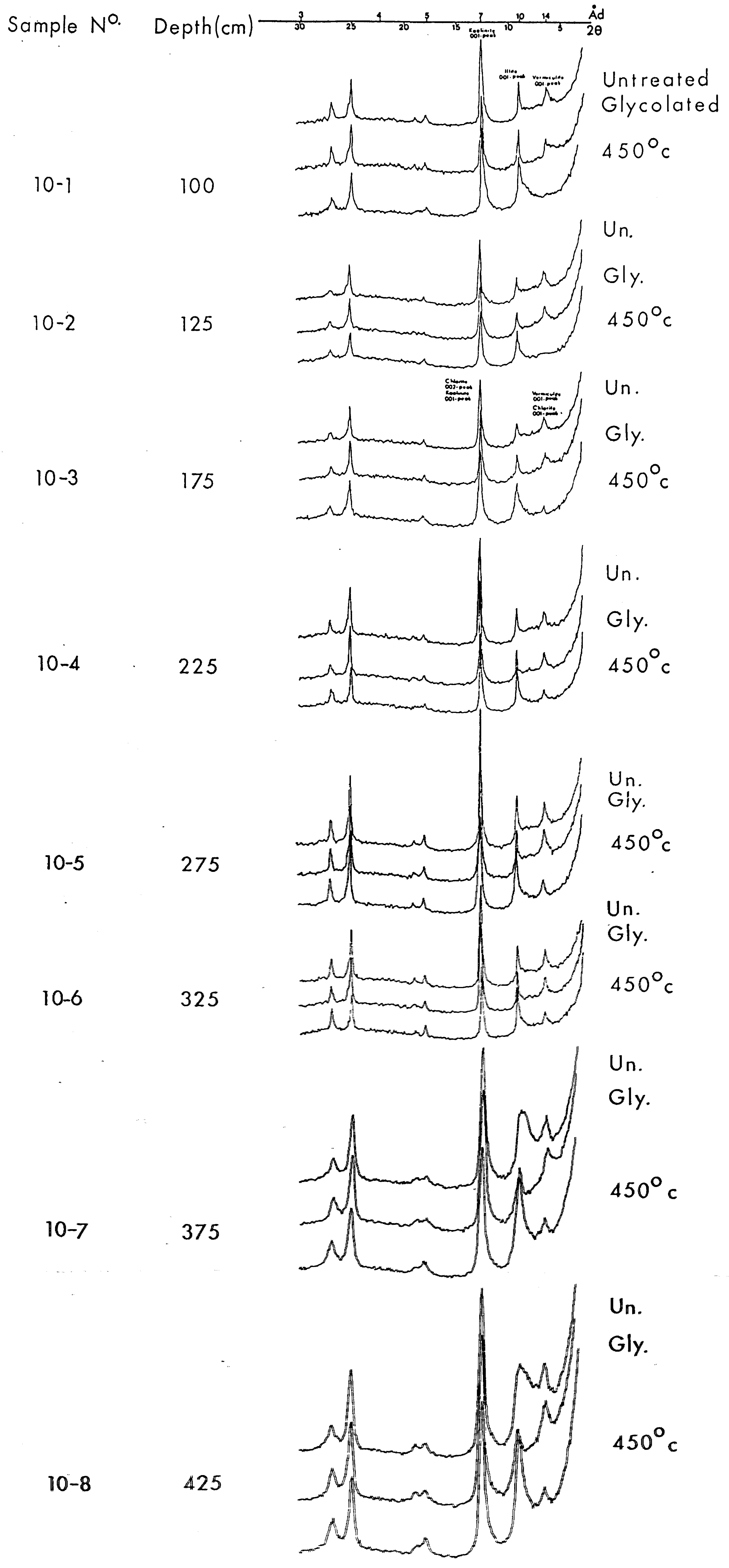


Figure 6.8 Till profile at Laighpark (NS 5360 7615): XRD diffractograms of the clay fraction (<2 μm) separated from the Red till at various depth levels below ground surface.

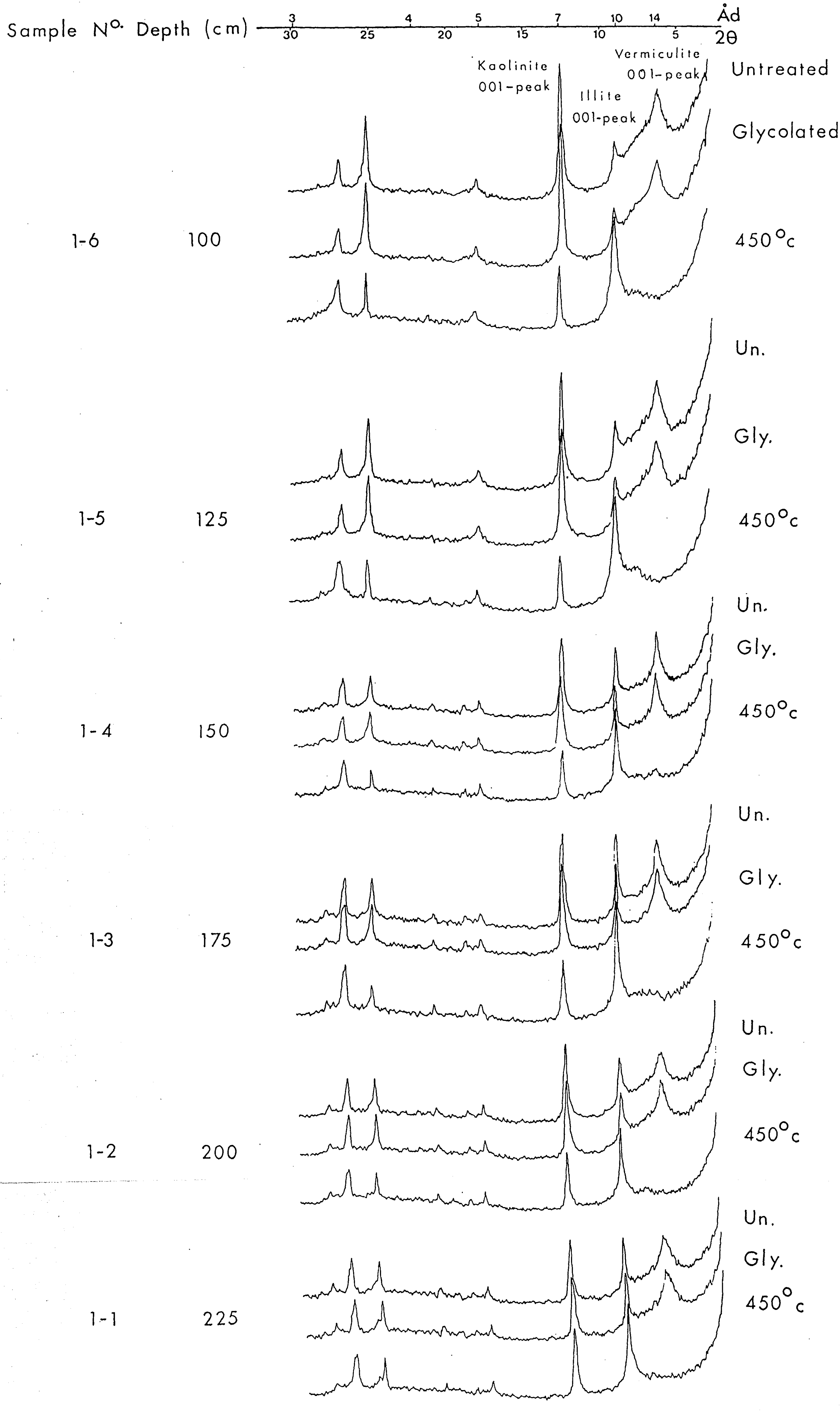


Figure 6.7 Till profile at Kelvinside - Great Western Road (NS 5581 6807): XRD diffractograms of the clay fraction (<2 μm) separated from the Grey till at various depth levels below ground surface.

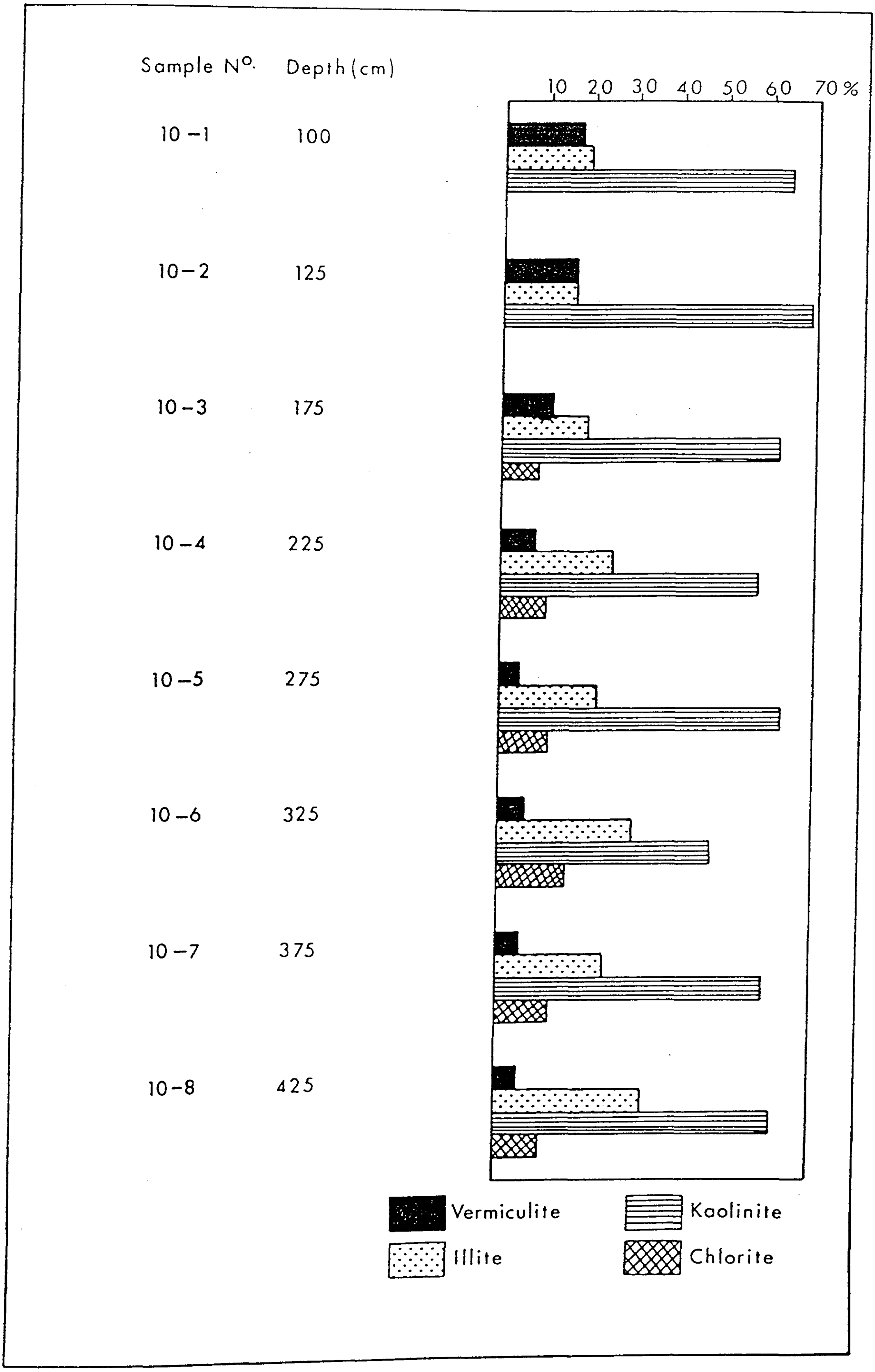


Figure 6.9 Distribution of clay minerals determined as XRD intensity percentages in a Grey till profile at Kelvinside - Great Western Road (NS 5360 7615).

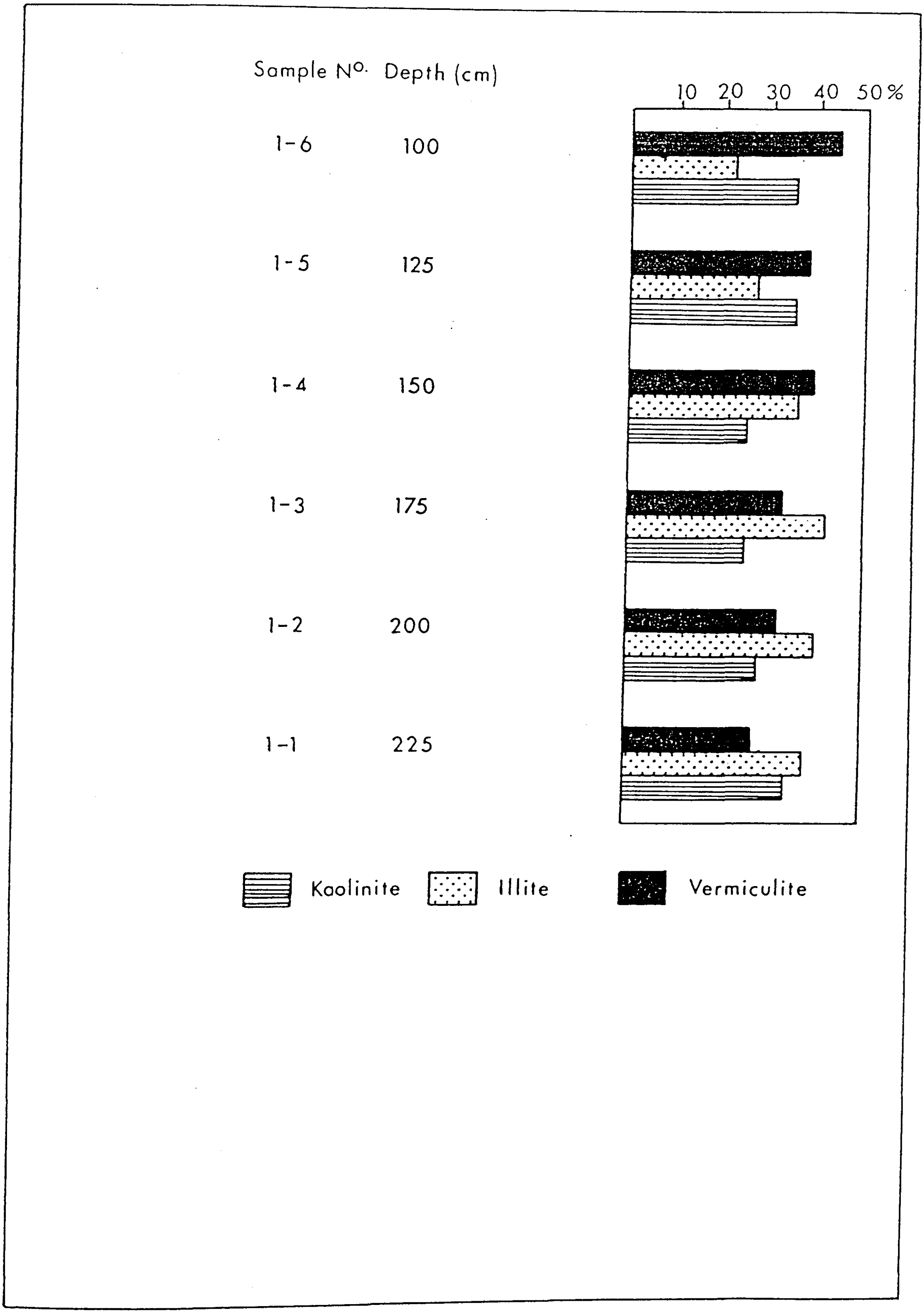


Figure 6.10 Distribution of clay minerals determined as XRD intensity percentages in a Red till profile at Laighpark (NS 5360 7615).

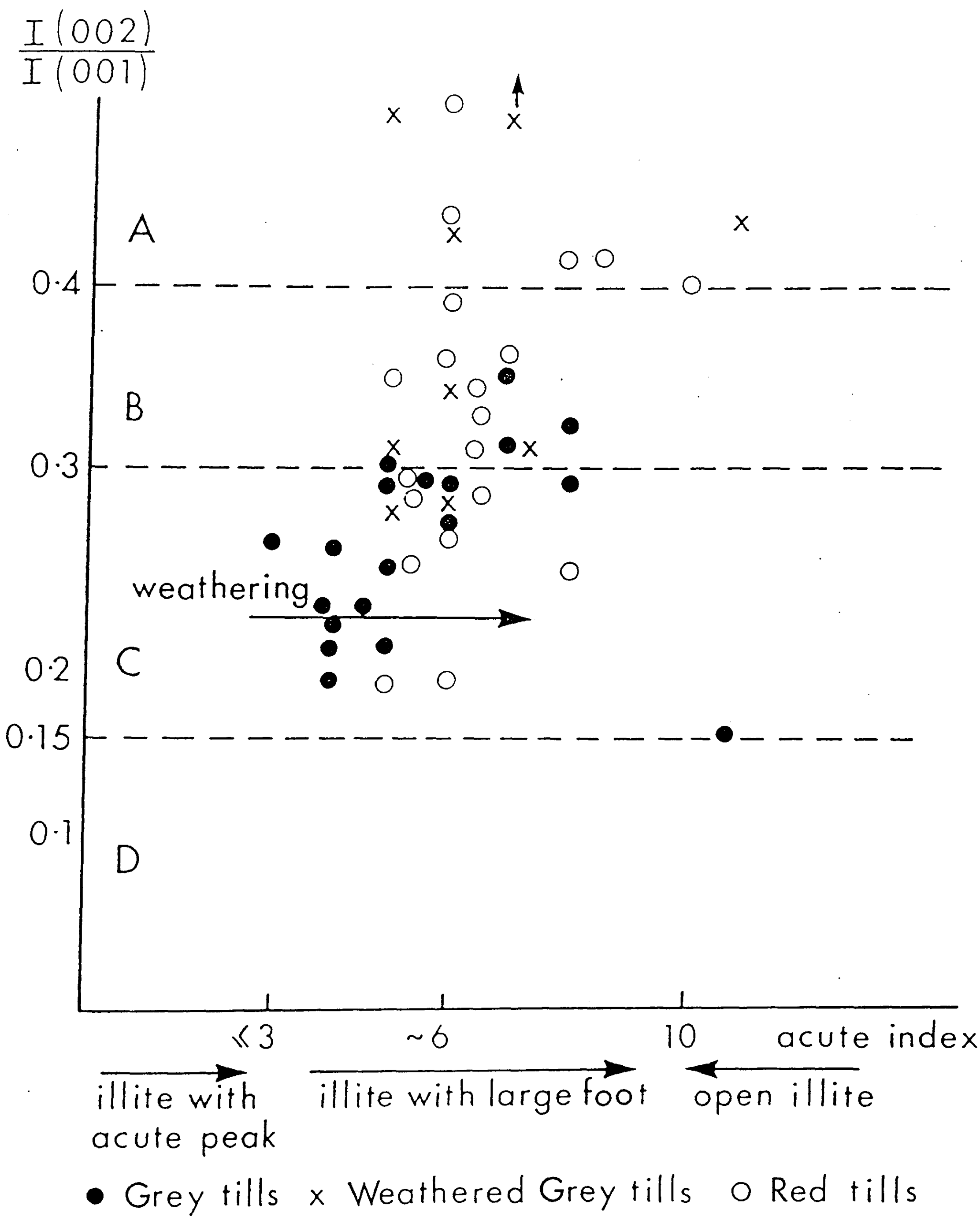


Figure 6.11 Illite varieties in the identified clay mineral assemblages (after Thorez 1976).

Table 6.1 Table of interplanar spacings for angle 2θ for CuK α-radiation

Ångströms	2θ in degrees
17.00	5.2
15.49	5.7
14.71	6.0
14.24	6.2
10.04	8.8
7.07	12.5
4.74	18.7
3.53	25.2

Table 6.2 Characteristics used for X-ray identification of clay minerals (<2 μm) in an oriented mount

Mineral	Effect of various pre-treatments on basal spacing		
	Air-dry basal spacing (Å)	Moistened with ethylene glycol	Heated for 45 minutes at 450°C
Chlorite	14	no change	no change
Vermiculite	14	no change	collapses to 10 Å
Montmorillonite	14	expands to ~17 Å	collapses to 10 Å
Swelling chlorite	14	expands to ~17 Å	collapses to 14 Å
Illite	10	no change	no change
Kaolinite	7	no change	no change

Table 6.3 Percentage clay mineral composition of the NW Glasgow till samples

No.	Field No.	Kaolinite	Illite	Vermiculite	Chlorite
	Red till				
1	R 1	52.90	19.60	27.50	—
2	2	47.10	20.40	32.50	—
3	4	34.00	21.30	44.70	—
4	8	43.80	20.80	35.40	—
5	16	53.20	22.50	24.30	—
6	30	54.50	18.20	27.30	—
7	31	40.60	29.00	30.40	—
8	32	31.60	26.30	42.10	—
9	34	34.10	22.70	43.20	—
10	35	39.10	23.00	37.90	—
11	37	53.20	16.20	30.60	—
12	39	39.50	23.30	37.20	—
13	41	37.70	21.30	41.00	—
14	42	41.70	27.80	30.60	—
15	43	48.50	14.70	36.80	—
16	44	35.60	22.20	42.20	—
17	45	33.30	30.30	36.40	—
18	47	35.80	29.90	34.30	—
19	48	61.30	16.10	22.60	—
20	49	56.80	22.70	20.50	—
	Weathered Grey till				
21	WG 6	55.10	20.40	24.50	—
22	7	58.10	23.30	18.60	—
23	12	63.80	15.40	20.80	—
24	13	59.90	16.30	23.80	—
25	14	56.70	18.50	24.80	—
26	15	69.20	16.10	14.60	—
27	17	59.40	13.30	27.30	—
28	28	60.70	15.40	23.90	—
29	29	58.40	17.50	14.10	—
30	33	57.50	15.30	27.20	—

Table 6.3 (continued)

No.	Field No.	Kaolinite	Illite	Vermiculite	Chlorite
	Grey till				
31	G 3	61.40	22.70	10.20	5.70
32	5	60.90	21.70	8.00	9.40
33	9	68.30	16.60	10.00	5.10
34	10	66.50	21.90	9.90	7.70
35	11	64.20	18.90	9.40	7.50
36	18	41.40	34.50	8.60	15.50
37	19	44.10	29.40	11.80	14.70
38	20	48.70	21.90	16.90	12.50
39	21	45.70	29.50	12.80	12.00
40	22	68.60	18.10	5.80	7.60
41	23	58.10	23.30	7.00	11.60
42	24	50.30	29.10	11.80	8.80
43	25	59.40	20.80	13.50	6.30
44	26	71.70	16.60	3.30	8.40
45	27	68.80	21.50	3.20	6.50
46	36	58.40	22.50	10.10	9.00
47	38	62.40	21.50	7.50	8.60
48	40	52.30	23.80	13.10	10.80
49	50	63.60	15.20	13.60	7.60
	Queen Margaret Hall, Grey till profile				
50	11 - 6	45.45	18.18	36.37	—
51	11 - 5	58.46	15.38	26.16	—
52	11 - 4	68.35	12.67	18.98	—
53	11 - 3	58.62	17.24	24.14	—
54	11 - 2	55.00	25.00	20.00	—
55	11 - 1	39.47	26.32	18.42	15.79
	Kelvinside, Grey till profile				
56	10 - 1	64.28	18.57	17.50	—
57	10 - 2	68.75	15.62	15.63	—
58	10 - 3	62.26	18.86	11.32	7.56
59	10 - 4	57.50	25.00	7.50	10.00
60	10 - 5	63.04	21.73	4.34	10.89
61	10 - 6	48.48	30.30	6.06	15.16
62	10 - 7	59.52	23.80	4.76	11.92
63	10 - 8	61.90	32.80	4.78	9.52

Table 6.3 (continued)

No.	Field No.	Kaolinite	Illite	Vermiculite	Chlorite
	Laighpark, Red till profile				
64	1 - 6	34.78	21.75	43.47	—
65	1 - 5	35.13	27.04	37.83	—
66	1 - 4	24.99	35.73	39.28	—
67	1 - 3	24.66	41.99	33.35	—
68	1 - 2	28.00	40.00	32.00	—
69	1 - 1	34.46	38.46	26.98	—
	Clober, Red till profile				
70	4 - 5	13.15	26.33	60.52	—
71	4 - 4	14.06	15.63	70.31	—
72	4 - 3	9.38	31.25	59.37	—
73	4 - 2	11.54	38.46	50.00	—
74	4 - 1	10.00	33.34	56.66	—

Table 6.4 Till samples from NW Glasgow area. Values of maximum (X max), minimum (X min), mean ($\overline{X}$) and standard deviation (S) of clay minerals (< 2 µm) for the three categories of till deposit. N gives number of samples.

Till category		Kaolinite	Illite	Vermiculite	Chlorite
Red till	X max	61.30	30.30	44.70	—
	X min	31.60	14.70	20.50	—
N = 20	$\overline{X}$	42.01	21.42	33.90	—
	S	9.05	6.12	6.90	—
Weathered	X max	69.2	23.30	27.30	—
Grey till	X min	55.10	13.30	14.10	—
N = 10	$\overline{X}$	59.88	17.15	21.96	—
	S	3.83	2.76	4.54	—
Grey till	X max	71.70	34.50	16.90	15.50
	X min	41.40	15.20	3.20	5.10
N = 19	$\overline{X}$	58.67	22.61	9.81	9.19
	S	8.87	4.85	3.45	2.86

Table 6.5 Clay mineralogy of the three categories of till in the NW Glasgow area

Category of till	Clay minerals present	Abundance			
		Dominant	Major	Subordinate	Minor
Red till	Kaolinite		——		
	Illite			——	
	Vermiculite		——		
Weathered Grey till	Kaolinite	——			
	Illite			——	
	Vermiculite		——		
Grey till	Kaolinite	——			
	Illite			——	
	Vermiculite				——
	Chlorite				——

Dominant >50%; Major 20–50%; Subordinate 10–20%; Minor <10%

CHAPTER 7

GEOCHEMICAL ANALYSIS OF TILLS OF THE NW GLASGOW AREA

7.1 Introduction

The tills of the NW Glasgow area, although comprising only two main types, Red till and Grey till, are derived from a great diversity of underlying bedrocks (Chapter 1.2). A detailed investigation of the major- and trace-element geochemistry of the matrix (<2mm) of samples of the tills, therefore, was carried out. The purposes of this investigation were to identify compositional differences between the varieties of tills and to relate till chemistry to the mineral composition of the till and, if possible, to the source rock. Both X-ray fluorescence and wet chemical analyses were employed. The results are shown in Tables 7.1 to 7.10.

An attempt was made to calculate the mineralogical composition of the till matrix by allocating the chemical constituents as realistically and accurately as possible to minerals known to occur in each sample. This comparison of the X-ray and chemical data ensured that the two sets of data were not conflicting, and facilitated the identification of compositional similarities and differences between Red and Grey tills.

7.2 Calculations described in the literature

Calculation of the mineralogical composition of igneous rocks from their chemistry was outlined by Cross, Iddings, Pirsson and Washington (1903). By their system, generally known as the CIPW system, a chemical analysis is used to calculate a theoretical mineral composition, called the norm of the rock. The original intention was to use the method to assist in the classification of igneous rocks, not to determine the mode (i.e. the actual mineralogy). The norm includes minerals of simple chemical composition that crystallise from magmas, but does not include complex minerals such as micas and amphiboles. The calculated norm may or may not agree with the actual mineralogical composition of the rock. CIPW normative calculations have been widely applied to igneous rocks.

Krumbein & Pettijohn (1938) indicated the possible value of chemical analyses in identifying minerals in fine-grained sedimentary rocks, and gave an example of the calculation of the norm of a greywacke. They pointed out that the calculations were only as appropriate as the assumptions underlying them. Miesch (1962) calculated the possible range of mineralogical compositions of sedimentary rocks from the chemistry and the known mineralogy. Nicholls (1962) proposed a scheme for recalculating chemical analyses first into normative formulae representing ideal muscovite, paragonite, kaolinite, magnesian antigorite and iron antigorite, which in turn may be regrouped into normative minerals of more probable natural occurrence, such as illite, chlorite and kaolinite.

Imbrie & Poldervaart (1959) described a method for the calculation of mineral compositions from chemical analyses of sedimentary rocks that contain minerals of complex and variable composition, including montmorillonite, illite and chlorite. In the shale studied by them, these minerals were carefully determined, using several analytical techniques. Once the norm minerals were determined and the chemical compositions of these minerals were assigned, the amounts of each mineral in the individual samples were determined by following a sequence of steps and allotting the chemical elements to the various norm minerals. This method obtained good agreement between norm value, amounts of insoluble residues and X-ray quantitative values for percent of carbonates, quartz and total clay minerals (Imbrie & Poldervaart 1959, Tables 5 and 6). However, there was little agreement between the norm calculations and X-ray values for the various clay minerals.

7.3 Description of Calculation Form

Selection of mineral suite

Mineral species identified in the till matrix by XRD (Fig. 7.1) are listed in Table 7.11. Four minerals had to be assumed in order to reflect completely the stated chemical analysis (Table 7.12; apatite, to use up all P_2O_5; rutile for TiO_2; hematite for Fe_2O_3; siderite for CO_2). It is apparent that the calculation system proposed by Imbrie & Poldervaart (1959) will not be applicable, for two reasons. Firstly, the total CaO and MgO are insufficient to use up all the CO_2, assuming that all CO_2 came only from calcite and dolomite. Secondly, if dolomite and/or ferrodolomite are formed, MgO will be insufficient to form vermiculite.

Four samples were tested for carbonate content, using 0.1 M HCl. From the amount of HCl that reacted with the sample powder, the CO_2 content in the four samples was calculated. In each sample, it was found that the CO_2 content determined by this method was lower than that determined by heating the sample at 1100°C in a stream of dry nitrogen. This means that the CO_2 results determined by combustion were not reliable, probably because S and halogens are being added to the CO_2. Therefore, in order to solve the CO_2 problem, the carbonates should be calculated as calcite and siderite, assuming that FeO came from siderite, and the MgO should be left for calculation of the clay minerals. This is because examination of the till matrix using dilute HCl reveals carbonate in the till matrix in amounts too small to be detected by X-ray analysis (Dr C.M. Farrow, personal communication). However, although there is no siderite detected by the XRD analysis, FeO is computed as siderite because siderite is a carbonate mineral that could be present in the tills, particularly in the Grey till, since siderite is present in some of the Carboniferous bedrocks over which the glacier has passed (Dr W.G. Jardine, personal communication). When the amounts of CaO and FeO are insufficient to use up all the CO_2 available, the remaining CO_2 unused to this point is ascribed to 'an analytical error'.

The K is partly in K-feldspar and partly in clay minerals and mica. If the K were largely in the K-feldspar, negative correlation of al-alk with Niggli k would be observed (K-feldspar has al-alk = 0, k = 1.0), whereas if the K were largely in sheet silicates a positive correlation would be present. The absence of both positive and negative correlations suggests a mixture of the two minerals was involved.

A plot of Niggli k against al-alk for the various till samples (Fig. 7.2a) shows a well-defined trend of increasing k and al-alk. This plot indicates that K in the till matrix is largely contributed by the clay minerals rather than K-feldspar. Hence, all K_2O is computed as a constituent of illite.

MgO is computed only as vermiculite for three reasons:

1) Vermiculite has been detected by the XRD analysis.
2) Dolomite has not been detected by the XRD analysis.
3) Chlorite is not present in either the Red or the Weathered Grey till samples, and the small amounts in which it occurs in the Grey till samples probably cause very little error in the chemical calculations.

From the above discussion it is possible to draw up the following preliminary list of minerals for computation: apatite, rutile, albite, calcite, siderite, hematite, illite, vermiculite, kaolinite and quartz.

Essentially, the procedure comprises the following steps:

1) Convert the wt% of the various oxides into molecular proportions (to five decimal places) by dividing the oxide wt% by the corresponding molecular weight. (For ease of reference, each molecular proportion is designated by a capital letter in the Form and examples given below.) For simplicity, each molecular proportion is multiplied by 1000. An entry of 1.34, for example, represents a molecular proportion of 0.00134.

2) Calculate the carbonate as follows. From the molecular proportion of CaO, subtract the proportion of CaO remaining after allowing for CaO used in apatite. From the molecular proportion of the CO_2, subtract the proportion of CaO remaining after allowing for CaO in calcite. From the molecular proportion of FeO, calculate the amount of siderite.

3) Calculate the analytical error of CO_2 as follows. From the molecular proportion of CO_2, subtract both the molecular proportion of CaO used in calcite and the molecular proportion of FeO used in siderite.

4) In the Form and examples given below, the quantities of 'M', 'H', 'L' and 'W' represent the molecular proportions of MgO, K_2O, Al_2O_3 and SiO_2 respectively, available for clays and quartz. All of K_2O is computed as illite, and all of MgO is computed as vermiculite. After calculating these two minerals, the remaining Al_2O_3 is computed as kaolinite. All Fe_2O_3 is computed as hematite and all TiO_2 is computed as rutile. The remainder of the SiO_2, after forming the clay minerals, is computed as quartz.

The calculation Form used in this study is:

1.	$P_2O_5 \div 141.95$	$= B \times 310.19$	= % Apatite
2.	TiO_2		= % Rutile
3.	$Na_2O \div 61.98$	$= T \times 524.30$	= % Albite
4.	$CO_2 \div 44.01$	$= A$	
5.	$CaO \div 56.08 = \quad - 3B$	$= C \times 100.09$	= % Calcite
6.	$FeO \div 71.84$	$= D \times 115.85$	= % Siderite
	$A - (C + D) = \quad \times 44.01$	$= \%CO_2$ analytical error	
7.	Fe_2O_3		= % Hematite
8.	$K_2O \div 94.20$	$= H \times 1050.60$	= % Illite
9.	$MgO \div 40.32 = M \div 3$	$= Q \times 471.18$	= % Vermiculite
10.	$Al_2O_3 \div 101.96 = K - (T + 4H + Q)$	$= S \times 256.12$	= % Kaolinite
11.	$SiO_2 \div 60.06 = W - (6T + 8H + 3Q + 2S)$	$= \quad \times 60.06$	= % Quartz

Example 1: Sample R 16

P_2O_5	0.09 ÷ 141.95	=	0.63 x 310.19	= 0.20 % Apatite
TiO_2	0.83			= 0.83 % Rutile
Na_2O	0.37 ÷ 61.98	=	5.97 x 524.30	= 3.13 % Albite
CO_2	3.86 ÷ 44.01	=	87.71	
CaO	0.34 ÷ 56.08 = 6.06 - 1.89	=	4.17 x 100.09	= 0.42 % Calcite
FeO	0.55 ÷ 71.84	=	7.66 x 115.85	= 0.89 % Siderite
	87.71 - (4.17 + 7.66)	=	75.88 x 44.01	= 3.33% CO_2 error
Fe_2O_3	4.27			= 4.27 % Hematite
K_2O	1.42 ÷ 94.20	=	15.07 x 1050.60	= 15.83 % Illite
MgO	0.63 ÷ 40.32 = 15.62 ÷ 3	=	5.20 x 471.18	= 2.45 % Vermiculite
Al_2O_3	13.18 ÷ 191.96 = 129.27 - 71.45	=	57.82 x 256.12	= 14.81 % Kaolinite
SiO_2	70.09 ÷ 60.06 = 1166.99 - 257.78	=	909.21 x 60.06	= 54.61 % Quartz
			Total	= 97.44%

Example 2: Sample R 39

P_2O_5	0.14 ÷ 141.95		=	0.99 x 310.19	=	0.31 % Albite
TiO_2	0.86				=	0.86 % Rutile
Na_2O	1.34 ÷ 61.98		=	21.60 x 524.30	=	11.34 % Albite
CO_2	1.26 ÷ 44.01		=	28.60		
CaO	0.92 ÷ 56.08	= 16.40 - 2.97	=	13.43 x 100.09	=	1.34 % Calcite
FeO	0.78 ÷ 71.84		=	10.86 x 115.85	=	1.26 % Siderite
	28.60 - (13.43 + 10.86)		=	4.31 x 44.01	=	0.19 % CO_2 error
Fe_2O_3	4.12				=	4.12 % Hematite
K_2O	1.24 ÷ 94.20		=	13.16 x 1050.60	=	13.83 % Illite
MgO	0.11 ÷ 40.32	= 2.73 ÷ 3	=	0.91 x 471.18	=	0.43 % Vermiculite
Al_2O_3	8.55 ÷ 101.96	= 83.86 - 75.15	=	8.71 x 256.12	=	2.23 % Kaolinite
SiO_2	76.08 ÷ 60.06	= 1266.73 - 255.03	=	1011.70 x 60.06	=	60.76 % Quartz
				Total	=	96.48 %

Example 3: Sample G 3

P_2O_5	0.19 ÷ 141.95	=	1.34 x 310.19	=	0.42% Apatite
TiO_2	1.02			=	1.02 % Rutile
Na_2O	1.64 ÷ 61.98	=	26.46 x 524.30	=	13.87 % Albite
CO_2	5.61 ÷ 44.01	=	127.47		
CaO	2.45 ÷ 56.08 = 43.69 - 4.02	=	39.67 x 100.09	=	3.97 % Calcite
FeO	1.66 ÷ 71.84	=	23.11 x 115.85	=	2.68 % Siderite
	127.47 - (39.67 + 23.11)	=	64.69 x 44.01	=	2.85 % CO_2 error
Fe_2O_3	4.31			=	4.31 % Hematite
K_2O	1.75 ÷ 94.20	=	18.58 x 1050.60	=	19.52 % Illite
MgO	1.99 ÷ 40.32 = 49.36 ÷ 3	=	16.45 x 471.18	=	7.79 % Vermiculite
Al_2O_3	13.54 ÷ 101.96 = 132.80 - 117.23	=	15.57 x 256.12	=	3.99 % Kaolinite
SiO_2	62.21 ÷ 60.06 = 1035.80 - 387.89	=	647.91 x 60.06	=	38 91 % Quartz
			Total		96.48 %

Example 4: Sample G 50

P_2O_5	0.15 ÷ 141.95	= 1.06 x 310.19	=	0.33 % Apatite
TiO_2	0.88		=	0.88 % Rutile
Na_2O	0.62 ÷ 61.98	= 10.00 x 524.30	=	5.24 % Albite
CO_2	7.48 ÷ 44.01	= 169.96		
CaO	1.47 ÷ 56.08 = 26.21 − 3.18	= 23.03 x 100.09	=	2.31 % Calcite
FeO	2.69 ÷ 71.84	= 37.44 x 115.85	=	4.34 % Siderite
	169.96 − (23.03 + 37.44)	= 109.49 x 44.01	=	4.81 % CO_2 error
Fe_2O_3	3.32		=	3.32 % Hematite
K_2O	1.60 ÷ 94.20	= 16.98 x 1050.60	=	17.78 % Illite
MgO	1.55 ÷ 40.32 = 38.44 ÷ 3	= 12.81 x 471.18	=	6.04 % Vermiculite
Al_2O_3	14.84 ÷ 101.96 = 145.55 − 90.73	= 54.82 x 256.12	=	14.04 % Kaolinite
SiO_2	60.22 ÷ 1002.66 − 343.91	= 658.75 x 60.06	=	39.56 % Quartz
		Total	=	93.84 %

The results in examples 1, 2, 3 and 4 are not satisfactory since the method gave erroneous concentrations for the clay minerals, presumably due to the difference in the orders of formation of these minerals, and also because the precise chemical composition of each clay mineral in the till matrix is not known. However, in cases where the ideal composition of a mineral in the till matrix is known within limits, the mineral composition of the till matrix can be computed within ranges. The widths of the ranges will depend on the degree of uncertainty regarding the composition of the mineral and on the abundance of the mineral of questionable composition in the till matrix. Clay minerals are the constituents of most questionable composition in the till matrix.

A check on the accuracy of the computed composition is provided by X-ray diffraction analysis of the same samples. Results are given in Table 7.13, where the chemical results are compared with the results obtained from the XRD analysis. Agreement between the two sets of figures for quartz, although imperfect, is remarkably good. The largest error (samples R39 and G3) is about 13%. In the remaining two samples (R16 and G50) it is about 2%.

Generally, it may be concluded that examination of Table 7.13 shows that there is no agreement between the two methods as regards proportions of the various clay minerals. Even where the principal clay minerals in a sample have been identified, the accuracy of computation of their relative quantities from the bulk chemical composition of the till matrix depends largely on the number and kind of mineral phases involved and on the variability of their composition due to isomorphous replacement.

Also, it may be concluded that calculation of the mineral composition of a till matrix from its chemical composition can be accurate in cases where:

1) The qualitative mineral composition of the matrix is known.
2) The chemical analysis of the matrix is accurate.
3) The exact composition of each of the minerals in the matrix is known.

7.4 Major Elements Geochemistry

7.4.1 Introduction

During the last decade much effort has been expended in interpreting the origin of glacial tills from their petrographic character, using the nature and abundance of their pebbles. Numerous criteria have been used to characterise, distinguish or correlate tills. Many of the criteria deal with the lithological composition, often by investigation of selected size fractions.

The chemical composition of a rock suite could be indicative of its provenance, but there is little published information about the chemical compositions of till matrices of known provenance. Chemical composition, except for quantitative carbonate determinations, has seldom been utilised. Analysis of till for selected elements has been made for specific purposes, such as geochemical prospecting of ore deposits (e.g. Kvalheim 1967), determination of plant nutrients and other significant constituents of till as a parent material of soils (e.g. Bear 1964), and determination of toxic elements (e.g. Warren _et al_. 1967).

One of the most extensive regional investigations of tills was made in Alberta by Pawluk & Bayrock (1969), who determined ten chemical parameters in 475 till samples from an area of 170,000 square miles. They concluded that Fe, B, Co, Cu, Zn and Mo, present in tills of Alberta, appear to have originated from a common source, and are principally associated with the clay size fraction.

Recently, Broster (1986) analysed the <0.037mm fraction of unleached samples of two Late Wisconsinan till units exposed at Port Albert, Ontario. It was concluded that Q-mode cluster and multivariate discriminant analysis could prove useful in delineation of compositional stratification where none is otherwise apparent.

A detailed description of the distribution and abundance of major elements in the tills of the NW Glasgow area is given in succeeding pages. The major elements used in the chemical correlation studies are discussed within the explanations for the chemical correlations. Ranges, means and standard deviations for major elements were calculated (Table 7.14).

7.4.2 SiO_2

The SiO_2 abundance of the Red till varies between 61 and 79%. The Weathered Grey till and the Grey till ranges are 58 to 75% and 60 to 71% respectively. The Red till has the highest average SiO_2 content (see Table 7.14). Generally, most of the samples from the Red till appear to be enriched in SiO_2 more than the samples from the Grey till. The high silica content in the Red till presumably is related to a high quartz content. The Grey till has an increased amount of clay content (compared with that of the Red till), which explains the Grey till's lower SiO_2 content. The high silica content in both Red and Grey tills suggests sandstone source rocks. The higher average SiO_2 content in the Weathered Grey till than in the Grey till (Table 7.14) suggests that, in the Weathered Grey till, silica has been increased at the expense of CaO, MgO, Na_2O and K_2O, which have been depleted by leaching.

7.4.3 Al_2O_3

The Al_2O_3 content of the Red till varies between 7 and 14%. The

Grey till and Weathered Grey till have a higher Al_2O_3 content, ranging between 10 and 17%. All three till categories show an inverse relationship of Al_2O_3 with SiO_2 (see Tables 7.15 to 7.18).

The abundance of Al_2O_3 may be directly related to the abundance of feldspars, micas and clays. The positive correlation between Al_2O_3 and K_2O (see Tables 7.15 to 7.18 and Fig. 7.2b) indicates that Al_2O_3 in the till is contained mainly in the clay minerals. The negative relationships between Al_2O_3 and SiO_2 (see Tables 7.15 to 7.18 and Fig. 7.3a) and SiO_2 and K_2O (see Tables 7.15 to 7.18 and Fig. 7.3b) support this view.

Because the Al_2O_3 in the tills is considered to be almost exclusively in the clay minerals, Al_2O_3 is believed to be a valid indicator of the content of the clay minerals in general, and this obviously influences the concentration of several elements, such as K, Fe and Mg and many trace elements, which are also present in the typical clay minerals.

The inverse relationship of Al_2O_3 with SiO_2 (Fig. 7.3a), seen in the three categories of tills, is due to decrease of clays with increasing amount of quartz. This trend could be interpreted as suggestive of a quartz-rich sandstone source-rock or rocks. The lower Al_2O_3 content for the Red till (average 11.63%) than for the Grey till (average 13.34%) suggests that the Red till has been derived from a sandstone source-rock with a higher quartz content than that of the Grey till.

7.4.4 TiO_2

The TiO_2 content varies between 0.77 and 1.58% for the Red till, 0.73 and 0.94% for the Weathered Grey till and 0.69 and 1.02% for the Grey till (Table 7.14). All three categories of till show inverse relationship of TiO_2 with SiO_2 (Tables 7.15 to 7.18 and Fig. 7.4a).

The Red till samples are richer in SiO_2 and TiO_2 than the Grey till samples (Table 7.14).

Wedepohl (1978) suggests that the TiO_2 content in sediments is due to terrigenous material consisting of: 1) residues of weathering in the form of chemically unaltered grains like rutile or in the form of partly decomposed minerals like micas; 2) new products of weathering such as anatase and clay minerals; and, 3) diagenetic minerals. The relationships of TiO_2 with Al_2O_3 and K_2O show positive correlations in the case of the Weathered Grey till and Grey till (Tables 7.16 and 7.17). Thus the Ti content in both Grey and Weathered Grey tills may be related to the clay minerals. In the case of the Red till, however, correlations of TiO_2 with Al_2O_3 and K_2O do not show any clear trends (Table 7.15). A tentative interpretation of these relations is that, in the Red till, TiO_2 does not favour an association with clay minerals and may be present in accessory minerals such as rutile and ilmenite.

7.4.5 FeO and Fe_2O_3

The FeO content of all three categories of till ranges between 0.4 and 4.2 wt%, and the Fe_2O_3 content falls within the range 1.5 to 8.0 wt%. The average Fe_2O_3 contents are 5.05%, 4.46% and 3.1% for the Red, Weathered Grey and Grey tills respectively, while the average FeO contents are 0.86%, 0.67% and 2.42% for Red, Weathered Grey and Grey tills respectively. All the Red till and Weathered Grey till samples appear to have more Fe_2O_3 than FeO, while the Grey till samples appear to have more FeO than Fe_2O_3 (Fig. 7.4b). The explanation of the higher amount of Fe_2O_3 in the Weathered Grey till than in the Grey till is that oxidation of ferrous minerals in the Weathered Grey till occurs during weathering, so the resulting sediment has a higher Fe^{3+}/Fe^{2+} ratio. However, the difference in the Fe^{3+}/Fe^{2+} ratio between Grey and Red tills could be due to different amounts of Fe_2O_3 and FeO in the source-rocks of the Grey and Red tills.

7.4.6 MgO

The MgO content of the three categories of till varies between 0.11 and 2.61 wt%. The average MgO contents are 1.12%, 1.21% and 1.65% for the Red, Weathered Grey and Grey tills respectively. All the categories of till show an inverse trend of MgO with SiO_2 (Tables 7.15 to 7.18 and Fig. 7.5a). The negative correlation of MgO with SiO_2 shows that both clay minerals and carbonates decrease with increasing silica content.

7.4.7 CaO

The CaO content of the Red till samples falls within a range of 0.3 to 2.3 wt%. The CaO content of the Weathered Grey till samples shows a wide spread of values, falling within the range 0.2 to 3.2 wt%. The Grey till samples show a narrow range of values, falling mostly within the range 1.0 to 2.4 wt%. The average CaO contents are 0.73%, 1.04% and 1.79% for the Red, Weathered Grey and Grey till respectively, and most of the Grey till samples seem to be richer in CaO than both Red and Weathered Grey till samples. Both Red and Weathered Grey tills show an inverse relationship of CaO with SiO_2 (Tables 7.15 and 7.16). The Grey till does not show any discernible trends (Table 7.17). The samples of Red and Grey till occupy two distinctly different positions in the plot of CaO against SiO_2 (Fig. 7.5b).

The negative correlation of CaO with SiO_2 (Fig. 7.5b) and the positive correlation of CaO with CO_2 and P_2O_5 (Figs. 7.6a and 7.7a) indicate that carbonates and apatite may be responsible for the abundance of CaO in the various categories of till. The CaO contribution from the Ca-plagioclases is very insignificant. The inverse $CaO-SiO_2$ and CO_2-SiO_2 relationships (Figs. 7.5b and 7.6b) indicate that the carbonate fraction decreases with increasing SiO_2 content.

7.4.8 Na_2O

The Na_2O content of the tills studied shows a small range of values, falling within 0.3 to 2.0 wt%. The Red till shows a mean value of 1.31%, which is insignificantly higher than the mean Na_2O content of 1.17% for the Grey till. The Weathered Grey till has a lower mean Na_2O content (0.95%) than both the Red and Grey tills. The positive correlation of Na_2O with SiO_2 (Table 7.18 and Fig. 7.7b) shows that the Na_2O content of the various categories of till is primarily in the Na-feldspar. The lower Na_2O content of the Weathered Grey till than that of the Grey till may be an indication of weathering.

7.4.9 K_2O

The K_2O contents of the Weathered Grey till (1.57 wt%) and the Red till (1.50 wt%) are smaller than that of the Grey till (1.74 wt%) (Table 7.14). All three categories of till show definite inverse relationships of K_2O with SiO_2 (Tables 7.15 to 7.18 and Fig. 7.3b). A good positive correlation was found between Al_2O_3 and K_2O (Tables 7.15 to 7.18 and Fig. 7.2b), supporting the dominance of K by clay minerals as discussed above (Chapter 7.3). The negative correlation of K_2O with SiO_2, exhibited by the three categories of till, is the result of clay content decreasing with increasing SiO_2 content (Fig. 7.8). The plot of K_2O against SiO_2 (Fig. 7.3b) shows that the Red and Grey tills occupy almost separate fields. This could be due to the different amounts of clays and quartz present in the two categories of till.

7.4.10 MnO

The MnO content of all three categories of till varies between 0.02 and 0.15 wt%, and MnO has a negative relationship with SiO_2 and positive relationship with Al_2O_3 (Table 7.18). MnO is probably associated with clay minerals.

7.4.11 P_2O_5

The P_2O_5 content of the Red till varies between 0.06 and 0.22 wt%. Values for the Weathered Grey and Grey tills vary between 0.07 and 0.17 wt% and 0.11 and 0.19 wt% respectively. The average P_2O_5 contents of the three categories of till do not show much variation (Table 7.14).

Wedepohl (1978) reports that apatite is the main P mineral in sediments, but absorption of P on clay minerals can also be significant. The high positive relationship of P_2O_5 with CaO in the Red till ($r = 0.87$) shows that P_2O_5 in the Red till may be ascribed mainly to apatite and not to the clay minerals. The negative correlation of P_2O_5 with Niggli al-alk ($r = -0.29$) for the Red till supports this view. The low positive correlation of P_2O_5 with CaO in the Grey till ($r = 0.20$) and the good correlation of P_2O_5 with Al_2O_3 and K_2O (correlation coefficients 0.50 and 0.55 respectively) suggest that P_2O_5 in the Grey till may be ascribed to both apatite and clay minerals.

7.5 Trace Elements Geochemistry

As the result of the chemical composition of a till being a function of its lithology, it was expected that differentiation of the tills of the NW Glasgow area could be established on the basis of trace element analysis of the till matrix.

The 16 trace elements analysed as part of the geochemical investigation are discussed in this section. The results of trace element analysis are shown in Tables 7.6 to 7.10. Table 7.19 gives a summary of the ranges, means and standard deviations of the trace element contents in the three till categories considered.

It is remarkable that the average trace elements of the Grey till (Table 7.19) show that, except for Zr, every trace element has a higher value than in the average Red till. While some of the differences are so trivial that they can have no significance (e.g. Y, U, Th, Pb, Cu, Cr and Co), others such as Sr, Rb, Ba and Ce show obvious differences between Red and Grey tills. The higher Sr, Rb and Ba contents in the Grey till correlate well with the higher K_2O and CaO contents in the Grey till compared with the Red till (Tables 7.14 and 7.19).

A number of plots have been made to establish correlations between elements for discrimination between the three categories of till.

The parameter al-alk provides a measure of the Al in the original sediments contained in the clay minerals and micas rather than the Al added in feldspar, because al-alk in albite and K-feldspar is zero while detrital anorthite-rich feldspar is excluded by the absence of a positive correlation of al-alk and Ca. Consequently, plots made against al-alk should show which elements were dominantly added to the sediments in clay minerals and mica. Plots involving al-alk fall into three different categories:

1) Plots that show a good positive correlation with al-alk, such as those for Ce, La, Ga, Th and Y (Figs. 7.9 to 7.11a). In the Th plot, the low positive correlation in the Grey till samples ($r = 0.18$) may indicate that the source of this element in these

samples was not in the clay minerals. A plot of K20 and al-alk against Rb (correlation coefficients are 0.7 and 0.56 respectively; Figs. 7.12a and 7.12b) suggests that much of the Rb is concentrated in the clay minerals.

2) Plots showing a poor positive correlation with al-alk. These include Ni, U, Cr, Zr and Pb (Figs. 7.11b, 7.13 and 7.14). In the Zr plot, the positive correlation is good in the Red till (r = 0.56), which may indicate that the source of this element in this category of till was predominantly in the clay. Also, in the Pb plot the positive correlation is good in the Grey till samples (r = 0.68), which may indicate that the source of Pb in these samples was predominantly in the clay minerals.

3) Plots showing no correlation with al-alk. These include Cu, Zn, Co, Sr and Ba (Figs. 7.15 to 7.17a). These plots suggest that these trace elements are not associated with clay minerals. The plot of Sr against al-alk (r = 0.38; Fig. 7.16b) suggests that Sr rarely enters clay minerals. Sr correlates positively with K_2O (r = 0 49) and CaO (r = 0.77) (Figs. 7.17b and 7.18a), suggesting that Sr is concentrated in calcite and K-feldspars. There is substantial evidence to show that, in the three categories of till, Ba is concentrated mainly in the K-feldspar rather than in clays, as suggested by its high positive correlation with K_2O (r = 0.64; Fig. 7.18b) and negative correlation with al-alk (r = -0.09; Fig. 7.17a).

7.6 Grain-size control of trace element concentrations

Grain size plays an important role in controlling trace element concentration in rocks; the silt plus clay fraction (<0.063mm) tends to adsorb cations and, during leaching, release them more readily than the coarser fraction. In effect, silt and clay are the chemically active part of a sediment or soil, and the amount of silt and clay in a sand-silt-clay mixture strongly controls cation concentration.

Table 7.20 illustrates grain-size control on trace element concentration. All elements except Zr show negative correlations with the sand fraction. This means that all elements except Zr show a tendency to be concentrated preferentially in the silt and clay size fractions. Zr is concentrated in the sand fraction. In view of the positive correlation of Zr with al-alk in the Red till (see above, Chapter 7.5), it appears that Zr has a dual role. It is present, (1) in clay minerals and (2) as detrital zircon in sands, i.e. with quartz.

It is suggested that regional trace element concentration in till should be interpreted with caution, and that variation in concentration be rationalised with respect to grain size (and clay mineralogy) before interpretations are made and background or theshold levels established.

7.7 Weathering ratios

The mobility of trace elements is widely documented (Mitchell 1964) and is used in pedology to determine horizon development, leaching and accumulation layers within soil profiles (Aubert & Pinta 1977). Certain elements (e.g. Co) move downwards upon weathering while others remain in a stable position (e.g. Zr) or in some circumstances move upwards (e.g. Pb) (McLaughlin 1955; Swaine 1955; Vinogradov 1959; Swaine & Mitchell 1960; Mitchell 1964; Le Riche 1968; Yaalon *et al*. 1974). Therefore, ratios of trace element correlations may provide a way of detecting weathering in till profiles.

The concept of an elemental weathering ratio depends on the view that any two elements present in the same mineral have different stabilities within a crystal lattice when that mineral is weathered

(Mitchell 1964). Under these circumstances, one element may be released and transported away from the host mineral in preference to the other (Krauskopf 1967). Thus, by tracing the ratios of a pair of elements through till profiles it is possible to recognise the depth of weathering, where chemical weathering has altered the till, assuming that the deposit was originally homogeneous.

Table 7.21 lists some commonly-used weathering ratios, and the ratio trend based upon some weathering parameters proposed by Burek (1985). Figures 7.19 to 7.22 show the results obtained for the weathering ratios of Table 7.21 in the four till profiles in the NW Glasgow area.

Burek (1985) reports that the ratio of Ga:Al_2O_3 decreases with weathering because gallium and aluminium have similar ionic radii (0.62 A and 0.57 A respectively), and can substitute each other in kaolinite and illite. Gallium is always lost relative to aluminium in weathering (Short 1961). The results obtained for Ga:Al_2O_3 for the Grey till profiles at Kelvinside (Fig. 7.19) and Queen Margaret Hall (Fig. 7.20) show minor breaks, indicating initial weathering at about 2m depth below the ground surface. At about 2m depth is the junction between Weathered Grey till and non-weathered Grey till in the two profiles. The results obtained for Ga:Al_2O_3 for the Red till profile at Clober (Fig. 7.21) show a minor break at 1m depth. Generally the ratio of Ga:Al_2O_3 increases with depth in the studied till profiles.

Burek (1985) reports that the MgO:Ni ratio decreases with weathering since Ni^{++} can proxy for Mg^{++} and, under weathering conditions, Ni^{++} is more stable and less mobile than Mg. The Ni becomes more soluble but less so than Mg (Short 1961; Yaalon et al. 1974). Mg can be absorbed onto clay minerals such as chlorite (Burek 1985). The results obtained for MgO:Ni for the two Grey till profiles at Kelvinside (Fig. 7.19) and Queen Margaret Hall (Fig. 7.20) show that the MgO:Ni ratio generally increases downwards and the MgO:Ni ratio mimics the Ga:Al_2O_3 ratio with a break at about 2m depth, whereas the MgO:Ni ratio for the Clober and Laighpark Red till profiles (Figs. 7.21 and 7.22) shows breaks at about 125cm and 100cm respectively.

Generally there is a decreasing FeO:Co ratio with weathering because Co^{++} (0.82 Å) has a similar ionic radius to Fe^{++} (0.83 Å) and replaces it in minerals such as illite, muscovite, biotite, montmorillonite and olivine (Vinogradov 1959; Kabata-Pendias 1968; Le Riche 1968). Cobalt is more stable than Fe^{++} as weathering progresses (Short 1961). The results obtained for the FeO:Co ratio in the two Grey till profiles show that this ratio generally increases downwards in these profiles (Figs. 7.19 and 7.20), but in the Queen Margaret Hall profile the FeO:Co ratio shows an obvious break at 125cm depth (Fig. 7.20). Also, the FeO:Co ratio in the two Red till profiles generally decreases downwards (Figs. 7.21 and 7.22) and there is an obvious break in the FeO:Co ratio for the Laighpark Red till profile at about 200cm depth (Fig. 7.22).

Nickel is less mobile than Cobalt, especially under strong leaching conditions, and it is strongly bonded in clays such as chlorite and illite (Burek 1985). The results obtained for the Ni:Co ratio in the studied profiles (Figs. 7.19 to 7.22) show a general increase in the Ni:Co ratio with increasing depth, except at the Laighpark Red till profile (Fig. 7.22).

7.8 Conclusions

1) In order to compute the precise mineral composition of the till matrix from its chemical composition, the precise composition of

each mineral in the till should be known. However, in cases where the composition of a mineral is known only within limits the mineral composition of the till matrix may be computed within ranges. The widths of the ranges will depend on the degree of uncertainty regarding the composition of the mineral and the abundance of the mineral of uncertain composition in the till matrix. In tills, clay minerals are the constituents of most questionable composition. The method given here can be used to compute the mineral composition of the till matrix, but modification of the method must be made to overcome the problems of the minerals of uncertain composition. Even when the principal clay minerals in a sample have been identified, the accuracy of computation of their quantities from the bulk chemical composition of the till matrix depends largely on the number and kinds of mineral phases involved and the variability of their composition due to isomorphous replacement.

2) The average major element composition of the various categories of till from the NW Glasgow area shows that the Red till is richer in SiO_2, TiO_2, Fe_2O_3 and Na_2O than the Grey till. On the other hand, the Grey till appears to be richer in Al_2O_3, FeO, MnO, MgO, CaO, K_2O and P_2O_5 than the Red till.

3) The SiO_2 content in the three categories of till is high (average values are 70.92 $\pm$ 6.88% and 63.76 $\pm$ 4.39% for Red and Grey tills respectively). This is consistent with these tills having a source in the local sandstone bedrocks, which are enriched in SiO_2. The higher SiO_2 content in the Red till than in the Grey till is considered as a sign that the Red till was derived from quartz-rich sandstone rocks of a higher degree of maturity than

the sandstone source-rocks of the Grey till (cf. Chapter 9.5, below).

4) Al_2O_3, TiO_2, FeO, MnO, MgO, CaO, K_2O and P_2O_5 show an inverse relationship with SiO_2 content. Such inverse relationships may be due to decreasing amount of clay minerals with increasing SiO_2 content.

5) The higher Al_2O_3 and K_2O contents in the Grey till than in the Red till may be related to the higher amount of clay in the Grey till than in the Red till.

6) The higher abundance of Fe_2O_3 and the lower abundance of FeO in the Weathered Grey till than in the Grey till suggests that the oxidation of FeO started after deposition of the Grey till.

7) The average trace element contents of the Red and Grey tills show close similarity, with the exception of Sr, Rb, Ba and Ce.

8) The trace elements Ce, La, Ga, Y and Rb are assumed to be derived from the clay fraction, as inferred from the good correlation between them and Niggli al-alk. Sr is concentrated in Ca minerals, as inferred from its good correlation with CaO, while Ba is mainly concentrated in the K-feldspar rather than the clays, as suggested by its high positive correlation with K_2O and negative correlation with al-alk.

9) The concentrations of trace elements are at least partially influenced by the grain size of the samples studied. All the trace elements studied, except Sr, are preferentially concentrated

in the silt plus clay fraction (<0.063mm). Zr appears to have a dual role. It occurs in clay minerals and also in the sand fraction (2.00mm - 0.063mm) as detrital zircon. Grain size is an important variable that should be evaluated when establishing and interpreting trace element concentrations in tills.

10) The value of the weathering ratios Ga:Al_2O_3, MgO:Ni, FeO:Co and Ni:Co lies in their ability to pick up weathering trends that cause initial movement of trace elements. Definite, although minor, breaks in trends can be seen, particularly in the Grey till profiles, at about 2m depth at the junction between Weathered Grey till and non-weathered Grey till.

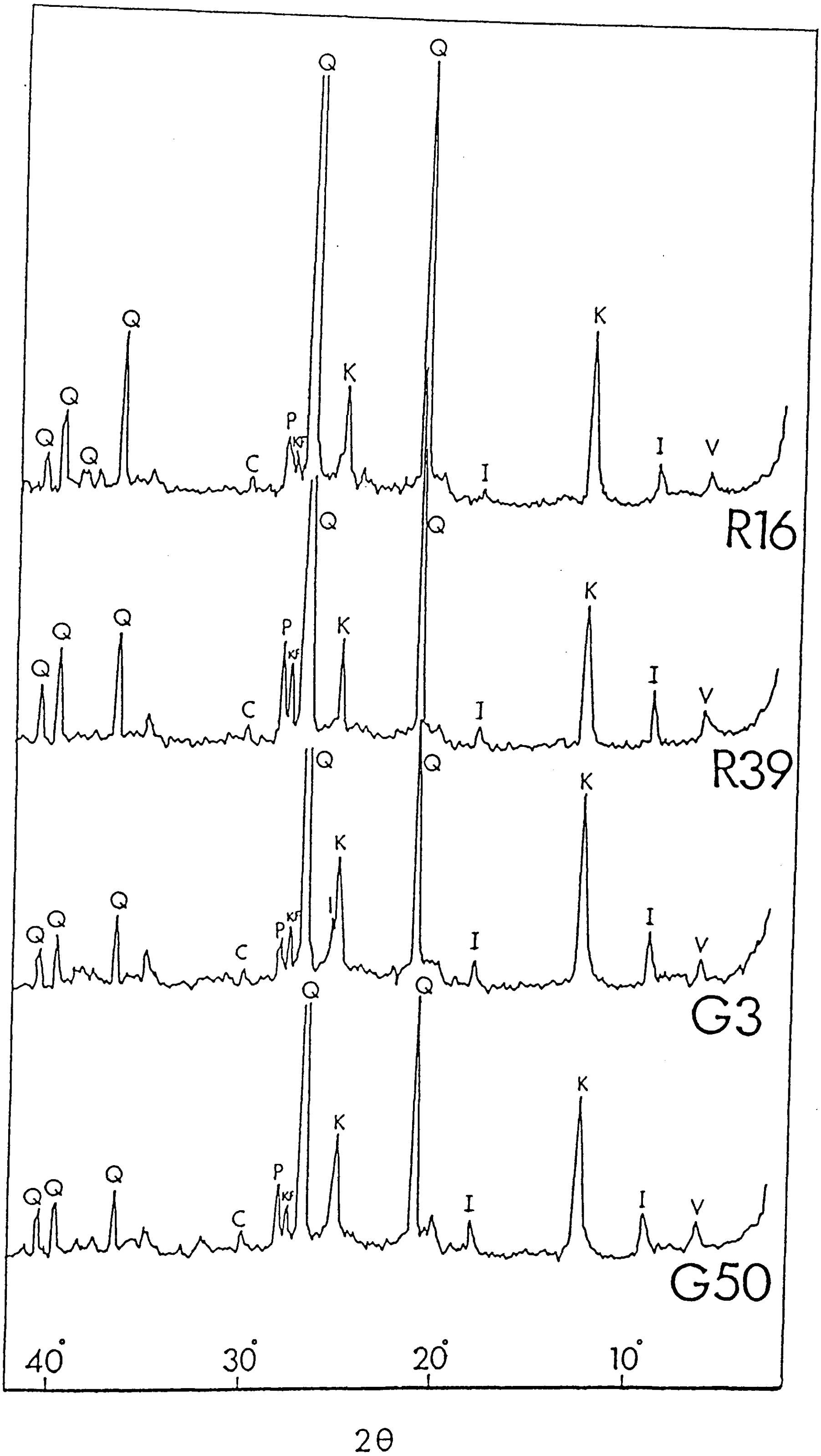


Figure 7.1 X-ray diffraction traces for matrices of the Red and Grey tills of the NW Glasgow area. Samples R16 and R39, Red till; samples G3 and G50, Grey till.
C = calcite, I = illite, K = kaolinite, KF = K-feldspar, P = plagioclase, Q = quartz, V = vermiculite.

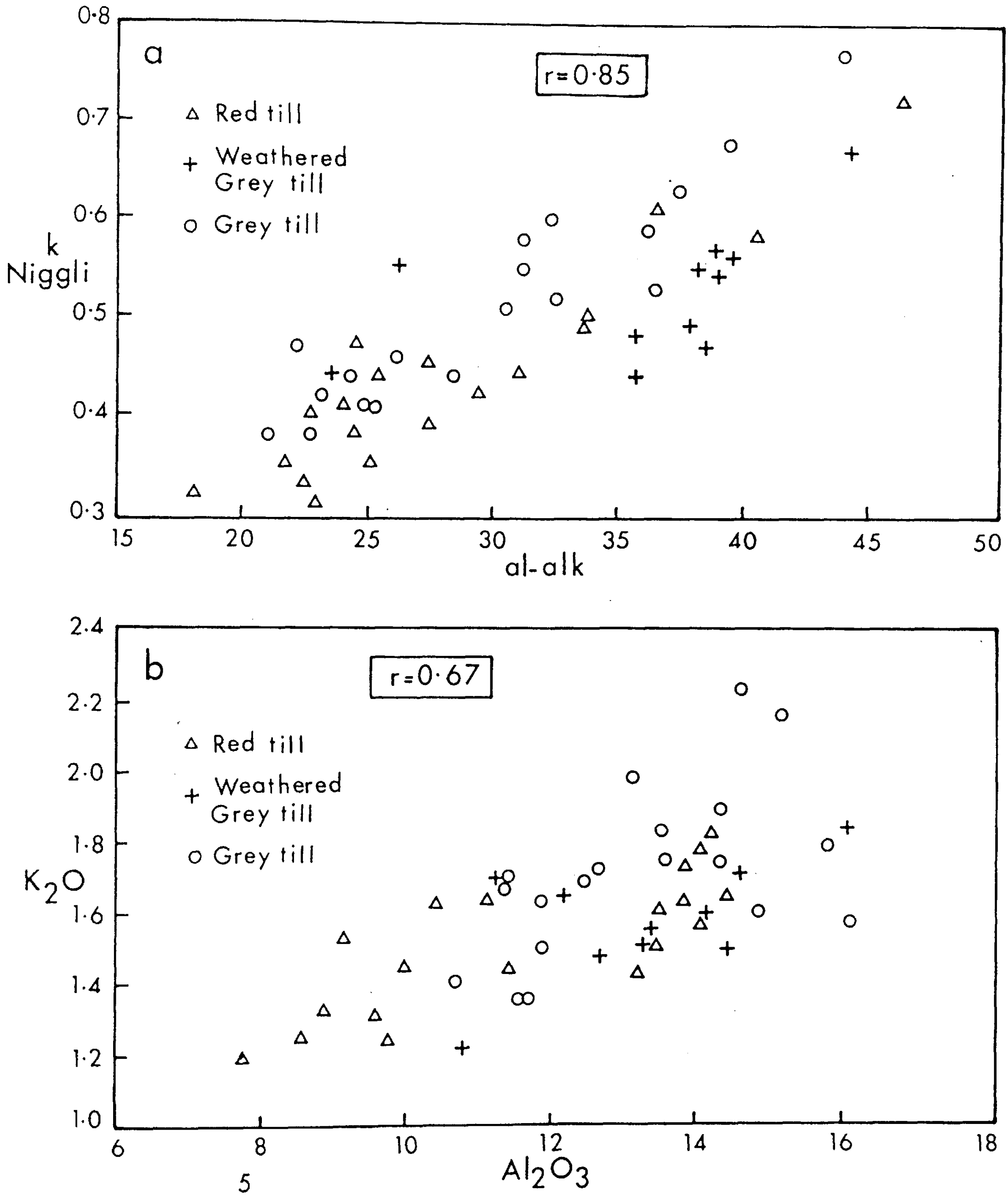


Figure 7.2 Plots of (a) k-Niggli against al-alk, and (b) K_2O against Al_2O_3

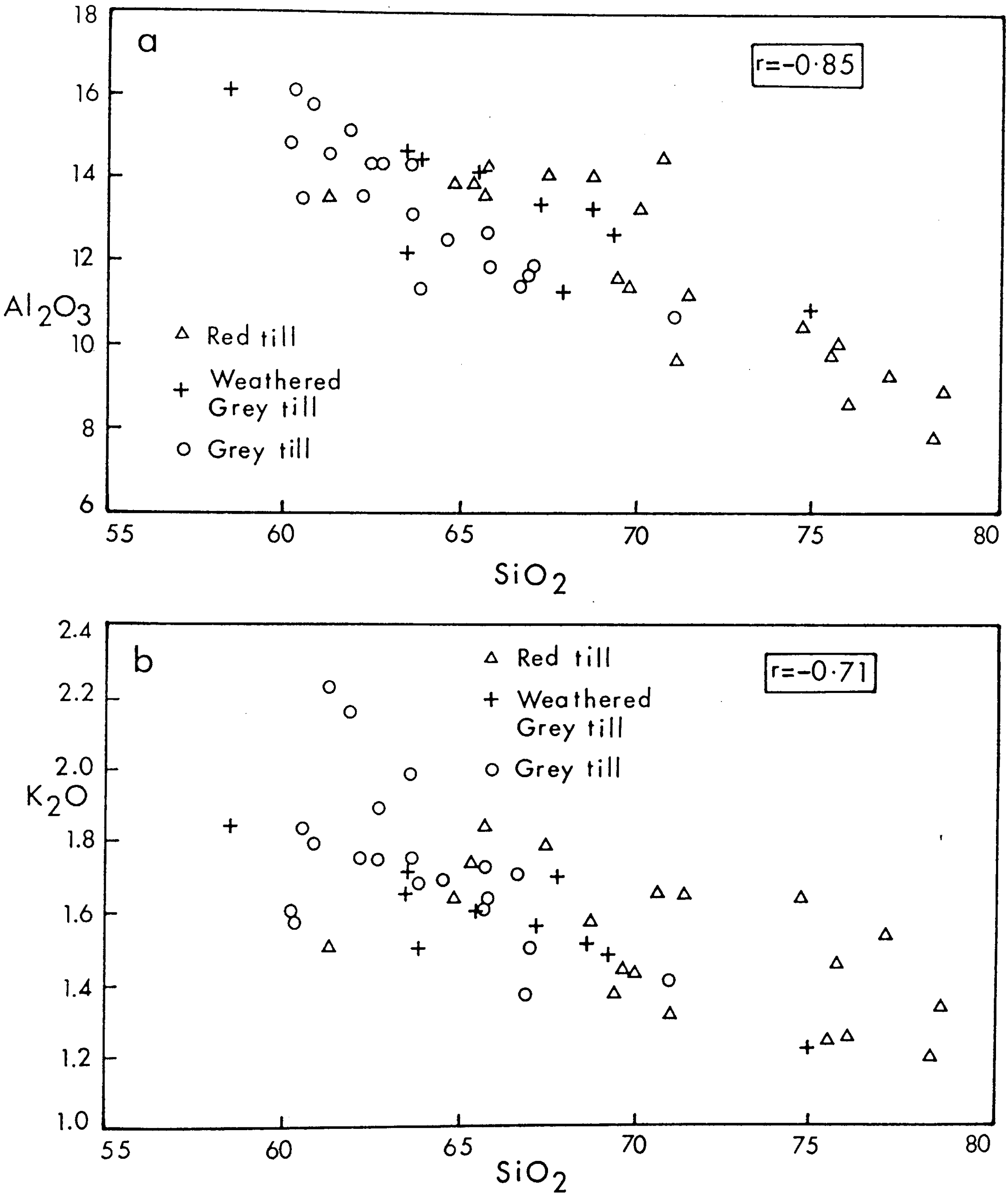


Figure 7.3 Plots of (a) Al_2O_3 against SiO_2, and (b) K_2O against SiO_2

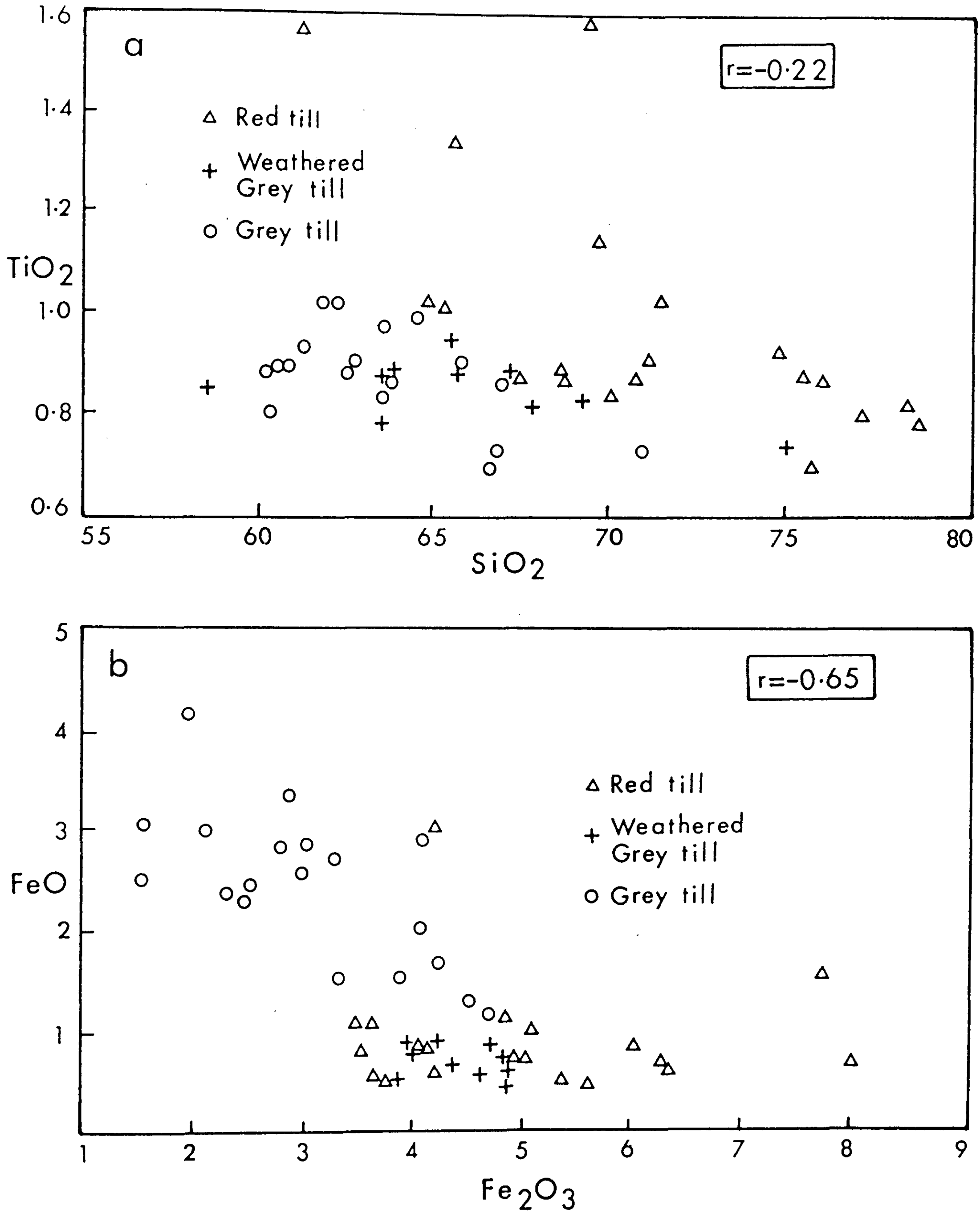


Figure 7.4 Plots of (a) TiO_2 against SiO_2, and (b) FeO against Fe_2O_3

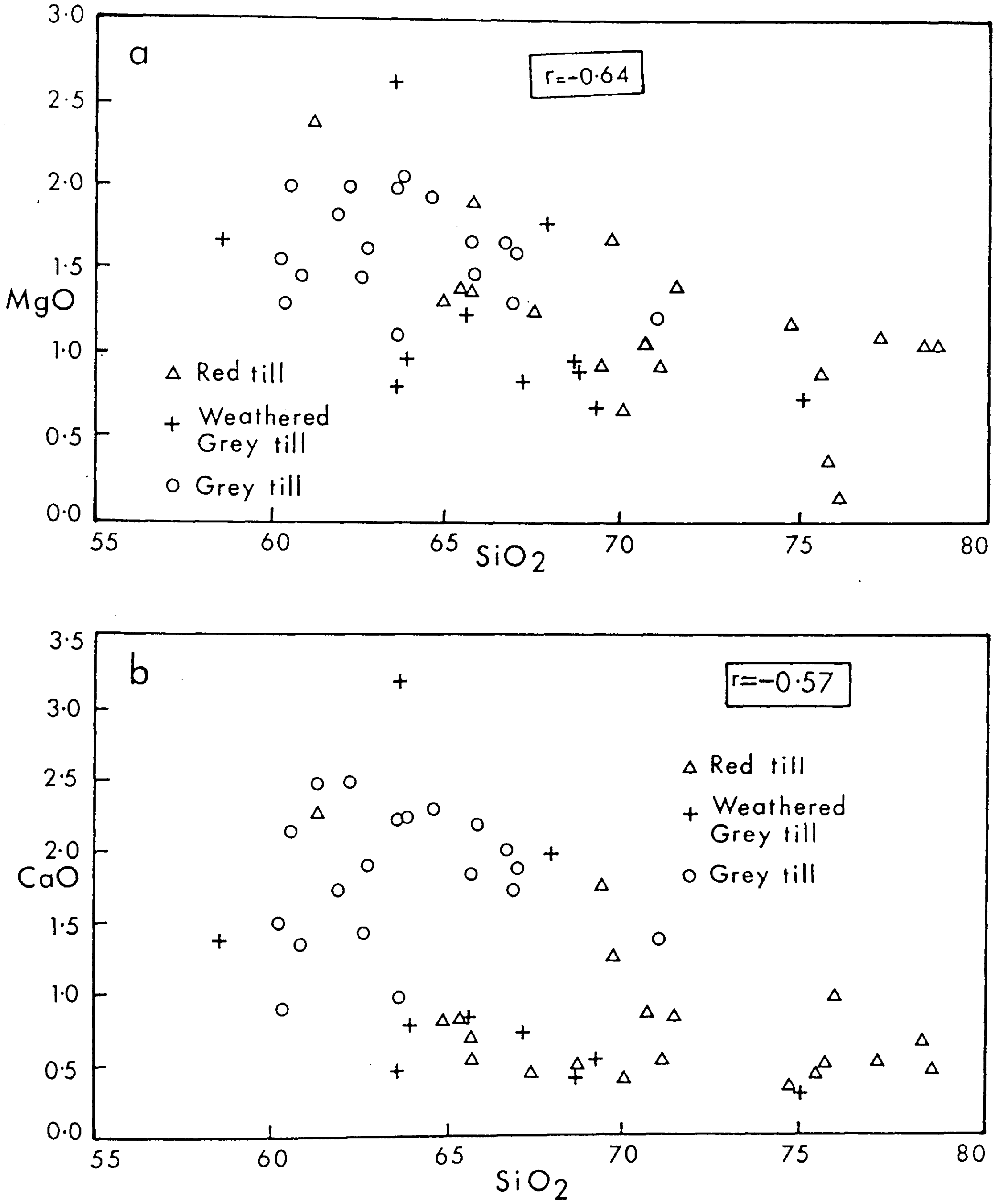


Figure 7.5 Plots of (a) MgO against SiO_2, and (b) CaO against SiO_2

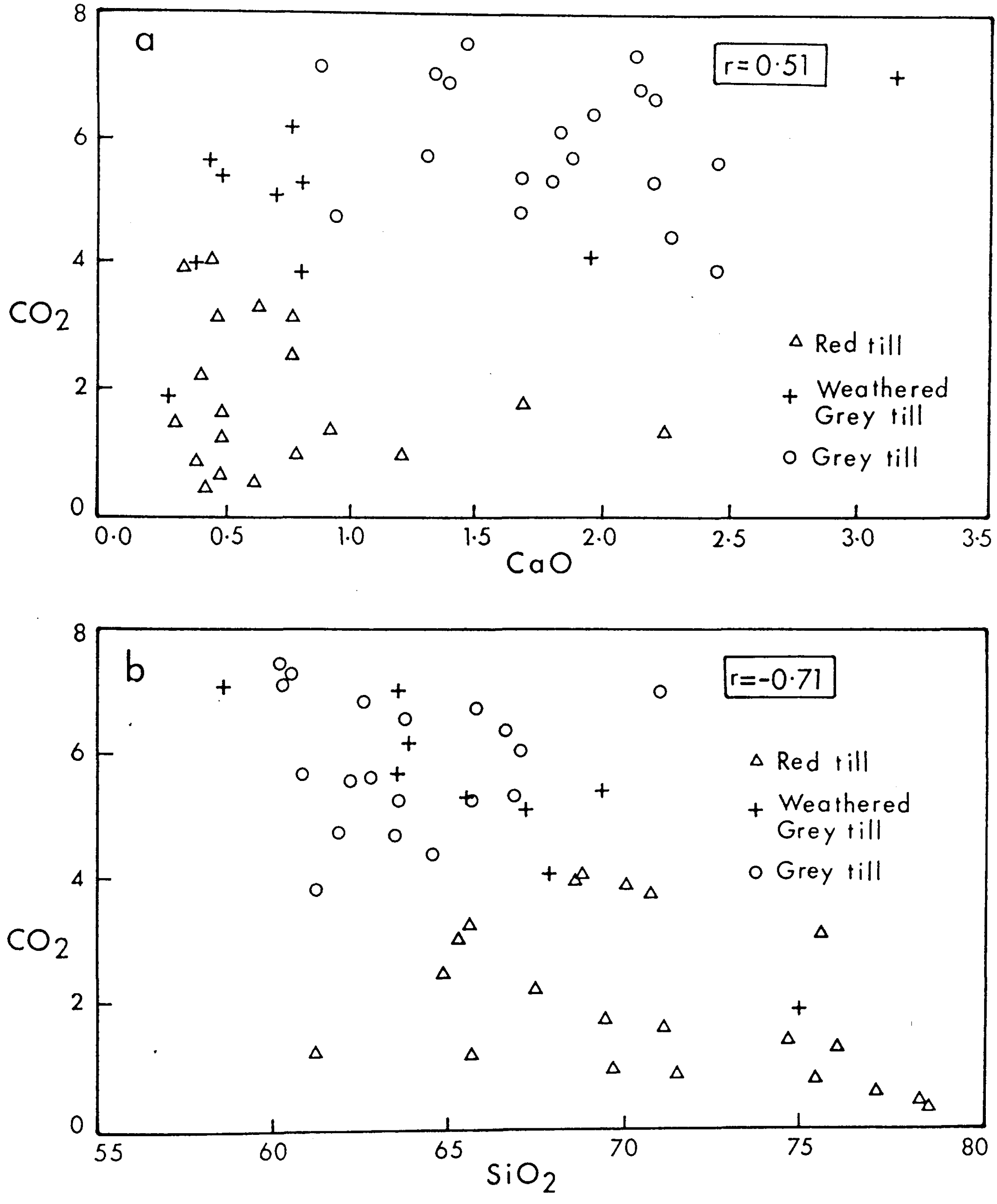


Figure 7.6 Plots of (a) CO_2 against CaO, and (b) CO_2 against SiO_2

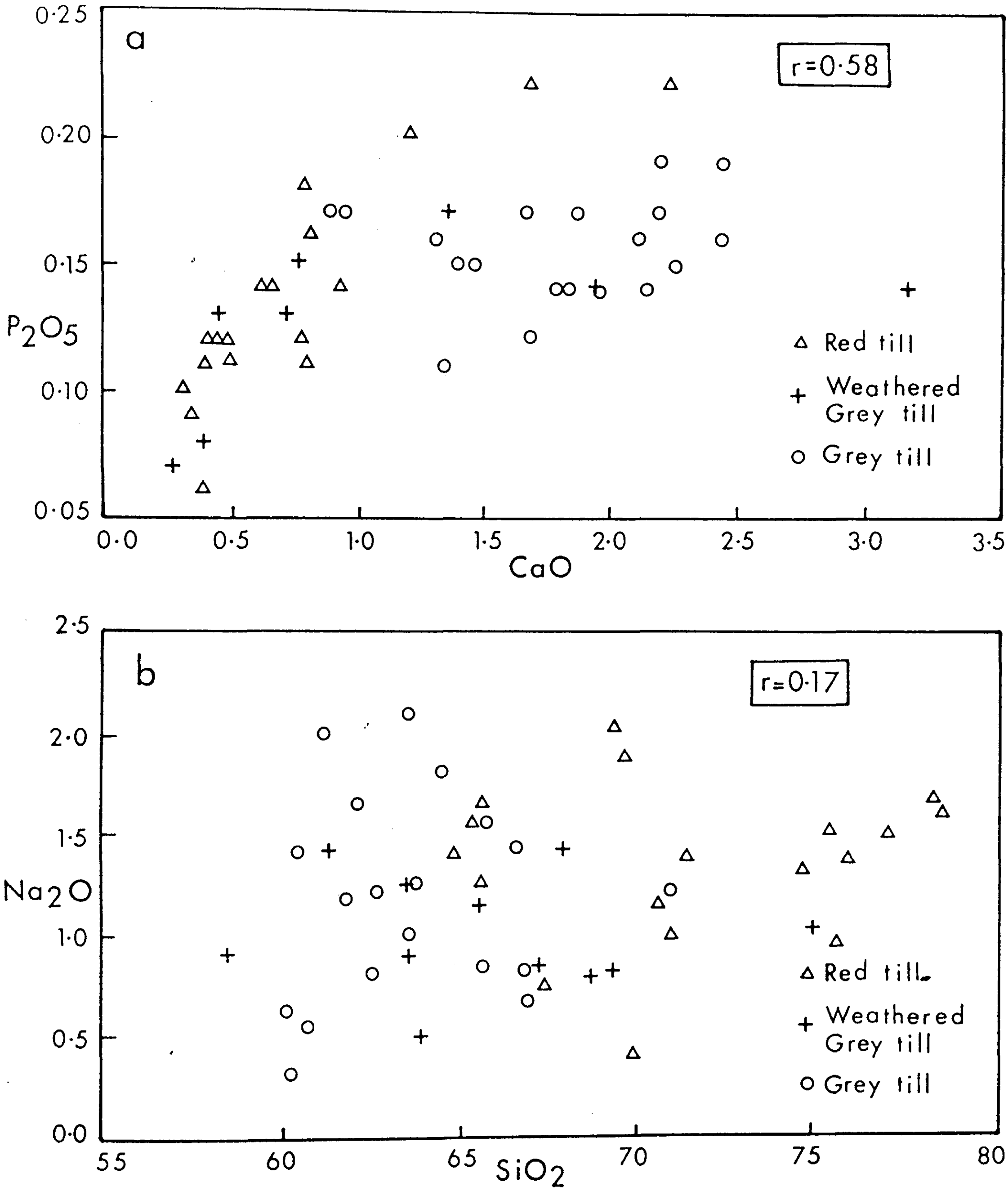


Figure 7.7 Plots of (a) P_2O_5 against CaO, and (b) Na_2O against SiO_2

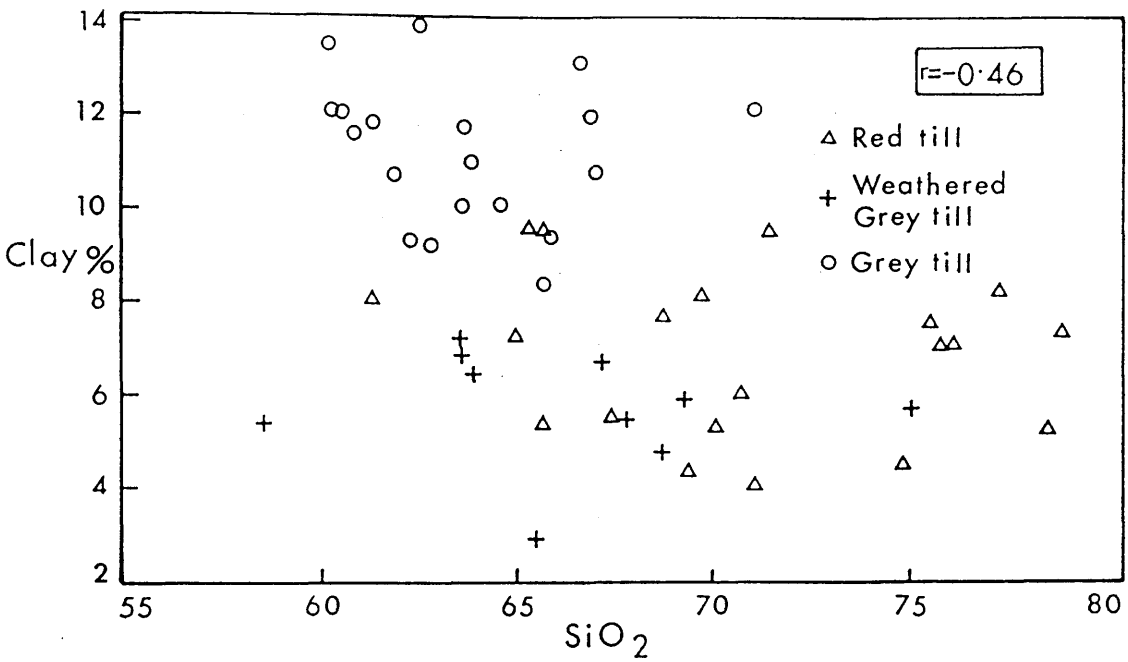


Figure 7.8 Plot of clay against SiO_2

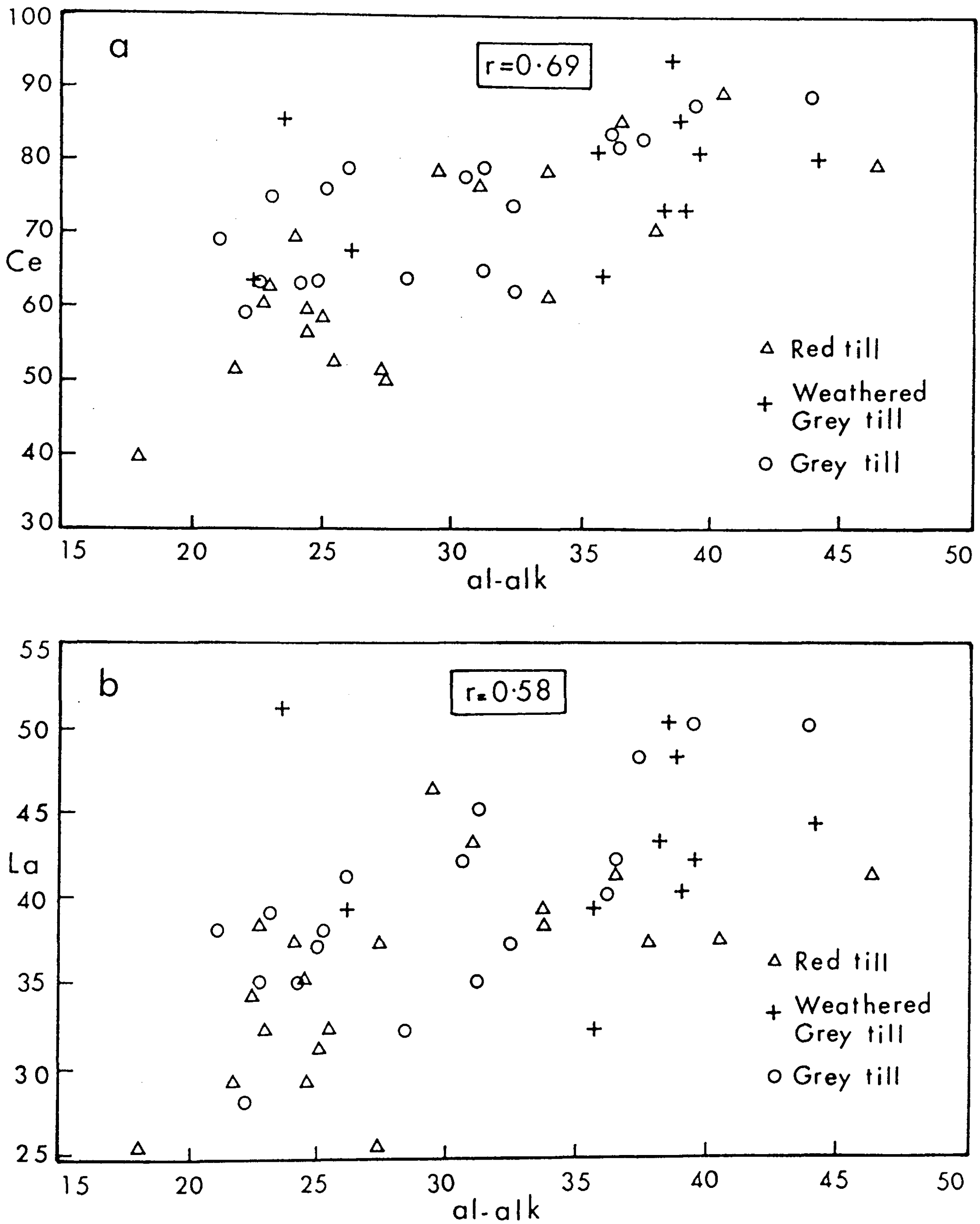


Figure 7.9 Plots of (a) Ce against al-alk, and (b) La against al-alk

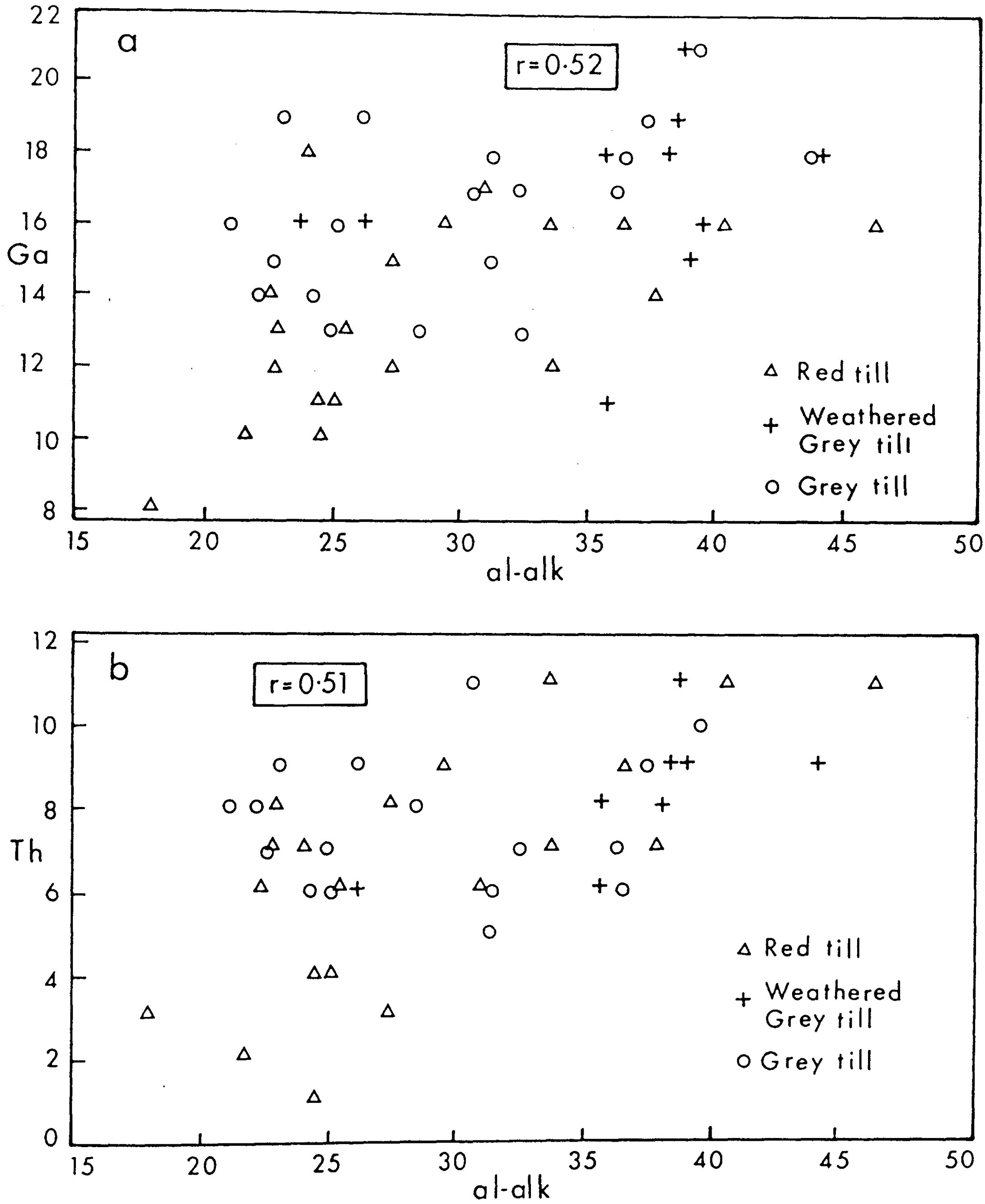


Figure 7.10 Plots of (a) Ga against al-alk, and (b) Th against al-alk

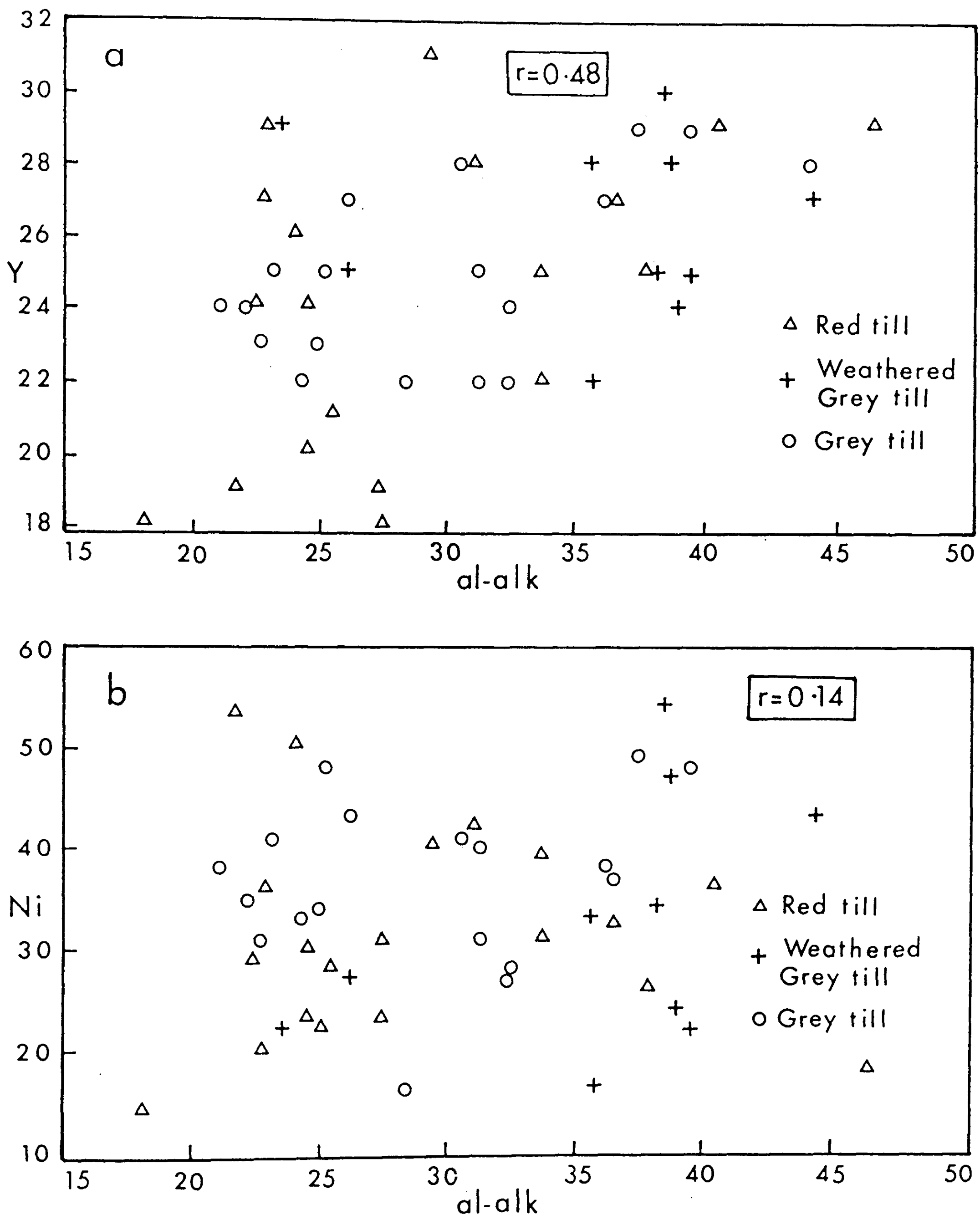


Figure 7.11 Plots of (a) Y against al-alk, and (b) Ni against al-alk

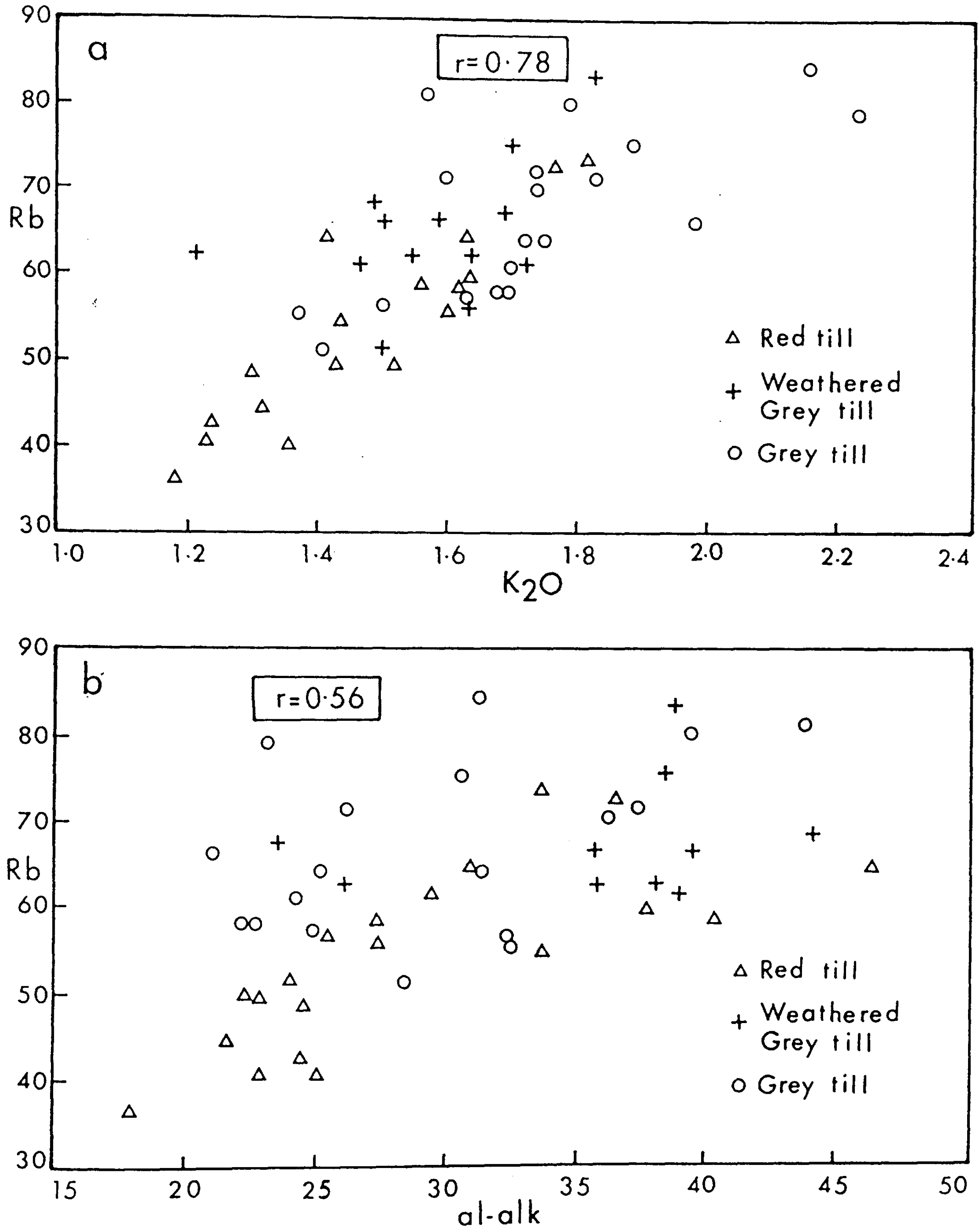


Figure 7.12 Plots of (a) Rb against K_2O, and (b) Rb against al-alk

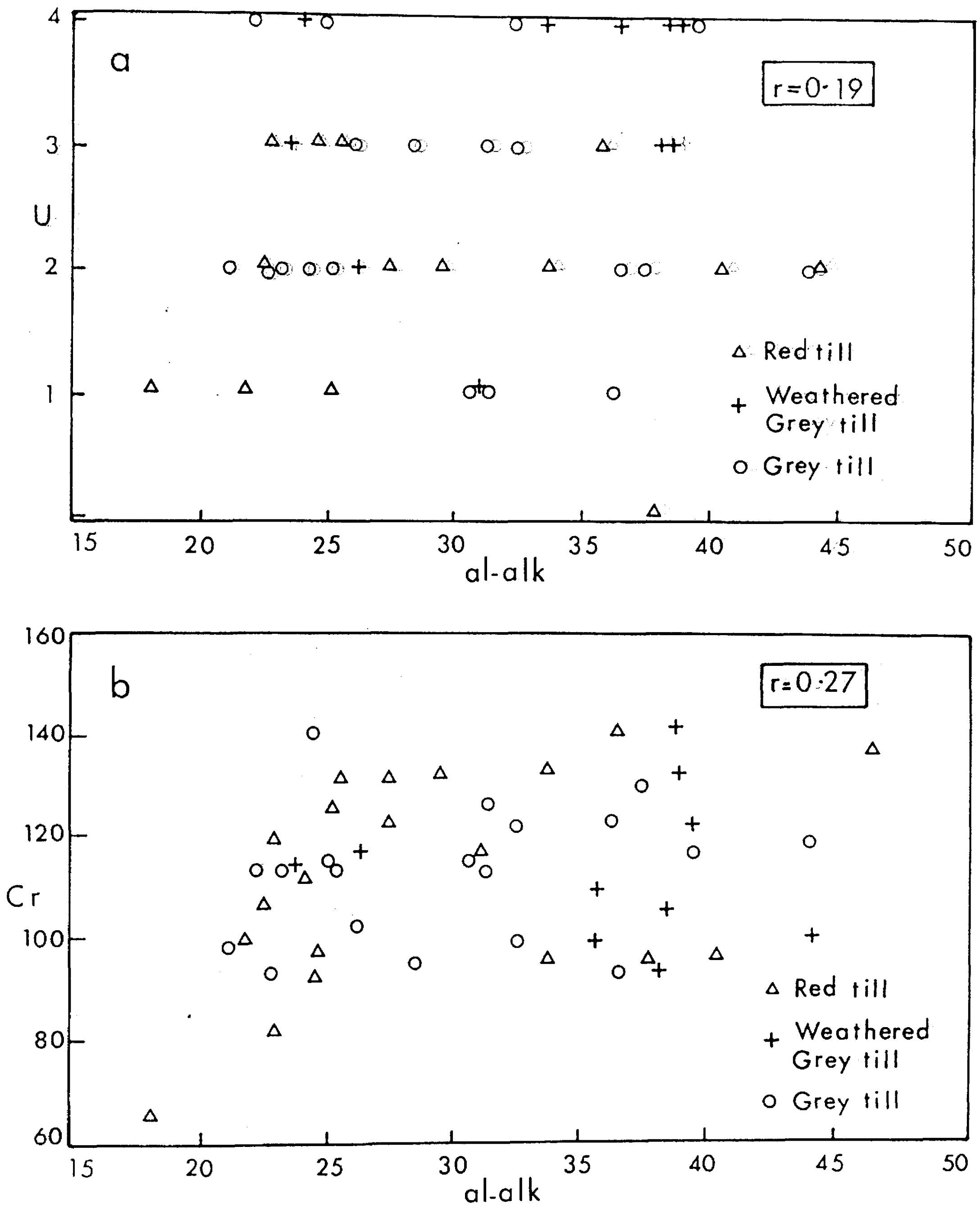


Figure 7.13 Plots of (a) U against al-alk, and (b) Cr against al-alk

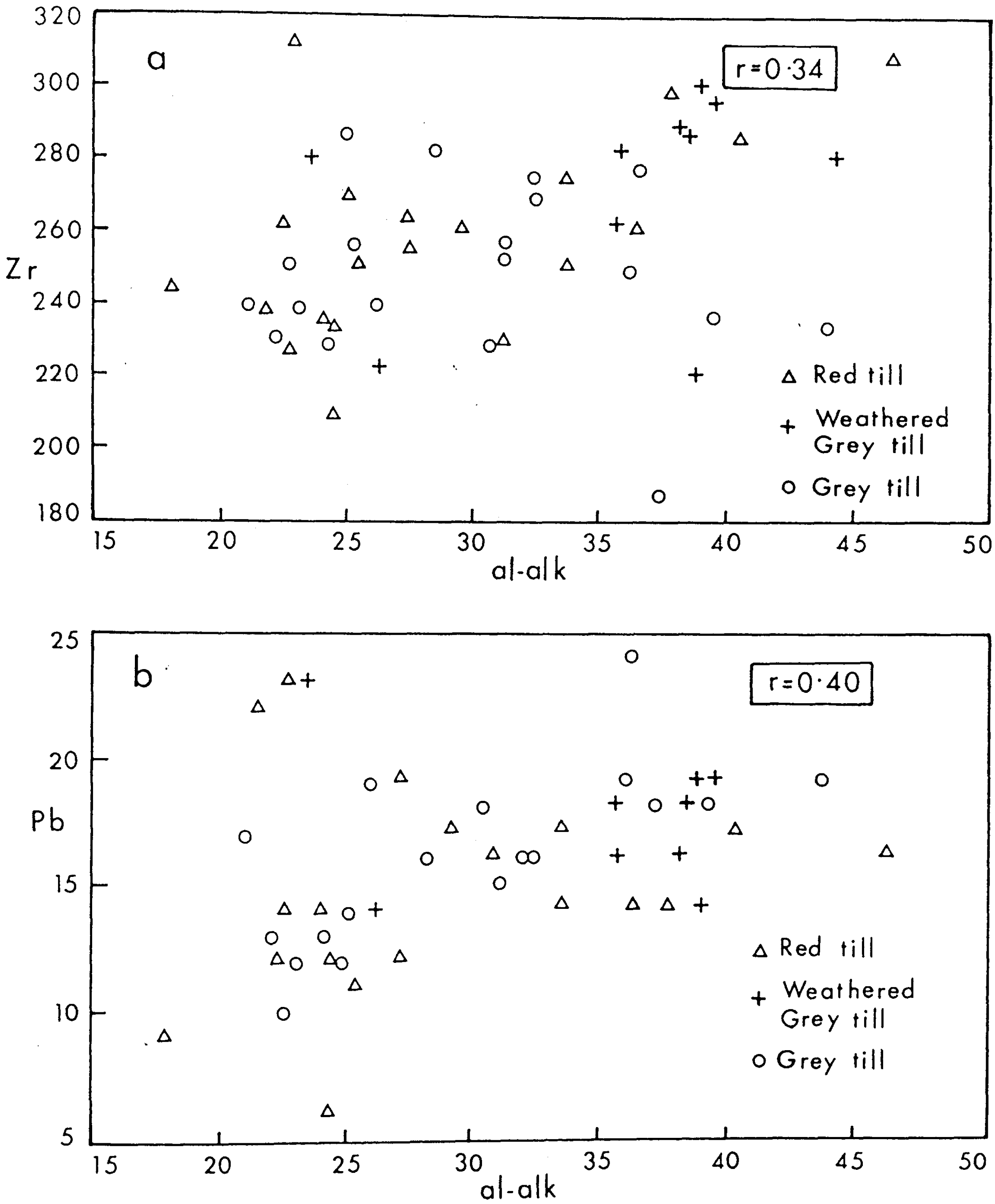


Figure 7.14 Plots of (a) Zr against al-alk, and (b) Pb against al-alk

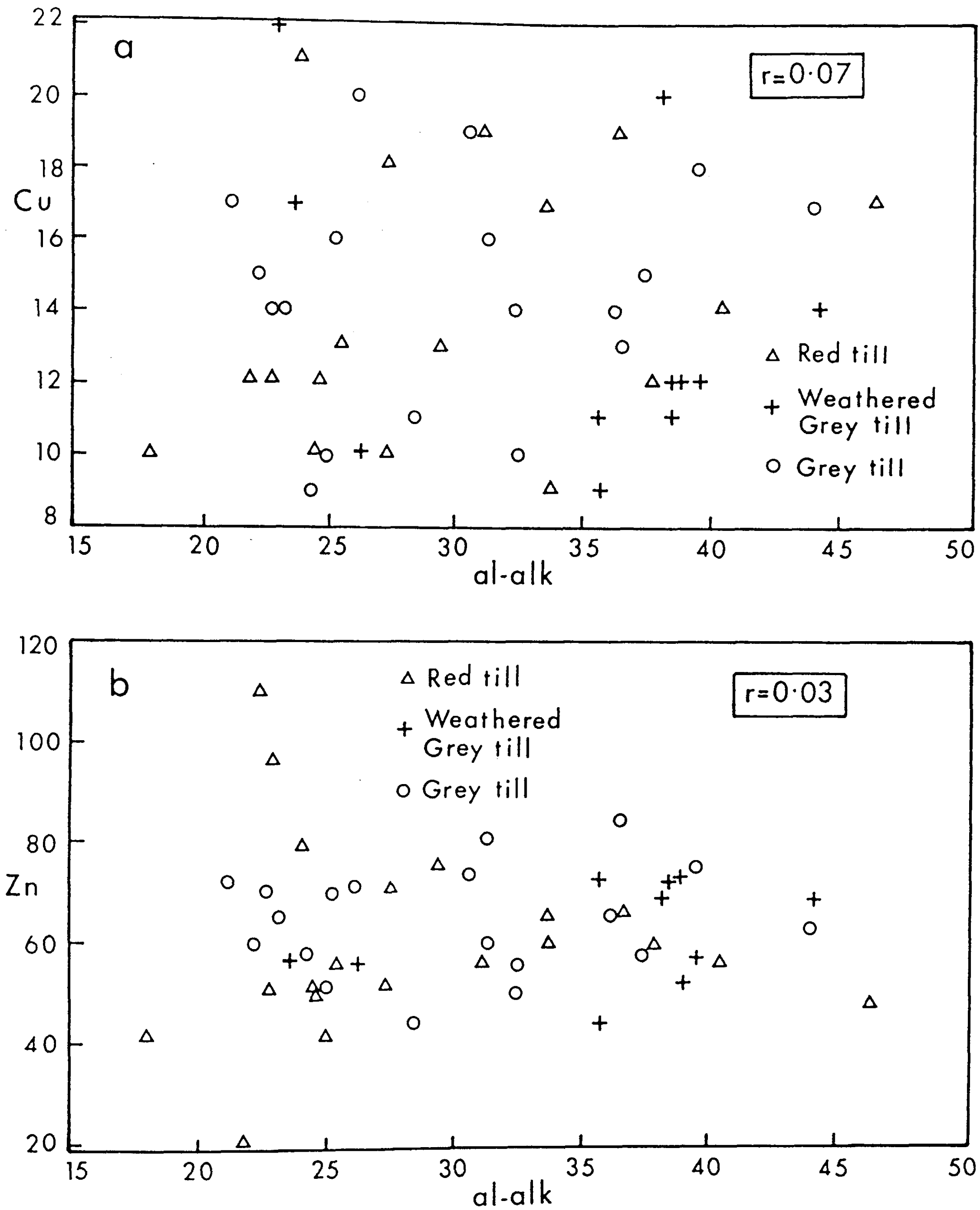


Figure 7.15 Plots of (a) Cu against al-alk, and (b) Zn against al-alk

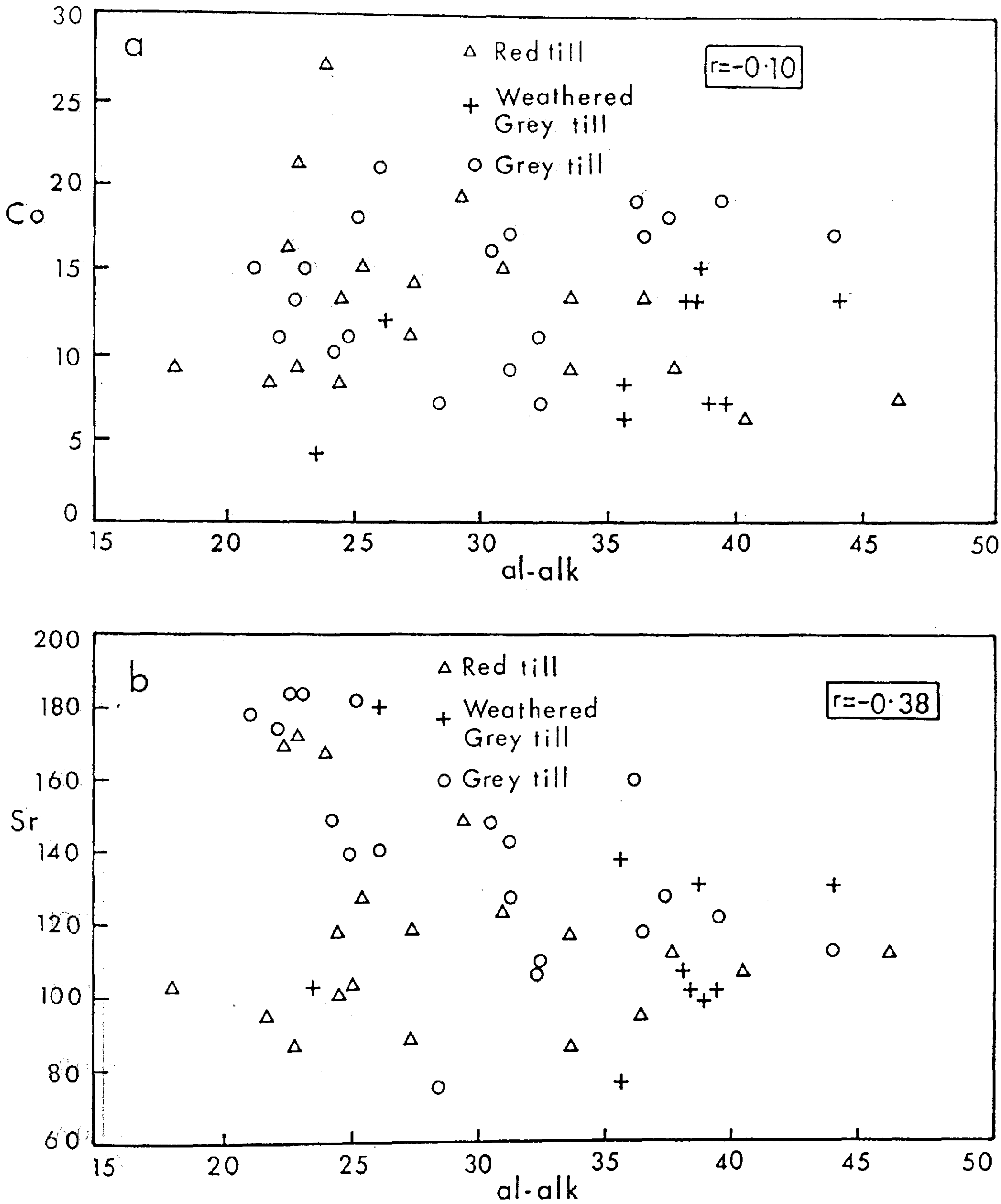
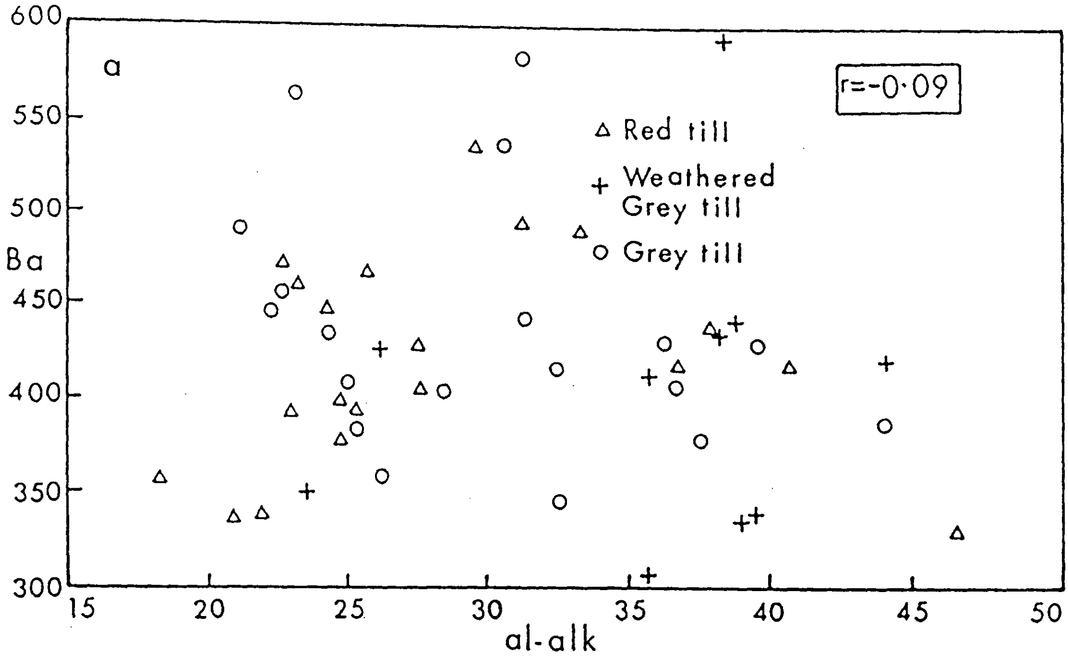


Figure 7.16 Plots of (a) Co against al-alk, and (b) Sr against al-alk



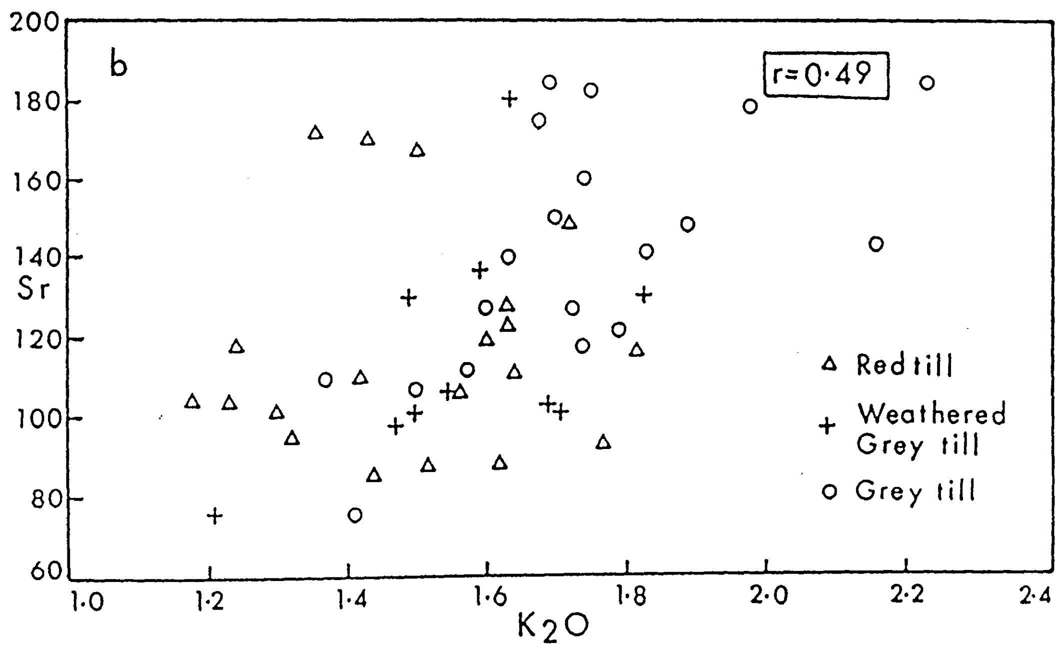


Figure 7.17 Plots of (a) Ba against al-alk, and (b) Sr against K_2O

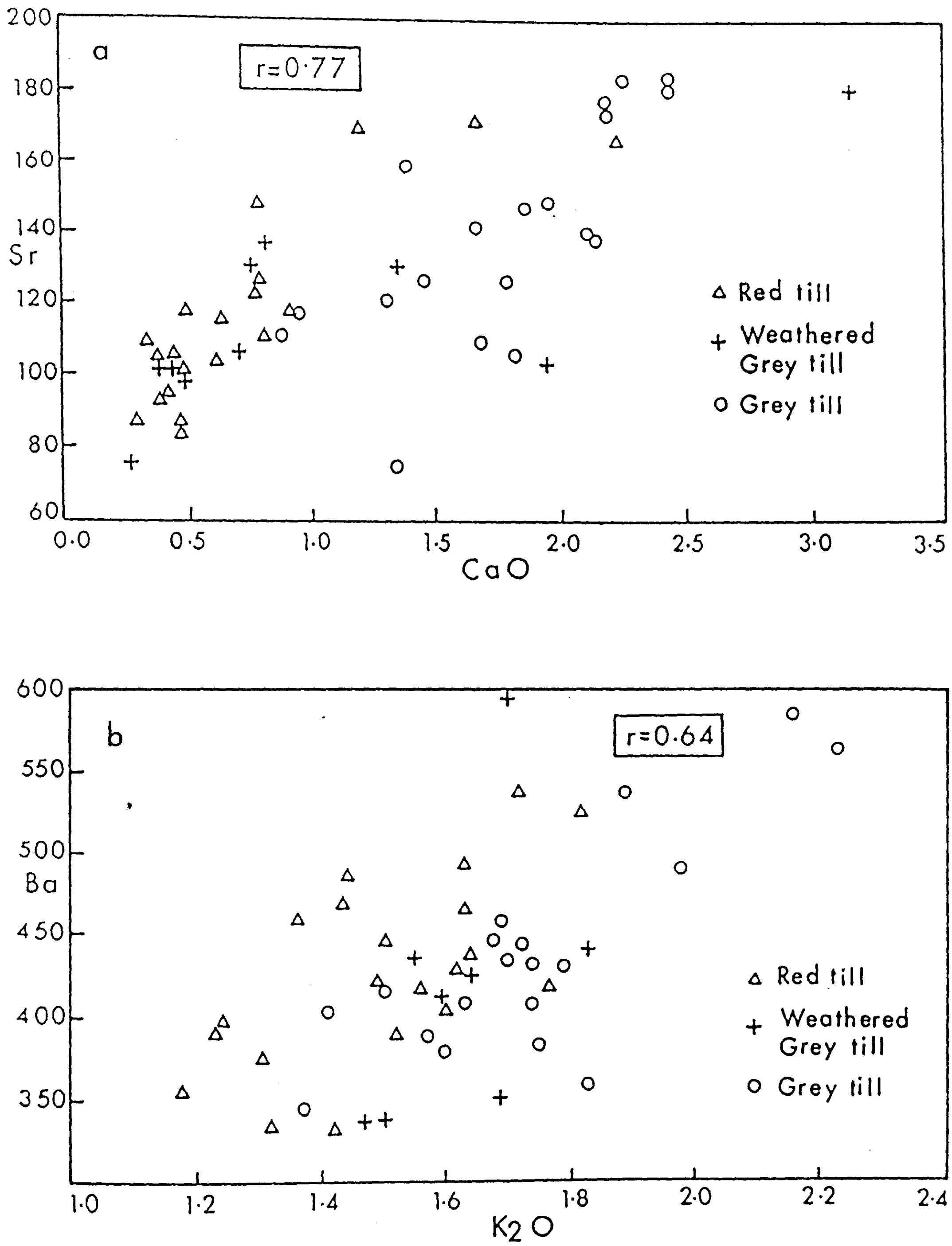


Figure 7.18 Plots of (a) Sr against CaO, and (b) Ba against K_2O

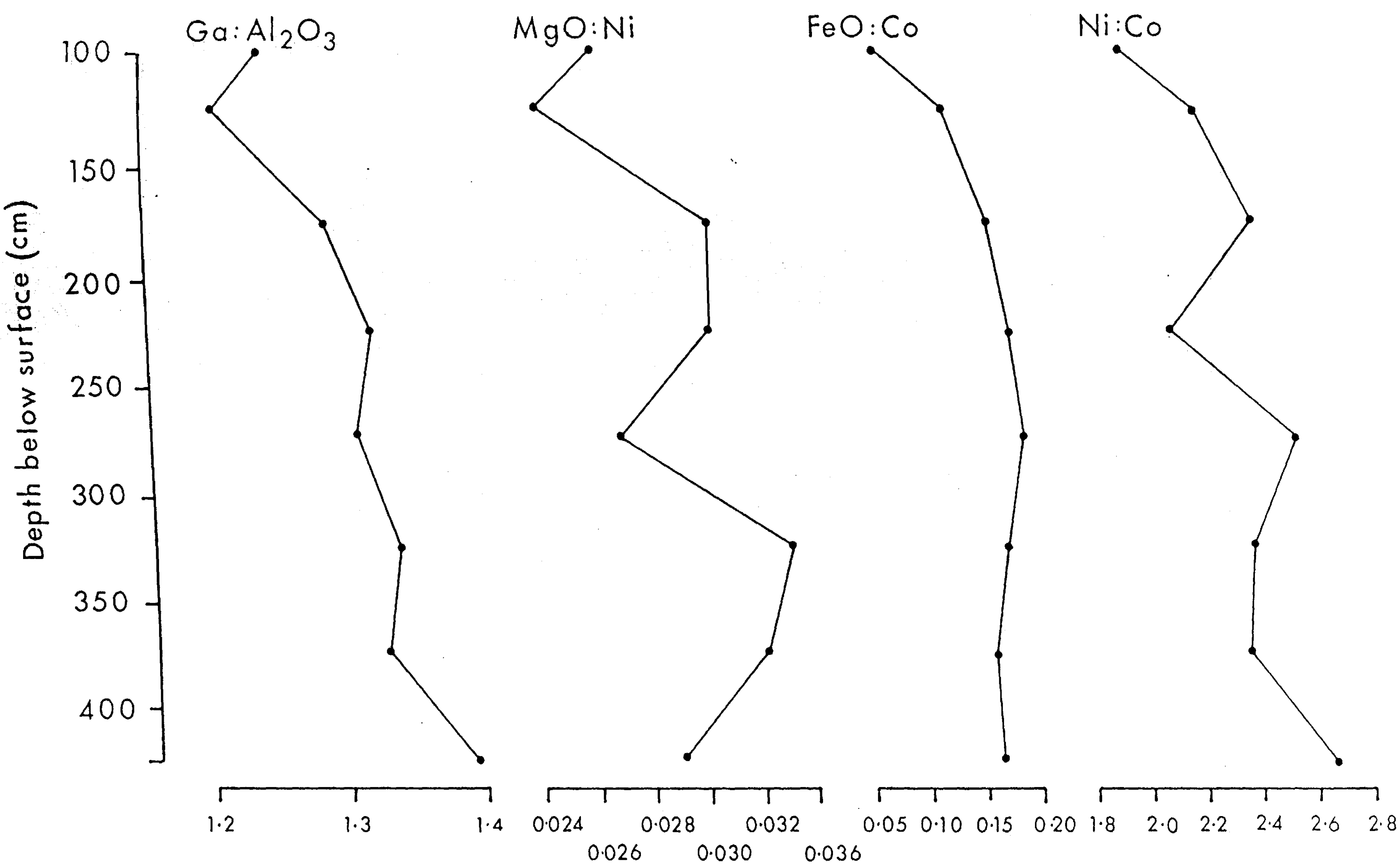


Figure 7.19 Weathering ratios from the Grey till profile at Kelvinside - Great Western Road (NS 5581 6807).

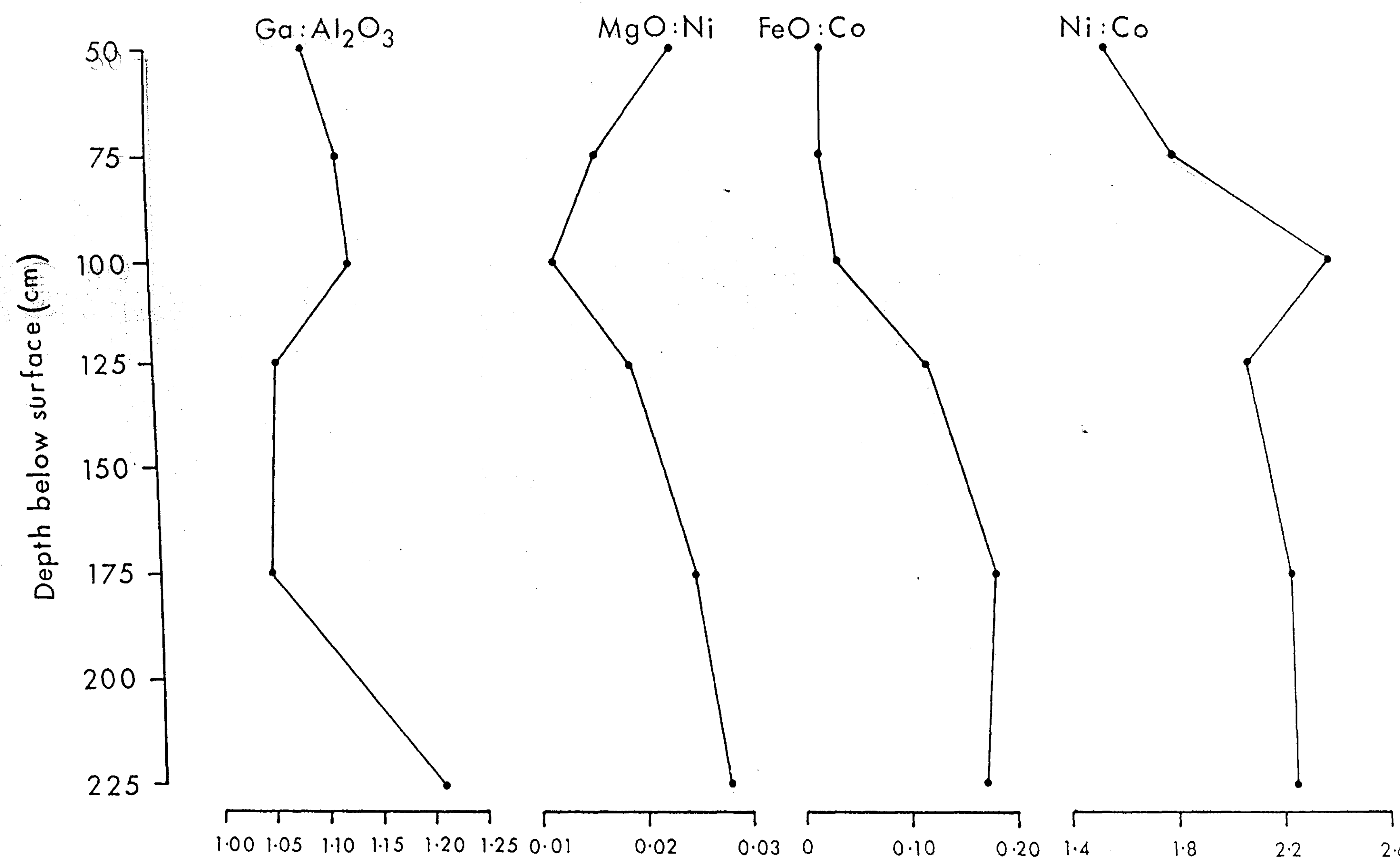


Figure 7.20 Weathering ratios from the Grey till profile at Queen Margaret Hall (NS 5633 6817).

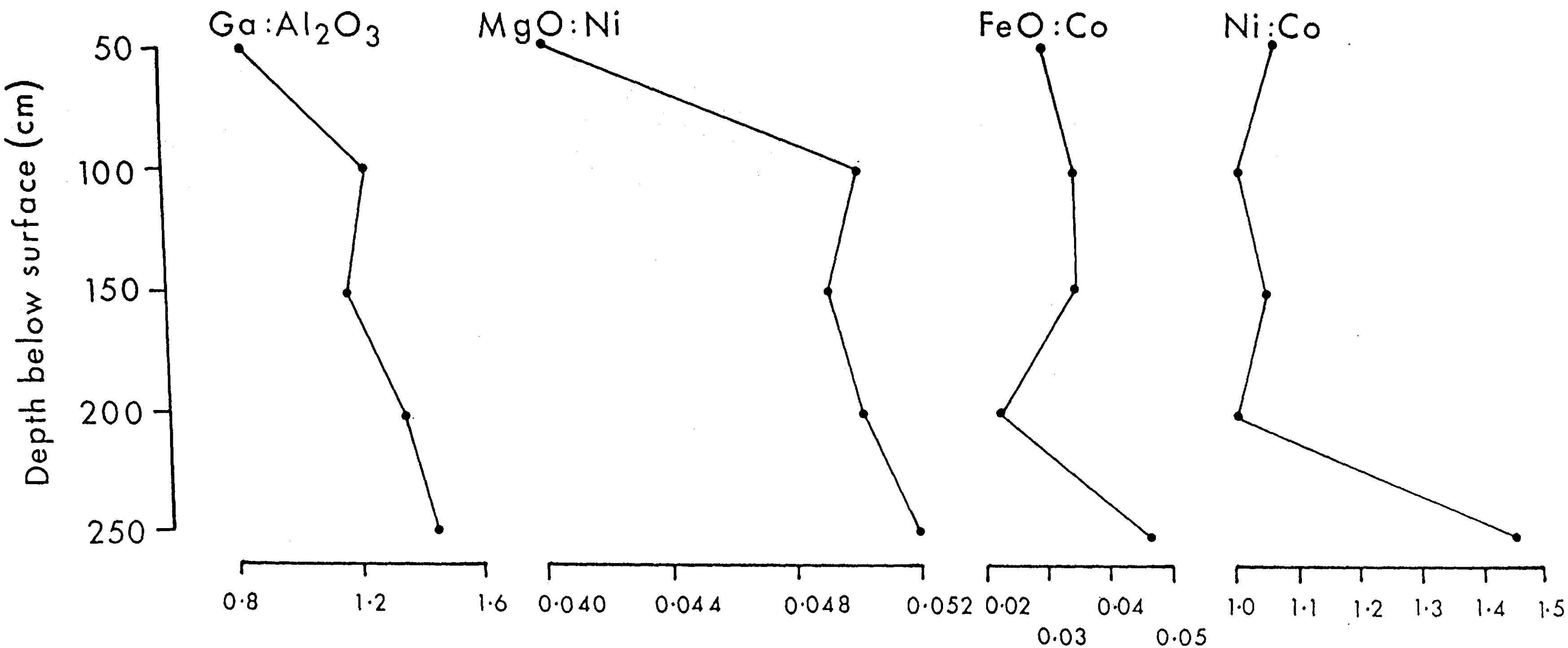


Figure 7.21 Weathering ratios from the Red till profile at Clober (NS 5460 7590).

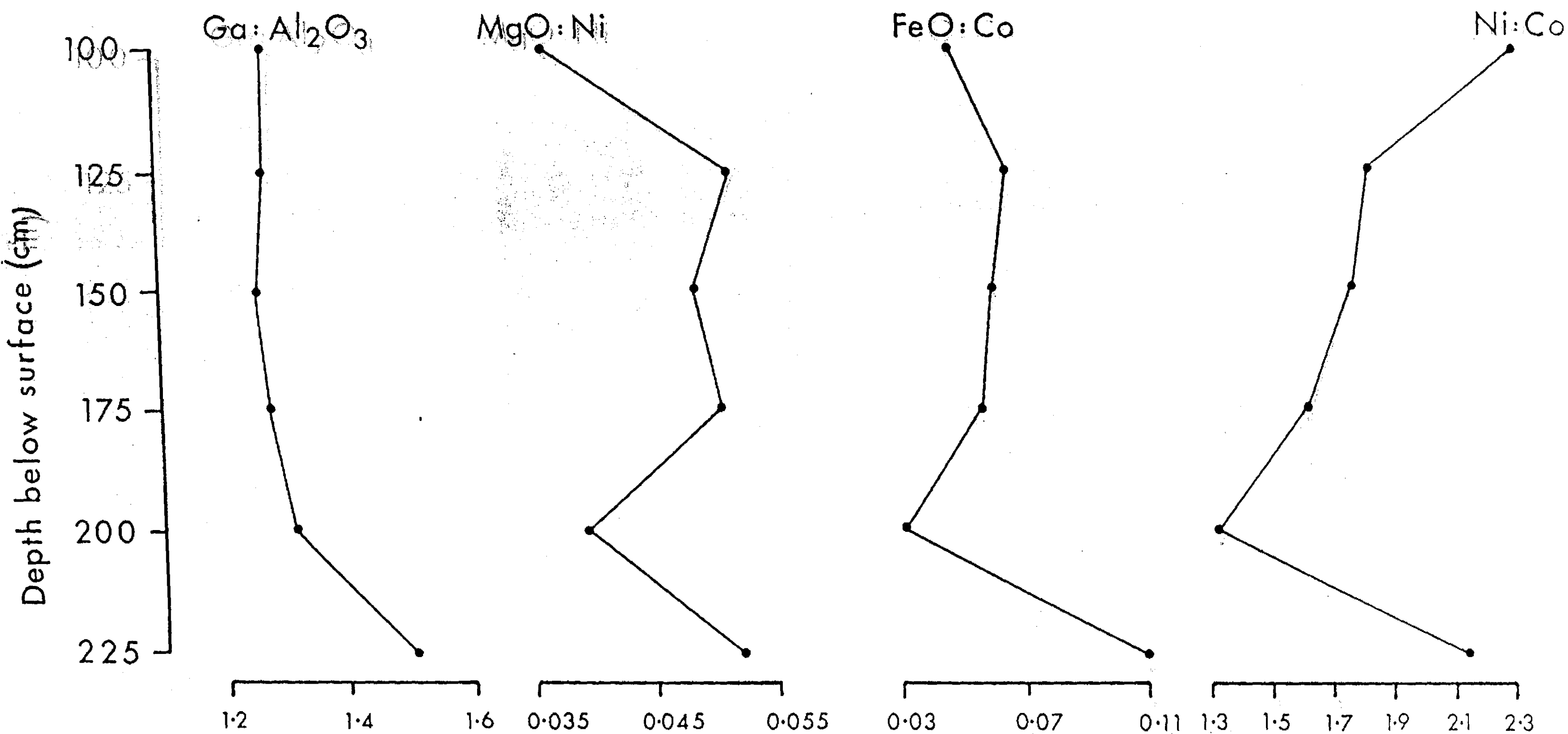


Figure 7.22 Weathering ratios from the Red till profile at Laighpark (NS 5360 7615).

Table 7.1 NW Glasgow area. Major element analysis of the till matrix (< 2 mm) of the twenty Red till samples, R 1 - R 49.

	R 1	R 2	R 4	R 8	R16
SiO_2	67.47	70.72	65.72	65.39	70.09
TiO_2	0.87	0.86	0.87	1.00	0.83
Al_2O_3	14.04	14.44	14.18	13.84	13.18
Fe_2O_3	6.07	4.19	5.07	6.33	4.27
FeO	0.79	0.78	0.68	0.61	0.55
MnO	0.11	0.04	0.10	0.13	0.02
MgO	1.24	1.04	1.36	1.35	0.63
CaO	0.40	0.81	0.84	0.78	0.34
Na_2O	0.73	1.12	1.23	1.54	0.37
K_2O	1.77	1.64	1.82	1.72	1.42
P_2O_5	0.11	0.16	0.14	0.18	0.09
H_2O	4.15	4.03	4.64	3.41	5.61
CO_2	2.20	3.78	3.22	3.04	3.86
Total	99.95	103.61	99.67	99.32	101.26

	R30	R31	R32	R34	R35
SiO_2	75.76	74.79	78.44	71.46	69.77
TiO_2	0.69	0.92	0.81	1.02	1.14
Al_2O_3	9.95	10.41	7.76	11.11	11.40
Fe_2O_3	3.81	3.67	3.68	5.13	4.89
FeO	0.48	1.03	0.52	0.93	1.08
MnO	0.09	0.04	0.07	0.07	0.07
MgO	0.32	1.14	1.02	1.38	1.65
CaO	0.47	0.31	0.62	0.79	1.21
Na_2O	0.94	1.29	1.65	1.36	1.87
K_2O	1.44	1.62	1.18	1.63	1.43
P_2O_5	0.12	0.10	0.14	0.11	0.20
H_2O	2.83	2.68	2.29	3.85	3.81
CO_2	3.07	1.37	0.43	0.84	0.88
Total	99.97	99.37	98.61	99.68	99.40

Table 7.1 (continued)

	R37	R39	R41	R42	R43
SiO_2	68.79	76.08	65.72	75.52	64.90
TiO_2	0.87	0.86	1.33	0.87	1.01
Al_2O_3	14.05	8.55	13.51	9.75	13.82
Fe_2O_3	5.39	4.12	4.24	4.98	6.37
FeO	0.45	0.78	2.95	0.68	0.57
MnO	0.03	0.15	0.05	0.06	0.09
MgO	0.90	0.11	1.87	0.85	1.28
CaO	0.44	0.92	0.49	0.39	0.77
Na_2O	0.73	1.34	1.63	1.50	1.38
K_2O	1.58	1.24	1.60	1.23	1.63
P_2O_5	0.12	0.14	0.11	0.06	0.12
H_2O	2.53	3.24	4.18	3.28	5.45
CO_2	4.01	1.26	1.12	0.78	2.47
Total	99.87	98.79	98.80	99.95	99.87

	R44	R45	R47	R48	R49
SiO_2	61.32	78.70	77.21	69.50	71.09
TiO_2	1.56	0.77	0.79	1.58	0.90
Al_2O_3	13.44	8.86	9.18	11.52	9.60
Fe_2O_3	7.80	3.53	3.58	5.66	8.03
FeO	1.49	1.04	0.76	0.42	0.60
MnO	0.12	0.07	0.06	0.12	0.04
MgO	2.37	1.02	1.07	0.90	0.90
CaO	2.24	0.41	0.47	1.68	0.48
Na_2O	1.41	1.59	1.47	2.01	0.97
K_2O	1.50	1.32	1.52	1.36	1.30
P_2O_5	0.22	0.12	0.12	0.22	0.12
H_2O	4.71	2.83	2.77	3.16	2.67
CO_2	1.16	0.34	0.58	1.69	1.59
Total	99.67	100.60	99.58	99.82	99.49

Table 7.2 NW Glasgow area. Major element analysis of the till matrix (<2 mm) of the ten Weathered Grey till samples, WG 6 - WG 33.

	WG 6	WG 7	WG12	WG13	WG14
SiO_2	63.55	58.52	65.55	68.73	69.32
TiO_2	0.77	0.84	0.94	0.88	0.82
Al_2O_3	12.18	16.05	14.12	13.27	12.65
Fe_2O_3	3.98	4.09	4.74	4.87	4.88
FeO	0.38	0.74	0.83	0.57	0.41
MnO	0.07	0.12	0.05	0.03	0.09
MgO	2.61	1.65	1.21	0.92	0.65
CaO	3.16	1.36	0.81	0.39	0.49
Na_2O	0.89	0.90	1.13	0.77	0.81
K_2O	1.64	1.83	1.59	1.50	1.47
P_2O_5	0.14	0.17	0.16	0.08	0.12
H_2O	3.82	5.35	4.96	5.63	3.98
CO_2	6.97	6.98	5.24	3.95	5.35
Total	100.66	98.60	101.33	101.59	101.04

	WG15	WG17	WG28	WG29	WG33
SiO_2	63.86	67.88	74.98	67.22	63.54
TiO_2	0.88	0.81	0.73	0.88	0.87
Al_2O_3	14.43	11.24	10.78	13.36	14.58
Fe_2O_3	4.24	4.64	3.87	4.86	4.39
FeO	0.86	0.53	0.49	0.70	0.64
MnO	0.09	0.09	0.04	0.07	0.10
MgO	0.94	1.77	0.70	0.83	0.78
CaO	0.76	1.95	0.28	0.71	0.44
Na_2O	0.48	1.41	1.03	0.83	1.24
K_2O	1.49	1.69	1.21	1.55	1.70
P_2O_5	0.15	0.14	0.07	0.13	0.13
H_2O	4.95	4.69	3.85	4.45	5.23
CO_2	6.10	4.04	1.85	5.06	5.61
Total	99.23	100.88	99.88	100.65	99.25

Table 7.3 NW Glasgow area. Major element analysis of the till matrix (< 2 mm) of the nineteen Grey till samples, G 3 - G 50.

	G 3	G 5	G 9	G10	G11
SiO_2	62.21	65.70	60.78	62.61	63.59
TiO_2	1.02	0.87	0.89	0.88	0.83
Al_2O_3	13.54	12.84	15.80	14.30	14.33
Fe_2O_3	4.31	2.54	4.12	2.13	3.92
FeO	1.66	2.45	1.99	2.96	1.52
MnO	0.10	0.09	0.10	0.10	0.07
MgO	1.99	1.66	1.45	1.43	1.10
CaO	2.45	1.80	1.32	1.40	0.95
Na_2O	1.64	0.83	0.55	0.81	1.00
K_2O	1.75	1.72	1.79	1.74	1.74
P_2O_5	0.19	0.14	0.16	0.15	0.17
H_2O	4.60	4.21	6.23	3.66	5.45
CO_2	5.61	5.25	5.70	6.87	4.70
Total	101.07	99.90	100.88	99.04	99.37

	G18	G19	G20	G21	G22
SiO_2	66.70	63.61	63.80	61.31	66.93
TiO_2	0.69	0.97	0.86	0.93	0.73
Al_2O_3	11.38	13.12	11.34	14.58	11.68
Fe_2O_3	2.49	3.07	4.12	2.84	1.64
FeO	2.28	2.83	2.88	2.81	3.03
MnO	0.08	0.07	0.14	0.11	0.12
MgO	1.65	1.99	2.04	2.37	1.29
CaO	1.97	2.20	2.21	2.45	1.69
Na_2O	1.42	2.10	1.25	2.00	0.82
K_2O	1.70	1.98	1.68	2.23	1.37
P_2O_5	0.14	0.17	0.19	0.16	0.12
H_2O	3.82	3.50	4.27	4.13	3.82
CO_2	6.39	5.26	6.62	3.88	5.40
Total	100.71	100.87	101.40	99.80	98.64

Table 7.3 (continued)

	G23	G24	G25	G26	G27
SiO_2	60.54	61.90	62.76	71.06	60.33
TiO_2	0.89	1.02	0.90	0.73	0.80
Al_2O_3	13.49	15.13	14.29	10.67	16.12
Fe_2O_3	2.91	4.55	4.72	1.57	2.00
FeO	3.32	1.29	1.18	2.50	4.16
MnO	0.10	0.09	0.11	0.08	0.13
MgO	1.98	1.82	1.61	1.21	1.28
CaO	2.13	1.68	1.88	1.35	0.89
Na_2O	1.41	1.18	1.21	1.20	0.31
K_2O	1.83	2.18	1.89	1.41	1.57
P_2O_5	0.16	0.17	0.17	0.11	0.17
H_2O	4.71	5.27	5.21	2.18	4.68
CO_2	7.31	4.80	5.67	6.96	7.14
Total	100.78	101.06	101.58	101.05	99.76

	G36	G38	G40	G50
SiO_2	65.81	64.60	66.99	60.22
TiO_2	0.90	0.99	0.86	0.88
Al_2O_3	11.86	12.45	11.86	14.84
Fe_2O_3	3.36	3.04	2.32	3.32
FeO	1.52	2.55	2.34	2.69
MnO	0.10	0.09	0.07	0.14
MgO	1.46	1.99	1.59	1.55
CaO	2.15	2.27	1.83	1.47
Na_2O	1.55	1.80	0.66	0.62
K_2O	1.63	1.66	1.50	1.60
P_2O_5	0.14	0.15	0.14	0.15
H_2O	4.33	3.85	4.22	5.88
CO_2	6.77	4.39	6.06	7.48
Total	101.58	99.80	100.44	100.82

Table 7.4A NW Glasgow area. Major element analysis of the till matrix (<2 mm) of the Grey till profile samples from the site at Kelvinside, NS 5581 6807.

	10 - 1	10 - 2	10 - 3	10 - 4
SiO_2	61.38	61.89	62.43	64.49
TiO_2	1.02	0.98	0.92	0.88
Al_2O_3	16.04	15.66	15.14	14.32
Fe_2O_3	4.55	5.69	2.39	1.87
FeO	1.58	2.58	3.14	3.38
MnO	0.10	0.07	0.10	0.11
MgO	1.36	1.20	1.42	1.25
CaO	1.27	1.36	1.46	1.32
Na_2O	1.36	1.11	1.09	1.62
K_2O	1.27	1.81	1.83	1.80
P_2O_5	0.09	0.16	0.16	0.16
H_2O	6.82	5.69	4.96	4.40
CO_2	3.15	2.95	5.09	4.53
Total	99.99	101.14	100.13	100.13

	10 - 5	10 - 6	10 - 7	10 - 8
SiO_2	66.11	63.90	60.48	60.61
TiO_2	0.87	0.88	0.88	0.93
Al_2O_3	13.64	14.84	16.86	15.82
Fe_2O_3	2.11	2.28	2.08	2.43
FeO	3.08	3.17	3.48	3.36
MnO	0.10	0.10	0.10	0.07
MgO	1.18	1.52	1.64	1.62
CaO	1.36	1.28	1.22	1.65
Na_2O	1.47	1.05	1.75	1.36
K_2O	1.77	1.90	1.92	1.87
P_2O_5	0.15	0.16	0.18	0.17
H_2O	3.63	3.73	4.49	4.35
CO_2	4.99	5.01	5.24	6.57
Total	100.43	99.82	100.32	100.81

Table 7.4B NW Glasgow area. Major element analysis of the till matrix (< 2 mm) of the Grey till profile samples from the site at Queen Margaret Hall, NS 5633 6817.

	11 - 6	11 - 5	11 - 4
SiO_2	58.33	58.15	56.74
TiO_2	1.13	1.08	1.07
Al_2O_3	20.02	20.37	19.34
Fe_2O_3	8.47	7.37	7.09
FeO	0.41	0.52	0.96
MnO	0.03	0.06	0.17
MgO	0.74	0.83	0.88
CaO	0.30	0.43	0.50
Na_2O	0.99	0.96	0.98
K_2O	1.83	1.88	2.04
P_2O_5	0.10	0.11	0.14
H_2O	3.32	4.44	5.17
CO_2	4.25	4.97	4.22
Total	99.92	101.18	99.30

	11 - 3	11 - 2	11 - 1
SiO_2	57.11	56.58	55.80
TiO_2	1.07	1.12	1.07
Al_2O_3	19.71	19.83	19.02
Fe_2O_3	4.34	3.39	2.51
FeO	3.10	4.07	4.21
MnO	0.23	0.19	0.10
MgO	0.98	1.25	1.50
CaO	0.54	0.53	1.24
Na_2O	0.52	0.90	1.04
K_2O	2.16	2.26	2.21
P_2O_5	0.19	0.21	0.20
H_2O	5.35	4.96	6.88
CO_2	5.01	5.46	5.15
Total	100.31	99.75	100.93

Table 7.5A NW Glasgow area. Major element analysis of the till matrix (< 2 mm) of the Red till profile samples from the site at Laighpark, NS 5360 7615.

	1 - 6	1 - 5	1 - 4
SiO_2	74.44	69.59	68.22
TiO_2	1.17	1.06	1.04
Al_2O_3	10.24	11.83	11.92
Fe_2O_3	5.34	4.67	4.74
FeO	0.70	1.21	1.24
MnO	0.11	0.07	0.08
MgO	1.23	1.87	1.79
CaO	1.07	3.23	3.36
Na_2O	2.43	2.24	2.10
K_2O	1.47	1.97	1.99
P_2O_5	0.18	0.16	0.17
H_2O	2.34	3.10	2.98
CO_2	0.30	0.71	1.80
Total	101.02	101.71	101.43

	1 - 3	1 - 2	1 - 1
SiO_2	68.48	71.07	67.51
TiO_2	1.19	1.05	1.02
Al_2O_3	12.60	12.18	11.91
Fe_2O_3	5.12	5.15	3.80
FeO	1.30	0.92	1.88
MnO	0.11	0.09	0.10
MgO	1.88	1.45	1.99
CaO	2.36	0.82	3.69
Na_2O	2.45	1.87	1.81
K_2O	2.01	2.15	1.98
P_2O_5	0.19	0.17	0.17
H_2O	2.86	3.22	2.34
CO_2	0.65	0.24	1.95
Total	101.20	100.38	100.15

Table 7.5B NW Glasgow area. Major element analysis of the till matrix (<2 mm) of the Red till profile samples from the site at Clober, NS 5460 7590.

	4 - 5	4 - 4	4 - 3	4 - 2	4 - 1
SiO_2	75.75	72.63	73.84	75.92	79.26
TiO_2	0.97	1.31	1.21	1.24	1.11
Al_2O_3	11.83	11.37	10.21	10.35	8.46
Fe_2O_3	4.42	5.65	5.11	5.59	4.55
FeO	0.59	0.85	0.68	0.50	0.62
MnO	0.06	0.11	0.09	0.11	0.08
MgO	0.84	1.27	1.04	1.09	0.98
CaO	0.28	0.51	0.57	0.62	0.61
Na_2O	2.02	2.01	2.35	2.37	2.63
K_2O	1.49	1.70	1.56	1.57	1.46
P_2O_5	0.10	0.15	0.17	0.17	0.15
H_2O	1.47	3.43	2.57	1.48	1.45
CO_2	0.26	0.25	0.11	0.16	0.12
Total	100.08	101.24	99.51	101.17	101.48

Table 7.6 NW Glasgow area. Trace element contents (in ppm) of the Red till samples, R 1 - R49.

	R 1	R 2	R 4	R 8	R16
Ba	415	435	522	533	327
Ce	85	70	78	78	79
Co	13	9	13	19	7
Cr	140	95	133	132	137
Cu	19	12	17	13	17
Ga	16	14	16	16	16
La	41	37	39	46	41
Ni	32	26	39	40	18
Pb	14	14	17	17	16
Rb	72	59	73	61	64
Sr	92	110	115	147	109
Th	9	7	11	9	11
U	4	0	4	2	4
Y	27	25	25	31	29
Zn	65	59	64	74	46
Zr	261	298	251	261	307

	R30	R31	R32	R34	R35
Ba	485	424	353	464	467
Ce	61	51	39	52	63
Co	9	11	9	15	16
Cr	95	131	64	131	106
Cu	9	10	10	13	14
Ga	12	12	8	13	14
La	38	25	25	32	34
Ni	31	23	14	28	29
Pb	14	12	9	11	12
Rb	54	58	36	56	49
Sr	84	87	103	126	169
Th	7	3	3	6	6
U	2	2	1	3	2
Y	22	19	18	21	24
Zn	59	51	41	55	110
Zr	274	263	243	250	261

Table 7.6 (continued)

	R37	R39	R41	R42	R43
Ba	415	394	401	388	491
Ce	89	56	50	58	76
Co	6	8	14	11	15
Cr	96	92	122	125	116
Cu	14	10	18	10	19
Ga	16	11	15	11	17
La	37	35	37	31	43
Ni	36	23	31	22	42
Pb	17	6	19	14	16
Rb	58	42	55	40	64
Sr	105	117	117	103	122
Th	11	1	8	4	6
U	2	3	2	1	1
Y	29	20	18	18	28
Zn	55	51	70	41	55
Zr	286	208	254	289	229

	R44	R45	R47	R48	R49
Ba	444	333	389	457	373
Ce	69	51	60	62	59
Co	27	8	9	21	13
Cr	111	99	119	81	97
Cu	21	12	12	22	12
Ga	18	10	12	13	10
La	37	29	38	32	29
Ni	50	53	20	36	30
Pb	14	22	14	23	12
Rb	51	44	49	40	48
Sr	166	94	88	171	100
Th	7	2	7	8	4
U	4	1	3	2	3
Y	26	19	27	29	24
Zn	79	20	50	98	49
Zr	235	237	228	311	233

Table 7.7 NW Glasgow area. Trace element contents (in ppm) of the Weathered Grey till samples, WG 6 - WG33.

	WG 6	WG 7	WG12	WG13	WG14
Ba	424	439	411	336	334
Ce	67	85	81	81	73
Co	12	15	8	7	7
Cr	117	141	99	122	132
Cu	10	12	11	12	12
Ga	16	21	18	16	15
La	39	48	39	42	40
Ni	27	47	33	22	24
Pb	14	19	18	19	14
Rb	66	66	61	68	67
Sr	136	100	97	129	102
Th	6	10	9	9	12
U	3	4	4	2	3
Y	28	25	24	27	29
Zn	72	56	51	68	56
Zr	262	296	300	280	279

	WG15	WG17	WG28	WG29	WG33
Ba	419	348	304	434	595
Ce	80	85	64	73	93
Co	13	4	6	13	13
Cr	100	114	109	93	105
Cu	14	17	9	20	11
Ga	18	16	11	18	19
La	44	51	32	43	50
Ni	43	22	16	34	54
Pb	22	23	16	16	18
Rb	62	62	75	64	64
Sr	75	105	100	182	126
Th	8	8	9	6	6
U	3	3	3	2	1
Y	22	25	30	25	25
Zn	43	68	71	69	59
Zr	282	288	286	256	257

Table 7.8 NW Glasgow area. Trace element contents (in ppm) of the Grey till samples, G 3 - G50.

	G 3	G 5	G 9	G10	G11
Ba	382	442	429	430	406
Ce	76	65	88	84	82
Co	18	9	19	19	17
Cr	113	126	117	123	93
Cu	16	16	18	14	13
Ga	16	15	21	17	18
La	38	35	50	40	42
Ni	48	31	48	38	37
Pb	14	15	18	19	24
Rb	62	83	80	70	72
Sr	179	129	121	159	117
Th	6	11	10	7	6
U	2	4	4	1	2
Y	25	28	29	27	27
Zn	55	72	74	65	84
Zr	222	220	237	249	277

	G18	G19	G20	G21	G22
Ba	434	490	445	594	345
Ce	63	69	59	75	62
Co	10	15	11	15	7
Cr	140	98	113	113	99
Cu	9	17	15	14	10
Ga	14	16	14	19	13
La	35	38	28	39	37
Ni	33	39	35	41	28
Pb	13	17	13	12	16
Rb	61	66	58	79	55
Sr	149	178	174	184	108
Th	8	8	8	9	7
U	2	2	4	2	3
Y	22	24	24	25	24
Zn	58	72	60	65	55
Zr	228	239	230	238	269

Table 7.8 (continued)

	G23	G24	G25	G26	G27
Ba	357	584	537	403	387
Ce	79	79	78	64	89
Co	21	17	16	7	17
Cr	102	113	115	95	119
Cu	20	16	19	11	17
Ga	19	18	17	13	18
La	41	45	42	32	50
Ni	43	40	41	16	43
Pb	19	15	18	16	19
Rb	71	84	75	51	81
Sr	140	142	147	75	111
Th	9	5	11	8	9
U	3	3	1	3	2
Y	27	22	28	22	28
Zn	71	80	73	43	62
Zr	239	252	228	282	234

	G36	G38	G40	G50
Ba	407	457	415	378
Ce	63	63	74	83
Co	11	13	11	18
Cr	115	93	122	130
Cu	10	14	14	15
Ga	13	15	17	19
La	37	35	37	48
Ni	34	31	27	49
Pb	12	10	16	18
Rb	57	58	56	71
Sr	139	184	106	127
Th	7	7	7	9
U	4	2	4	2
Y	23	23	22	29
Zn	51	70	49	57
Zr	286	250	275	186

Table 7.9A NW Glasgow area. Trace element contents (in ppm) of the Grey till profile samples from the site at Kelvinside, NS 5581 6807.

	10 - 1	10 - 2	10 - 3	10 - 4
Ba	507	488	416	408
Ce	94	86	82	73
Co	27	23	20	20
Cr	136	108	123	92
Cu	28	25	21	18
Ga	20	19	20	19
La	45	39	42	40
Ni	51	49	47	41
Pb	24	26	20	17
Rb	78	76	76	69
Sr	127	128	132	135
Th	10	9	9	9
U	3	3	2	3
Y	29	28	27	26
Zn	86	89	72	57
Zr	223	219	215	223

	10 - 5	10 - 6	10 - 7	10 - 8
Ba	370	446	382	375
Ce	80	88	85	78
Co	17	19	22	21
Cr	123	101	130	110
Cu	15	22	25	22
Ga	18	23	22	22
La	39	48	38	42
Ni	43	45	52	56
Pb	22	19	22	25
Rb	67	74	82	77
Sr	143	187	145	151
Th	8	12	10	11
U	2	2	4	3
Y	22	25	29	26
Zn	70	76	75	76
Zr	228	230	220	212

Table 7.9B NW Glasgow area. Trace element contents (in ppm) of the Grey till profile samples from the site at Queen Margaret Hall, NS 5633 6817.

	11 - 6	11 - 5	11 - 4
Ba	317	374	460
Ce	75	104	102
Co	21	28	31
Cr	99	100	100
Cu	18	20	22
Ga	22	23	22
La	38	55	42
Ni	32	50	73
Pb	33	26	27
Rb	68	72	77
Sr	125	132	127
Th	11	12	10
U	3	3	3
Y	24	39	29
Zn	54	71	77
Zr	237	228	242

	11 - 3	11 - 2	11 - 1
Ba	481	465	377
Ce	85	86	88
Co	25	22	24
Cr	90	97	96
Cu	20	24	24
Ga	21	21	23
La	42	42	41
Ni	51	49	54
Pb	26	24	22
Rb	73	79	81
Sr	121	131	141
Th	12	11	9
U	3	3	3
Y	29	28	28
Zn	106	135	82
Zr	297	242	212

Table 7.10A NW Glasgow area. Trace element contents (in ppm) of the Red till profile samples from the site at Laighpark, NS 5360 7615.

	1 - 6	1 - 5	1 - 4
Ba	435	493	495
Ce	59	62	60
Co	13	15	21
Cr	91	150	89
Cu	26	22	19
Ga	15	18	15
La	36	25	28
Ni	34	33	37
Pb	12	14	14
Rb	42	57	55
Sr	156	141	151
Th	6	6	7
U	2	2	2
Y	27	24	23
Zn	85	65	71
Zr	252	231	235

	1 - 3	1 - 2	1 - 1
Ba	463	526	492
Ce	61	58	53
Co	23	28	17
Cr	116	160	143
Cu	23	26	24
Ga	16	16	18
La	28	22	23
Ni	37	37	38
Pb	13	13	14
Rb	56	64	58
Sr	156	135	155
Th	6	5	4
U	1	3	3
Y	25	24	22
Zn	63	77	71
Zr	254	243	223

Table 7.10B NW Glasgow area. Trace element contents (in ppm) of the Red till profile samples from the site at Clober, NS 5460 7590.

	4 - 5	4 - 4	4 - 3	4 - 2	4 - 1
Ba	381	457	458	498	443
Ce	53	75	59	61	46
Co	20	25	20	22	13
Cr	88	83	75	103	119
Cu	23	23	30	18	21
Ga	10	14	12	14	12
La	28	39	31	23	19
Ni	21	25	21	22	19
Pb	11	13	13	10	11
Rb	38	48	41	41	37
Sr	109	133	155	147	130
Th	3	4	5	4	4
U	2	2	3	2	3
Y	16	32	26	25	20
Zn	102	71	63	60	60
Zr	213	257	241	260	251

Table 7.11 NW Glasgow area. Minerals identified in the till matrix using X-ray technique, and chemical compositions used in calculation of the mineral components of the till matrix.

Mineral observed	Ideal composition
Quartz	SiO_2
Albite (plagioclase)	$Na_2O.Al_2O_3.6SiO_2$
K-feldspar	$K_2O.Al_2O_3.6SiO_2$
Kaolinite	$Al_2O_3.2SiO_2.2H_2O$
Illite	$K_2O.4Al_2O_3.8SiO_2.4H_2O$
Vermiculite	$3MgO.Al_2O_3.3SiO_2.4H_2O$
Calcite	$CaO.CO_2$

Table 7.12 Minerals assumed to be present in the matrices of the three categories of till in the NW Glasgow area.

Mineral	Ideal composition
Apatite	$3CaO.P_2O_5$
Rutile	TiO_2
Siderite	$FeO.CO_2$
Hematite	Fe_2O_3

Table 7.13 X-ray and calculated analyses of the bulk till matrix of four samples of till (two Red, two Grey) from the NW Glasgow area.

Sample number	X-ray analysis							Calculated analysis							
	quartz	illite	vermiculite	kaolinite	K-feldspar	plagioclase	calcite	quartz	illite	vermiculite	kaolinite	plagioclase	carbonates	hematite	accessory minerals
R16	52.5	4.5	4.3	30.5	2.2	4.3	1.7	54.61	15.83	2.45	14.81	3.13	1.31	4.27	1.03
R39	47.2	6.8	6.4	26.6	3.9	8.2	0.9	60.76	13.83	0.43	2.23	11.34	2.6	4.12	1.17
G 3	47.7	8.6	6.1	30.2	2.5	3.5	1.3	38.91	19.52	7.79	3.99	13.87	6.65	4.31	1.44
G50	41.5	6.6	6.1	35.5	2.2	6.6	1.4	39.56	17.78	6.04	14.04	5.24	6.65	3.32	1.21

Table 7.14 Summary statistics - Range, mean ($\overline{X}$) and standard deviation (S) - of major element data for Red, Weathered Grey and Grey tills of the NW Glasgow area.

		SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	CO_2	H_2O
Red till (N = 20)	Range	61.32 to 78.70	0.77 to 1.58	7.76 to 14.44	3.53 to 8.03	0.42 to 2.95	0.02 to 0.15	0.11 to 2.37	0.31 to 2.24	0.37 to 2.01	1.23 to 1.82	0.06 to 0.22	0.34 to 4.01	2.29 to 5.61
	$\overline{X}$	70.92	0.98	11.63	5.05	0.86	0.08	1.12	0.73	1.31	1.50	0.14	1.88	3.62
	S	4.88	0.25	2.51	1.30	0.54	0.03	0.43	0.47	0.39	0.18	0.04	1.19	0.93
Weathered Grey till (N = 10)	Range	58.22 to 74.98	0.73 to 0.94	10.78 to 16.50	3.87 to 4.88	0.41 to 0.88	0.03 to 0.12	0.65 to 2.61	0.28 to 3.16	0.48 to 1.41	1.21 to 1.83	0.07 to 0.17	1.85 to 6.98	3.82 to 5.63
	$\overline{X}$	66.32	0.84	13.27	4.46	0.67	0.08	1.21	1.04	0.95	1.57	0.13	5.12	4.69
	S	4.19	0.06	1.53	0.37	0.16	0.03	0.59	0.85	0.25	0.16	0.03	1.46	0.61
Grey till (N = 19)	Range	60.22 to 71.06	0.69 to 1.02	10.67 to 16.12	1.57 to 4.72	1.16 to 4.16	0.07 to 0.14	1.10 to 2.37	0.95 to 2.45	0.55 to 2.00	1.41 to 2.23	0.11 to 0.19	3.88 to 7.48	2.18 to 6.23
	$\overline{X}$	63.76	0.88	13.34	3.10	2.42	0.10	1.65	1.79	1.17	1.74	0.16	5.91	4.43
	S	2.80	0.09	1.57	0.95	0.74	0.02	0.33	0.46	0.54	0.22	0.02	1.02	0.91

Table 7.15 NW Glasgow area. Correlation coefficients for the Red till major element data; N = 20

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
SiO_2	1.00										
TiO_2	-0.61	1.00									
Al_2O_3	-0.86	0.32	1.00								
Fe_2O_3	-0.69	0.47	0.40	1.00							
FeO	-0.29	0.45	0.17	-0.07	1.00						
MnO	-0.23	0.31	0.00	0.27	-0.09	1.00					
MgO	-0.65	0.63	0.46	0.41	0.60	0.04	1.00				
CaO	-0.47	0.81	0.17	0.47	0.10	0.54	0.47	1.00			
Na_2O	0.09	0.51	-0.31	-0.08	0.27	0.37	0.34	0.45	1.00		
K_2O	-0.62	0.07	0.78	0.17	0.16	0.06	0.44	-0.07	-0.23	1.00	
P_2O_5	-0.41	0.66	0.20	0.35	0.01	0.53	0.39	0.87	0.49	0.42	1.00

Table 7.16 NW Glasgow area. Correlation coefficients for the Weathered Grey till major element data; N = 10.

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
SiO_2	1.00										
TiO_2	-0.41	1.00									
Al_2O_3	-0.81	0.67	1.00								
Fe_2O_3	0.16	0.62	0.05	1.00							
FeO	-0.68	0.38	0.50	-0.31	1.00						
MnO	-0.68	0.02	0.50	-0.17	0.12	1.00					
MgO	-0.47	-0.28	-0.08	-0.38	0.50	0.19	1.00				
CaO	-0.40	-0.34	-0.18	-0.35	0.45	0.23	0.98	1.00			
Na_2O	0.12	-0.13	-0.30	0.04	-0.29	0.07	0.19	0.17	1.00		
K_2O	-0.87	0.35	0.59	0.07	0.39	0.68	0.54	0.48	0.29	1.00	
P_2O_5	-0.83	0.43	0.61	-0.03	0.64	0.69	0.46	0.44	0.05	0.77	1.00

Table 7.17 NW Glasgow area. Correlation coefficients for the Grey till major element data; N = 19.

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
SiO_2	1.00										
TiO_2	-0.52	1.00									
Al_2O_3	-0.86	0.40	1.00								
Fe_2O_3	-0.49	0.62	0.37	1.00							
FeO	-0.13	-0.33	0.02	-0.68	1.00						
MnO	-0.45	-0.05	0.26	0.09	0.38	1.00					
MgO	-0.33	0.60	-0.01	0.31	0.05	0.09	1.00				
CaO	0.03	0.46	-0.40	0.22	-0.13	-0.02	0.85	1.00			
Na_2O	0.09	0.43	-0.31	0.21	-0.20	-0.30	0.69	0.80	1.00		
K_2O	-0.55	0.64	0.49	0.54	-0.27	-0.12	0.66	0.36	0.51	1.00	
P_2O_5	-0.71	0.60	0.50	0.74	-0.13	0.24	0.47	0.20	0.19	0.55	1.00

Table 7.18 NW Glasgow area. Correlation coefficients for the combined Red, Weathered Grey and Grey tills major element data; N = 49.

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
SiO_2	1.00										
TiO_2	-0.22	1.00									
Al_2O_3	-0.85	0.16	1.00								
Fe_2O_3	0.06	0.50	0.03	1.00							
FeO	-0.50	-0.01	0.26	-0.65	1.00						
MnO	-0.45	0.14	0.22	-0.10	0.35	1.00					
MgO	-0.64	0.29	0.33	-0.12	0.53	0.24	1.00				
CaO	-0.57	0.18	0.16	-0.29	0.50	0.43	0.81	1.00			
Na_2O	0.17	0.44	-0.35	0.09	0.00	0.07	0.31	0.29	1.00		
K_2O	-0.71	0.06	0.67	-0.12	0.34	0.25	0.62	0.47	0.13	1.00	
P_2O_5	-0.55	0.51	0.35	0.10	0.26	0.56	0.49	0.58	0.29	0.39	1.00

Table 7.19. NW Glasgow area. Average trace element composition (in ppm) of the till matrix (< 2 mm) of the three categories of till.

	Red till			Grey till			Weathered Grey till		
	Range	Mean ($\overline{X}$)	σ	Range	Mean ($\overline{X}$)	σ	Range	Mean ($\overline{X}$)	σ
Ba	327 - 533	425.50	58.1	345 - 584	436.4	66.1	304 - 595	404.40	82.9
Ce	39 - 89	64.30	13.26	59 - 89	73.4	9.6	64 - 93	78.2	8.9
Co	6 - 27	12.60	5.22	7 - 21	14.2	4.3	6 - 15	9.80	3.8
Cr	64 - 140	111.10	20.80	93 - 140	112.5	13.1	93 - 141	113.20	15.2
Cu	9 - 22	14.20	4.00	9 - 20	14.6	3.4	9 - 20	12.80	3.4
Ga	8 - 18	13.50	2.70	13 - 21	16.4	2.4	11 - 21	16.80	2.7
La	25 - 46	35.30	5.7	28 - 50	39.4	5.8	32 - 51	42.80	5.8
Ni	14 - 53	31.10	10.2	16 - 49	36.8	8.2	16 - 54	32.20	12.4
Pb	6 - 23	14.60	4.0	10 - 24	16.0	3.3	14 - 23	17.90	3.0
Rb	36 - 73	53.60	10.3	51 - 84	67.0	9.9	61 - 83	67.20	6.9
Sr	84 - 171	116.10	27.2	75 - 182	140.5	30.9	75 - 179	115.20	29.0
Th	1 - 11	6.50	2.9	5 - 11	7.6	1.6	6 - 12	8.80	1.9
U	0 - 4	2.30	1.2	1 - 4	2.4	1.0	2 - 4	3.10	0.7
Y	18 - 31	23.90	4.3	22 - 29	25.0	2.5	22 - 30	26.30	2.5
Zn	20 - 110	59.50	19.8	43 - 84	64.0	10.7	43 - 72	61.20	10.3
Zr	208 - 311	257.80	27.5	186 - 286	248.0	23.9	220 - 300	271.50	28.5

Table 7.20 NW Glasgow area. Correlation coefficients of sand, silt and clay with the trace elements for all samples of the three categories of till (N = 49).

Trace elements	sand (2.000 - 0.063 mm)	silt (0.063 - 0.002 mm)	clay (< 0.002 mm)
Ba	-0.15	0.18	0.11
Ce	-0.34	0.37	0.12
Cu	-0.15	0.14	0.10
Co	-0.27	0.19	0.36
Ni	-0.29	0.22	0.31
Cr	-0.16	0.18	0.11
Sr	-0.42	0.38	0.35
Zn	-0.21	0.20	0.11
Zr	0.28	-0.24	-0.38
Th	-0.23	0.27	0.06
U	-0.11	0.19	-0.12
Ga	-0.52	0.53	0.28
La	-0.41	0.46	0.18
Rb	-0.45	0.46	0.27
Y	-0.17	0.23	0.01
Pb	-0.07	0.07	0.02

Table 7.21 Effect of weathering on weathering ratios (after Burek 1985)

Ratio	Effect of weathering
Ga : Al_2O_3	Decreases with weathering
MgO : Ni	Decreases with weathering
FeO : Co	Decreases with weathering
Ni : Co	Decreases with weathering

CHAPTER 8

RESULTS OF ANALYSIS OF TILLS OF THE NW GLASGOW AREA IN RELATION TO THE SPECIFIC AIMS OF THE RESEARCH PROJECT

8.1 Introduction

Aim 1 of the research project, presentation of grain-size, clay mineralogical and geochemical data for the tills of the NW Glasgow area, and general discussion of these data, is fulfilled in Chapters 5, 6 and 7, above. The purpose of this chapter is to consider the grain-size, clay mineralogical and geochemical data collectively in relation to the more specific Aims, 2 to 5, of the research project (Chapter 4.1.1).

8.2 Amendment of and confirmation of field-determined categories of the till samples (Aim 2)

Aim 2 of the research project is to assign each of the till samples from the NW Glasgow area to one of three categories on the basis of laboratory analysis, rather than on the less accurate method of field observation of the sample and the appearance of the till unit from which the sample was taken. In Table 8.1 the 49 samples collected in the 1960s are listed as Grey till, Weathered Grey till or Red till on the basis of both field determination and laboratory analysis. The more obviously relevant laboratory analyses are those of grain-size and clay mineralogy. Geochemistry is a less effective means of distinguishing between one till category and another, although percentage silica content aids distinction between Red and Grey tills.

In the case of ten samples, the laboratory identification of the category of the sample differed from the field assessment of the category of the sample. In each of these cases the category of till as determined in the laboratory has been accepted as the 'true' category of the till sample concerned. As a result, the 49 samples are found to comprise 19 samples of Grey till, 10 samples of Weathered Grey till and 20 samples of Red till, and the various calculations of the properties and characteristics of the 'average' Grey till, Weathered Grey till and Red till (discussed in Chapters 5, 6 and 7) have been based on this grouping of the samples.

It should also be noted that laboratory analysis confirmed the category of ten samples (different from the ten mentioned above) which had been only tentatively identified on the basis of field observation. The laboratory determination and field identification of the 29 'remaining' samples agreed completely.

8.3 Mineralogical and geochemical criteria for distinction between Red till and Weathered Grey till (Aim 3)

In the field, difficulty had been experienced in distinguishing between Red till and Weathered Grey till in the SW-NE oriented zone near to the 'feather edge' of the Red till. The site at Cleveden School, for example, presented such a problem (Table 8.1, samples 13, 15 and 16). Grain-size and clay mineralogical data given in Chapters 5 and 6, above, suggest reasons for this difficulty in distinction:

1) The average percentages of the sand-silt-clay fractions of these two categories of till are fairly close. Although the average Red till contains a higher percentage of sand and lower percentage of silt than the average Weathered Grey till, the <u>ranges</u> of the sand and silt percentages of the two categories of till overlap. Grain-size data therefore cannot be used to determine the category of an 'unknown' sample.

2) The values of the grain-size parameters, mean size (Mz), inclusive graphic standard deviation (σ_I), inclusive graphic skewness (Sk_I) and inclusive graphic kurtosis (K_G), for the Red till and Weathered Grey till samples overlap, and therefore are not of diagnostic value.

The clay mineralogy of the two categories of till offers a possible means of distinction, although the clay mineral assemblages of the till categories resemble each other in comprising kaolinite, vermiculite and illite. In all but two of the twenty Red till samples that were analysed the percentage of kaolinite was less than 55, whereas all ten analysed samples of Weathered Grey till contained more than 55% of kaolinite. Also, in all but three samples, the percentage of vermiculite in the analysed Red till exceeded 27 (range, 20-45%), whereas all the Weathered Grey till samples contained less than 27% vermiculite (range, 14-27%). Most 'unknown' samples therefore are capable of being assigned with confidence to either the Red till or the Weathered Grey till category on the basis of the laboratory determination of their percentage contents of kaolinite and vermiculite.

8.4 Mineralogical changes that occur through the vertical profile of the Grey till in combination with the Weathered Grey till (Aim 4a)

The profiles at Kelvinside (NS 5581 6807) and Queen Margaret Hall (NS 5633 6817) were sampled and analysed with the specific aim of determining the mineralogical and geochemical changes that have occurred, since glacial deposition, in what originally was Grey till but now, in its upper part, is Weathered Grey till. The following conclusions result from the data presented in Chapters 5, 6 and 7:

1) The sand-silt-clay distribution changes noticeably from the top to the base of the profiles, the size grades being biased to finer at the base than at the top. This is regarded as an indication of downward leaching of the finer grades through time.

2) Related to 1), one of the grain-size parameters, mean size (Mz in mm), decreases noticeably downwards through the profiles. Skewness (Sk_I) also changes noticeably, but in this case there is an increase downwards.

3) Notable changes in clay mineralogy are the reduction in percentage content and eventual disappearance of chlorite (present only in the Grey till) upwards through the profiles, and the increase in vermiculite upwards through the profiles at the expense of chlorite and illite.

4) Geochemical changes are an increase in Fe_2O_3 (and accompanying reduction in FeO) upwards through the profiles, and a decrease upwards in the values of the weathering ratios Ga:Al_2O_3, MgO:Ni, FeO:Co and Ni:Co that indicate a definite, although minor, break in trend at about 2m below ground level, where the (transitional) junction between Weathered Grey till (above) and non-weathered Grey till (below) occurs.

It is interesting to compare the results obtained for the sites at Kelvinside and Queen Margaret Hall in 1986 with those for the site at Cleveden School, Location A (NS 5602 6833, Table 8.1), where samples 11, 12 and 14 were collected from a vertical exposure in 1965. At the time of collection, there was some uncertainty regarding the precise identity of samples 12 and 14. By laboratory analysis, both are confirmed as Weathered Grey till. The succession at that site therefore is:

sample number WG14, Weathered Grey till *c.* 0.6m below ground level;
sample number WG12, Weathered Grey till *c.* 1.2m below ground level;
sample number G11, Grey till *c.* 1.8m below ground level.
Relevant grain-size, clay mineralogical and geochemical data for the three samples are given in Table 8.2.

When the data for samples WG12 and G11 are compared it is seen that the same vertical changes between Weathered Grey till (above) and Grey till (below) are present as are present in the Kelvinside and Queen Margaret Hall profiles. A similar result is obtained when the data for samples WG14 and G11 are compared. What does not fit the thesis based on the evidence from the Kelvinside and Queen Margaret Hall sites, that there is a regular upward and downward change throughout the combined Weathered Grey and Grey till profile, is that the succession WG14, WG12, G11 fails to show this regular change.

8.5 Mineralogical and geochemical changes that occur through the vertical profile of the Red till (Aim 4b)

The profiles at Laighpark (NS 5360 7615) and Clober (NS 5460 7590) were sampled and analysed with the specific aim of determining the mineralogical and geochemical changes that have occurred since glacial deposition of the Red till at these sites. Geochemical evidence is rather inconclusive in relation to weathering and profile development in the Red till. The following conclusions result from the data given in Chapters 5 and 6:

1) The sand-silt-clay distribution changes noticeably from the top to the base of the two profiles, the size grades being finer at the base than at the top. This is thought to be an indication of downward leaching through time.

2) Related to 1), one of the grain-size parameters (Mz in mm) decreases noticeably downwards through the profiles. Skewness (Sk_I) also changes noticeably, but in this case there is an increase downwards.

3) Although it is difficult to distinguish between weathered and non-weathered Red till in the same vertical profile, the amount of vermiculite increases upwards through the profiles at the expense of illite.

8.6 Till successions at sites in the NW Glasgow area where two categories of till are superimposed (Aim 5)

Identification of till categories of the 49 samples from the NW Glasgow area on the basis of laboratory analysis, as shown in the final column of Table 8.1 (see also Chapter 8.2, above), leads to the conclusion that, at several sites within the area, two different categories of till are superimposed. The relevant sites and the successions at these sites are given below; the stratigraphical significance of such superimposed relationships between the tills is discussed in Chapter 14.

8.6.1 Weathered Grey till superimposed on Grey till

The only site where Weathered Grey till was sampled directly above Grey till was at Cleveden School, Location A (NS 5602 6833), where samples WG14 and WG12 were taken vertically above sample G11 (see also Chapter 8.5, above).

8.6.2 Red till superimposed on Grey till

At the Veterinary College site, Location A (NS 5509 6982), a downward succession of samples from R37 (c. 1.5m below ground surface) through R39 (c. 1.9m below ground surface) and G36 (c. 4.0m below ground surface) to G38 (c. 5.0m below ground surface) was collected from a vertical section where, clearly, it is established that Red till rests directly on Grey till.

8.6.3 Red till superimposed on Weathered Grey till

The laboratory analyses, in conjunction with field observations (in 1965), show that Red till rests on Weathered Grey till at two sites:

1) At Cleveden School, Location C (NS 5598 6833), sample R16 (c. 1.2m below ground level) was obtained from directly above sample WG15 (c. 2.0m below ground level).
2) At Broomhill Cross (NS 548 671), sample R2 (c. 0.9m below ground level) was taken from directly above sample WG6 (c. 1.5m below ground level) in a small vertical section.

Table 8.1 Comparison of laboratory and field identification of categories of 49 till samples collected in the NW Glasgow area. * field identification amended; + field identification confirmed.

Field number	Site name	National Grid Reference	Till category determined in the field	Till category determined in the laboratory
1	Broomhill Cross	NS 548 671	Red(weathered)	Red
2	Broomhill Cross	NS 548 671	Red	Red
3	Broomhill Cross	NS 548 671	Grey (weakly weathered)	Grey *
4	Broomhill Cross	NS 548 671	Red	Red
5	Broomhill Cross	NS 548 671	Grey	Grey
6	Broomhill Cross	NS 548 671	Grey (weakly weathered)	Weathered Grey +
7	Jordanhill area	NS 5410 6857	Grey	Weathered Grey *
8	Jordanhill College	NS 5376 6830	Red	Red
9	Jordanhill area	NS 5395 6859	Grey	Grey
10	Anniesland Cross	NS 5471 6879	Grey	Grey
11	Cleveden School	NS 5602 6833	Grey	Grey
12	Cleveden School	NS 5602 6833	Grey (weakly weathered)	Weathered Grey +
13	Cleveden School	NS 5599 6837	?Weathered Grey	Weathered Grey +
14	Cleveden School	NS 5602 6833	Grey (weakly weathered)	Weathered Grey +
15	Cleveden School	NS 5598 6833	?Weathered Grey	Weathered Grey +
16	Cleveden School	NS 5598 6833	?Red	Red +
17	Cleveden School	NS 5596 6835	Weathered Grey	Weathered Grey
18	Elderslie Dock	NS 517 681	?Red	Grey *
19	Elderslie Dock	NS 517 681	?Weathered Grey	Grey *
20	Elderslie Dock	NS 517 681	Red	Grey *
21	Elderslie Dock	NS 517 681	Red	Grey *
22	Elderslie Dock	NS 517 681	Grey	Grey
23	Queen Margaret Union	NS 5673 6687	Grey	Grey
24	Queen Margaret Union	NS 5673 6687	?Weathered Grey	Grey *
25	Queen Margaret Union	NS 5673 6687	?Weathered Grey	Grey *

Table 8.1 (continued)

Field number	Site name	National Grid Reference	Till category determined in the field	Till category determined in the laboratory
26	Balmore Road	NS 5881 6918	Grey	Grey
27	Balmore Road	NS 5881 6918	Grey	Grey
28	Balmore Road	NS 5878 6930	?Weathered Grey	Weathered Grey +
29	Weymouth Drive	NS 5576 6897	Weathered Grey	Weathered Grey
30	Weymouth Drive	NS 5582 6895	?Red	Red +
31	Wilderness pit	NS 5992 7220	Red	Red
32	Killermont golf course	NS 5601 7126	Red	Red
33	Dawsholm Park	NS 5508 6979	Grey (weakly weathered)	Weathered Grey
34	Switchback Road	NS 5478 7046	Red	Red
35	Canniesburn Hospital entrance	NS 5473 7084	Red	Red
36	Veterinary Coll.	NS 5509 6982	Red	Grey *
37	Veterinary Coll.	NS 5509 6982	Red	Red
38	Veterinary Coll.	NS 5509 6982	?Red	Grey *
39	Veterinary Coll.	NS 5509 6982	Red	Red
40	Veterinary Coll.	NS 5514 6981	?Grey	Grey +
41	Pendicle Road, Bearsden	NS 5387 7146	Red	Red
42	Lochend Drive, Bearsden	NS 5411 7123	Red	Red
43	U. Westbourne Drive, Bearsden	NS 5328 7233	Red	Red
44	Garscadden Hill	NS 5334 7168	Red	Red
45	Garscadden Mains	NS 5364 7115	Red	Red
47	Garscadden Mains	NS 5364 7115	Red	Red
48	Burnbrae Hotel	NS 5529 7334	Red	Red
49	Burnbrae Hotel	NS 5535 7332	?Red (weathered)	Red +
50	Burnbrae Hotel	NS 5530 7329	Grey	Grey

Table 8.2 Grain-size, clay mineralogical and geochemical data for three samples from a vertical profile through Weathered Grey till and Grey till at Cleveden School, NS 5602 6833.

(a) Grain-size data

Sample number	Category of till	%			grain-size parameters	
		sand	silt	clay	Mz(ø)	Sk_I
14	Weathered Grey	50.68	44.47	5.85	4.22	-0.08
12	Weathered Grey	54.22	42.92	2.86	3.90	-0.11
11	Grey	47.15	42.71	10.11	5.20	0.25

(b) Clay mineralogical and geochemical data

Sample number	Category of till	%		%	
		vermiculite	illite	Fe_2O_3	FeO
14	Weathered Grey	24.80	18.50	4.88	0.41
12	Weathered Grey	20.80	15.40	4.74	0.83
11	Grey	9.40	18.90	3.92	1.52

CHAPTER 9

ANALYSIS OF BEDROCKS UNDERLYING TILLS IN THE NW GLASGOW AREA

9.1 Introduction

The geological setting of the NW Glasgow area is described in Chapter 1.2, where it is noted that the main source rocks of the Red till and Grey till (including Weathered Grey till) of that area are probably the Devonian and Carboniferous sedimentary and igneous rocks that underlie the area or outcrop a short distance to the north and west of the area. Dalradian (metamorphic) rocks, which outcrop to the NW of the Highland Boundary Fault, also constitute a very minor component of the tills, especially the Red tills of the NW Glasgow area.

Samples of bedrock in the NW Glasgow area were collected with a view to comparing the mineralogical and geochemical characteristics of these rocks with the corresponding characteristics of the Red and Grey tills (Aim 6 of the research project). There is very limited exposure of solid rock in the NW Glasgow area, so the samples collected and analysed may not be truly typical of the major lithological units that underlie that area (see Chapter 4.2.1). However, it is thought that for the purposes of this part of the research project (Part II of this thesis) - which is concerned mainly with the characteristics of the tills of the NW Glasgow area rather than their sources - the samples of bedrock analysed are sufficiently representative to allow inferences regarding the origins of the tills to be made. The laboratory study of the bedrock samples was carried out using two procedures, mineralogical analysis and geochemical analysis, discussed below.

The positions of sites where samples of bedrock were collected are shown in Figure 1.2. The stratigraphical positions of the samples are shown in Table 9.1. The sedimentary successions at two of the sites, Dawsholm Bridge Quarry and Cleddans Burn, are given in Tables 9.2 and 9.3.

9.2 Mineralogical analysis

9.2.1 Carboniferous sandstones

Bedrock specimens of Carboniferous sandstones were studied in thin section. These revealed a generally similar mineral assemblage in all three specimens, strongly dominated by quartz with minor occurrence of plagioclase feldspar, potassium feldspars and traces of muscovite.

The modal composition of the bedrock as established by X.R.D. analysis (Table 9. 4) indicates a generally close similarity in the mineralogy of the sandstone bedrock samples. X.R.D. analysis showed an average modal composition of 51.1% quartz, 8.8% potassium feldspar, 4.5% albite-plagioclase, with high amounts of chlorite, 32.8%, and trace amounts of muscovite, 2.8%.

9.2.2 Carboniferous conglomerate

Specimens of the conglomerate studied in thin section revealed a mineral composition completely dominated by quartz, with traces of muscovite and chlorite (Table 9.5). X.R.D. analysis showed a modal composition of 90% quartz, with trace amounts of muscovite (2%) and chlorite (8%).

9.2.3 Upper O.R.S. sandstone

Thin sections of Upper O.R.S. sandstone specimens revealed a mineral composition dominated by quartz and potassium feldspars, with traces of muscovite and plagioclase. X.R.D. analysis (Table 9.6) showed a modal composition which confirmed the findings of the microscopic studies. The main components are quartz (average 77.8%) and potassium feldspars (average 18.1%). Muscovite and plagioclase are only of minor occurrence.

9.2.4 Carboniferous shale

The bedrock specimens from shale, all brown and fine-grained, revealed a mineral assemblage of quartz, biotite, albite and dominated by fine-grained chlorite. X.R.D. analysis (Table 9.7) showed the phyllosilicates (biotite and chlorite) to be dominant (57% by weight) with high chlorite (50.2%) and lesser quartz (27.2%) and feldspars (15.8%).

9.2.5 Carboniferous limestone

Thin sections of the lower and upper limestone bedrocks showed that both consist of microcrystalline to very finely crystalline aggregates of calcite. The crystals generally are distinguishable under the microscope. Skeletal fragments, mainly of foraminifers and crinoids, occur with very small amounts of clay and quartz sand. X.R.D. analysis of the crushed specimens (<200 mesh) supported the findings of the microscopic studies, and Table 9.8 shows modal compositions of calcite (84.2 - 91.6%), quartz (4.2 - 6.2%) and chlorite (3.4 - 8.6%). These analyses indicate that dolomite is rather rare.

9.2.6 Basalt

Thin sections of basaltic bedrock show three principal minerals: labradorite, olivine and augite, with minor occurrence of fine-grained hornblende. Alteration has commenced even in the apparently fresh rock, olivine having partly altered to chlorite. Magnetite is notable among the accessory minerals. No quartz was detected. X.R.D. analysis showed labradorite as the dominant mineral (61.8% by weight), potassium feldspar (10.0% by weight) and hornblende (2.7% by weight). Chlorite (9.0%) and vermiculite (12.8%) are notable among the secondary minerals (Table 9.9).

9.2.7 Dolerite

Thin sections of the Milngavie dolerite show coarse-grained labradorite-type plagioclase with abundant augite, altered olivine and magnetite. Decomposition products such as chlorite are abundant. Small amounts of calcite are present. Accessories are generally quartz. X.R.D. analysis of the crushed specimens (<200 mesh) confirmed the findings of the microscopic studies, and Table 9.10 shows the modal composition of the dolerite bedrock. The main components are labradorite (45.4% by weight) and chlorite (10.7% by weight) with a distinctly high secondary calcite content (12.8% by weight). Hornblende, quartz and magnetite are only of minor occurrence (Table 9.10).

9.3 Geochemical analysis

X.R.F. results of trace element analysis of the bedrock samples crushed to <250 mesh are shown in Table 9.11. The trace elements associated with the various bedrock types are compared with those of bedrocks in other areas (Tables 9.12 to 9.15).

9.3.1 Carboniferous sandstone

As seen in Table 9.11 there are only minor differences in trace element contents between the five Carboniferous sandstone samples. Thus, Ba, Cu, Ga and U display almost identical values in each sample. Comparing the average trace element composition of the Carboniferous sandstone samples with the average sandstone values noted by Krauskopf (1983) in Table 9.12, Ba, Sr, Zn, Pb, Ni and Co show enrichment, while Ce, Rb and Y are markedly depleted.

9.3.2 Carboniferous conglomerate

All trace elements in the Carboniferous conglomerate bedrock samples display major differences in metal content relative to the Carboniferous sandstone bedrock. Compared with the metal contents of the average sandstone as noted in Table 9.12, generally low trace element contents are noted in the conglomerate relative to the sandstone, while Ba, Sr and Rb are markedly depleted.

9.3.3 Upper O.R.S. sandstone

Almost identical mean trace element contents are noted between the Upper O.R.S. sandstone and the Carboniferous sandstone bedrocks. The two sandstone bedrocks are slightly different in metal contents, as the Upper O.R.S. sandstone tends to be higher in Rb but lower in Ce, Co, Ni, Pb, Y and Zr relative to the Carboniferous sandstone bedrock (Table 9.12).

9.3.4 Carboniferous shale

The Carboniferous shale is markedly high in Ba (544 ppm), Ce (72 ppm), Cr (111 ppm), Pb (68 ppm), Y (35 ppm) and La (43 ppm) (Table 9.13). The Ce, Cr, Th, U, Y and Ga contents are close to the values found in average shale rocks (Table 9.13), while the Co, Ni and Rb contents are lower.

9.3.5 Carboniferous limestone

The carbonate rocks (Table 9.14) are particularly high in Ba (296.5 ppm) and Sr (470 ppm). The similarity in trace element contents in the lower and upper limestones is very close (Table 9.11). The Sr content is lower and Ba content higher than in average world carbonate (Table 9.14).

9.3.6 Basalt

The basaltic lava studied has Cr (122 ppm), Ni (124 ppm) and Cu (62 ppm) contents that are relatively low compared with those in the average basalt (Table 9.15). Sr (747 ppm) and Ba (557 ppm) tend to be high. The Co content (66 ppm) is close to the general average for mafic rocks.

9.3.7 Dolerite

Of the trace elements particularly associated with the mafic bedrocks as shown in Table 9.15, the Cr content of 68 ppm in the sampled dolerite is lower than in most mafic rocks, but the Ni (49 ppm), Co (40 ppm) and Cu (93 ppm) contents are similar to those of typical basaltic rocks (Table 9.15). All these trace elements vary over a wide range in basic rocks, as a consequence of igneous fractionation.

9.4 Discussion of the results

9.4.1 Sandstones and conglomerate

The mineralogical compositions of the Carboniferous sandstones and conglomerate differ significantly from each other, with higher

K-feldspar and lower quartz contents in the sandstones compared with those in the conglomerate. The Carboniferous sandstones have high chlorite and minor muscovite, while no chlorite has been detected in the Upper O.R.S. sandstone, which is richer in quartz.

Only the Cr content in the Carboniferous sandstones tends to yield higher values than the reference data (Table 9.12). The high Cr content may be correlatable with the high chlorite content in this bedrock, and suggests the presence of basic igneous detritus.

The minerals - such as phyllosilicates and feldspars - most likely to contain trace elements, vary in amounts between the various sandstone bedrocks. The chemical analyses display no significant differences in trace elements between these rocks. Thus it is probable that the relatively high phyllosilicate content, particularly in the Carboniferous sandstones, is correlatable with the high Cr, Ni and Co, whilst in the Upper O.R.S. sandstone the relatively high feldspars content is correlatable with the high Rb content.

9.4.2 Carboniferous shale bedrock

In the Carboniferous shale bedrock, chlorite is the dominant mineral, together with a markedly high content of quartz and plagioclase feldspar, while mica and K-feldspars are of only minor occurrence.

No previously recorded modal composition of this bedrock in the study area is available. Hence the data can only be compared with shale studies as obtained from the literature. As seen in Table 9.16, the modal composition of the Carboniferous shale generally is in agreement with data given by Yaalon (1962) and Clark (1924), with the markedly high chlorite and mica content as a common distinguishable feature of shales.

The high concentrations of Cr in the shale can be correlated with the major amounts of chlorite present in this bedrock type.

9.4.3 Carbonate bedrock

The mineralogical composition of the Carboniferous limestone bedrock is different from the other bedrocks studied, as the calcite content is high in both the lower and upper limestones. The high Ba and Sr contents in the Carboniferous limestones can be correlated with the high carbonate content since both Ba and Sr substitute for Ca^{+2}.

9.4.4 Basic igneous bedrocks, basalt and dolerite

The results indicate that the two basic igneous bedrocks are composed of labradorite, augite and altered olivine, but the dolerite contains secondary calcite and accessory quartz, while the basalt is completely barren of these two minerals but contains vermiculite.

9.5 Summary of results of bedrock analyses, and their relevance to the origin of the Grey till and Red till (Aim 6 of the research project)

The results of the mineralogical studies indicate the differences in mineralogical composition among the major bedrock types examined, with calcic plagioclase, pyroxene and olivine in the basic rocks, high chlorite in the shales, high quartz in the sandstones and conglomerate and high calcite in the limestones. The Lower Carboniferous sandstones generally contain large amounts of chlorite while the Upper O.R.S. sandstone contains much quartz and feldspars, particularly the K-feldspars, with extremely low phyllosilicates.

The trace element contents of the various rock types are similar to those of typical samples of these rocks from elsewhere. Only the basic igneous rocks (high in Cu and Ni) and the Carboniferous shale (high in Pb and Rb) can be distinguished from other rock types on the basis of metal content. The trace element contents of the main bedrocks of the NW Glasgow area are compared with the trace element contents of the Grey and Red tills of that area in Table 9.17.

The mineralogical results summarised above suggest that the matrix of the Grey till, which contains chlorite whereas the matrix of the Red till does not (Chapter 6.11), has been derived mainly from Carboniferous shales and sandstones. The matrix of the Red till, on the other hand, appears to have been derived largely from Upper O.R.S. rather than Lower Carboniferous sandstones. The trace element data, although not especially helpful in relation to indicating the sources of the Grey and Red tills, support rather than refute the view that the matrix of the Grey till was derived from Carboniferous shales. Grain-size analyses of the Grey and Red tills (Chapter 5, above) also support these views of the main sources of these tills.

The significance of the analyses of the bedrock samples from the NW Glasgow area carried out in the course of this study is that, taken together with the detailed analyses of the Grey and Red till matrices presented in Chapters 5, 6 and 7 above, and in conjuction with the more limited analyses of till matrices and pebble lithology carried out by Menzies (1981, 160-161 and figs. 4 and 5), they indicate that both the matrix and the clast fraction of the Grey till were derived largely from Carboniferous shales and sandstones and those of the Red till from O.R.S. bedrock.

Table 9.1 Devonian and Carboniferous rock succession of the NW Glasgow area, showing the approximate stratigraphical positions and National Grid References of the bedrock units that were sampled. Not to scale.

System	Series	Group	Key stratal units	Bedrock sample numbers	Rock type	Site name	National Grid Reference
CARBONIFEROUS SYSTEM	Carboniferous Limestone Series	Upper Limestone Group	Index Limestone	S3, S10	sandstone	Dawsholm Bridge quarry	NS 5591 6969
				S8	sandstone	Dawsholm Bridge quarry	NS 5591 6969
		Limestone Coal Group	Top Hosie Limestone				
		Lower Limestone Group	Hurlet Limestone	S16, S17	limestone	Cleddans Burn	NS 5107 7278
				S15	shale	Cleddans Burn	NS 5107 7278
	Calciferous Sandstone Series	Upper Sedimentary Group	Craigmaddie Muir Sandstone	S4	dolerite (in sill within sandstone)	Milngavie town centre	NS 5535 7451
			Quartz conglomerate	S1	quartz conglomerate	Douglas Muir, north scarp	NS 5231 7500
		Clyde Plateau Lavas		S20	basalt	Tod Hill Moor (south)	NS 5130 7528
		Lower Sedimentary Group					
DEVONIAN SYSTEM	Upper Old Red Sandstone			S9	red sandstone	Dalreoch quarry (north)	NS 3867 7608
				S14	red sandstone	Dalreoch quarry (south)	NS 3879 7595

Table 9.2 Sedimentary succession in Carboniferous rocks at Dawsholm Bridge quarry, NS 5591 6969.

Rock type	Thickness	Bedrock sample number
sandstone	8+ m	S3, S10 (from basal 0.25m)
clay/coal	_c._ 0.20m	
shaley sandstone	_c._ 0.55m	
sandstone	at least 0.60m	S8 (from top 0.20m)

Table 9.3 Sedimentary succession in Carboniferous rocks at Cleddans Burn, NS 5107 7278.

Rock type	Thickness	Bedrock sample number
calcareous sandy shale	at least 0.50 m	
upper limestone	c. 0.15 m	S17
sandy shale with calcareous lenses	c. 0.70 m	
lower limestone	c. 0.10 m	S16
shale	c. 0.75 m	
sandstone	c. 0.35 m	S 2
shale	c. 0.10 m	
'coal'	c. 0.15 m	
shale	at least 0.25 m	S15 (from top 0.15 m)

Table 9.4 Mineralogical composition of Carboniferous sandstone bedrock, NW Glasgow area

Site, and Nat. Grid Reference	Sample number	Mineralogical composition wt %							
		quartz	K-feld.	plagioclase	amphibole	mica including illite	hematite	chlorite	vermiculite
Dawsholm Bridge Quarry NS 5591 6969	S 3	49.6	20.4	-	-	2.3	-	27.7	-
	S 8	55.4	-	1.3	-	3.9	-	39.4	-
	S10	48.2	6.1	12.1	-	2.3	-	31.3	-
	ave.	51.1	8.8	4.5	-	2.8		32.8	-

Table 9.5 Mineralogical composition of Carboniferous conglomerate bedrock, NW Glasgow area.

Site, and Nat. Grid Reference	Sample number	Mineralogical composition wt %							
		quartz	K-feld.	plagioclase	amphibole	mica including illite	hematite	chlorite	vermiculite
Douglas Muir (North Scarp) NS 5231 7500	S1	90.0	-	-	-	2.0	-	8.0	-

Table 9.6 Mineralogical composition of Upper O.R.S. sandstone bedrock, NW Glasgow area

Site, and Nat. Grid Reference	Sample number	Mineralogical composition wt %							
		quartz	K-feld.	plagioclase	amphibole	mica including illite	hematite	chlorite	vermiculite
Dalreoch Quarry (N) NS 3867 7608	S 9	72.6	22.5	1.7	-	3.2	-	-	-
Dalreoch Quarry (S) NS 3879 7595	S14	83.1	13.7	-	-	3.2	-	-	-
	ave.	77.8	18.1	0.8	-	3.2	-	-	-

Table 9.7 Mineralogical composition of Carboniferous shale bedrock, NW Glasgow area

Site, and Nat. Grid Reference	Sample number	Mineralogical composition wt %							
		quartz	K-feld.	plagioclase	amphibole	mica including illite	hematite	chlorite	vermiculite
Cleddans Burn NS 5107 7278	S15	27.2	2.3	13.5	-	6.8	-	50.2	-

Table 9.8 Mineralogical composition of Carboniferous limestone bedrock, NW Glasgow area

Site and Nat. Grid Reference	Sample number	Mineralogical composition wt %					
		quartz	K-feld.	plagioclase	chlorite	calcite	dolomite
Cleddans Burn	S16	6.2	-	-	8.6	84.2	1.0
NS 5107 7278	S17	4.2	-	-	3.4	91.6	0.8
	ave.	5.2	-	-	6.0	87.9	0.9

Table 9.9 Mineralogical composition of basalt bedrock, NW Glasgow area

Site, and Nat. Grid Reference	Sample number	Mineralogical composition wt %					
		quartz	K-feld.	plagioclase	hornblende	chlorite	vermiculite
Tod Hill Moor (S) NS 5130 7528	S20	-	10.0	61.8	2.7	9.0	12.8

Table 9.10 Mineralogical composition of dolerite bedrock, NW Glasgow area

Site, and Nat. Grid Reference	Sample number	Mineralogical composition wt %								
		qtz.	K-feld.	plag.	amph.	chlorite	iron oxides	calcite	mica including illite	vermiculite
Milngavie town centre NS 5535 7451	S 4	6.8	10.1	45.4	2.5	10.7	4.3	12.8	3.6	2.8

Table 9.11 Mean and range of the trace element contents (in ppm) in the sampled bedrocks of the NW Glasgow area.

Bedrock type	Carboniferous conglomerate	Carboniferous sandstone						Upper O.R.S. sandstone			Carbonif. shale	Carboniferous limestone lower lst.	Carboniferous limestone upper lst.		Dolerite	Basalt
Site	Douglas Muir	Cleddans Burn	Dawsholm Bridge	Dawsholm Bridge	Dawsholm Bridge	Douglas Muir	Average Carbonif. sandstone	Dalreoch North	Quarry South	Average Upper O.R.S. sand-stone	Cleddans Burn	Cleddans Burn	Cleddans Burn	Average Carbonif. limestone	Milngavie	Tod Hill Moor
Sample number	S1	S2	S3	S8	S10	S13		S9	S14		S15	S16	S17		S4	S20
Ba	47	298	306	289	337	271		340	235		544	325	268		429	557
	42 - 50	262 - 321	243 - 398	282 - 295	319 - 364	266 - 279	300.0	339 - 340	230 - 239	287.5	498 - 505	322 - 329	266 - 269	296.5	423 - 435	545 - 563
Ce	20	37	59	37	45	18		28	20		72	41	32		52	93
	16 - 22	30 - 41	46 - 71	32 - 38	21 - 66	11 - 25	39.0	26 - 29	17 - 23	24.0	71 - 73	40 - 41	26 - 38	36.5	52 - 53	89 - 96
Co	0	0	1	8	13	3		1	1		13	20	12		40	66
	0	0	1	6 - 11	12 - 14	1 - 5	5.0	0 - 1	0 - 2	1	10 - 18	19 - 21	10 - 15	16.0	39 - 40	65 - 68
Cr	23	74	40	85	43	24		53	29		111	58	28		68	122
	21 - 26	69 - 82	30 - 58	82 - 89	33 - 56	16 - 34	53.0	32 - 71	11 - 42	41	110 - 111	55 - 66	27 - 29	43.0	66 - 71	114 - 134
Cu	1	0	2	2	5	3		2	1		20	11	13		93	62
	0 - 2	0	1 - 3	0 - 3	2 - 8	1 - 7	2.4	2 - 3	1	1.5	18 - 23	9 - 12	12 - 13	12.0	84 - 99	59 - 66
Ga	4	4	7	16	7	5		4	3		36	10	8		23	28
	3 - 4	3 - 4	4 - 9	15 - 16	7 - 8	4 - 6	8.0	2 - 5	2 - 4	3.5	34 - 39	9 - 10	7 - 9	9.0	22 - 24	22 - 33
La	8	20	28	18	19	8		17	11		43	21	17		26	49
	7 - 10	16 - 25	24 - 31	10 - 27	14 - 26	4 - 14	19.0	17 - 18	9 - 13	14.0	43 - 44	14 - 26	15 - 20	19.0	27 - 28	46 - 52
Ni	1	1	5	12	21	2		1	1		17	32	21		49	124
	0 - 2	0 - 1	2 - 7	10 - 14	19 - 23.	1 - 3	8.0	0 - 2	1	1	14 - 18	30 - 34	16 - 27	26.5	46 - 54	118 - 132
Pb	6	7	15	38	19	16		7	5		68	30	21		15	9
	4 - 7	4 - 9	14 - 16	37 - 38	19 - 20	14 - 17	19.0	6 - 7	2 - 7	6.0	66 - 70	29 - 30	16 - 27	25.5	13 - 16	6 - 11
Rb	4	7	22	9	25	6		44	29		54	12	11		17	22
	3 - 4	6 - 7	16 - 29	9 - 10	23 - 28	6 - 7	14.0	36 - 58	26 - 30	36.5	51 - 59	12	9 - 12	11.5	16 - 18	20 - 24
Sr	13	34	48	30	58	20		45	32		449	456	484		587	747
	9 - 16	32 - 36	44 - 53	30	56 - 59	19 - 20	38.0	42 - 47	24 - 39	38.5	411 - 489	422 - 501	479 - 487	470.0	583 - 592	738 - 759
Th	0	2	6	6	3	1		1	1		14	3	1		3	5
	0	1 - 2	5 - 7	5 - 6	3 - 4	1	3.6	0 - 2	0 - 1	1.0	13 - 14	2 - 4	0 - 2	2.0	2 - 4	4 - 6
U	2	3	3	3	3	1		2	1		4	3	4		2	2
	1 - 3	0 - 3	1 - 4	2 - 3	2 - 3	0 - 1	2.6	1 - 3	0 - 2	1.5	3 - 5	3 - 4	2 - 5	3.5	1 - 3	0 - 3
Y	7	14	48	10	7	6		8	8		35	14	11		25	28
	6 - 7	13 - 15	46 - 49	8 - 11	7	6 - 7	17.0	7 - 9	6 - 9	8.0	34 - 36	9 - 20	10 - 12	12.5	24 - 25	26 - 29
Zn	15	13	52	28	60	17		10	16		14	31	32		83	131
	10 - 17	10 - 15	49 - 54	22 - 39	52 - 65	14 - 19	34.0	9 - 10	12 - 17	13.0	11 - 17	29 - 33	32 - 33	31.5	80 - 88	120 - 144
Zr	154	384	249	163	185	115		132	109		288	108	78		129	326
	151 - 159	379 - 388	242 - 255	160 - 165	184 - 188	113 - 120	219.0	129 - 135	101 - 123	120.5	282 - 295	98 - 116	74 - 83	93.0	122 - 136	315 - 345

Table 9.12 A comparison of the trace element contents (in ppm) of the Carboniferous sandstone, Carboniferous conglomerate and Upper O.R.S. sandstone bedrocks of the NW Glasgow area with the average trace element contents of sandstones.

Trace elements	Present study			Comparable sandstone*
	Carboniferous sandstone	Carboniferous conglomerate	Upper O.R.S. sandstone	
Ba	300.0	47.0	287.5	X_0
Ce	39.0	20.0	24.0	92.0
Co	5.0	0.0	1.0	0.3
Cr	53.0	23.0	41.0	35.0
Cu	2.4	1.0	1.5	X
Ga	8.0	4.0	3.5	12.0
La	19.0	8.0	14.0	30.0
Ni	8.0	1.0	1.0	2.0
Pb	19.0	6.0	6.0	7.0
Rb	14.0	4.0	36.0	60.0
Sr	38.0	13.0	38.0	20.0
Th	3.6	0.0	1.0	1.7
U	2.6	2.0	1.5	0.45
Y	17.0	7.0	8.0	40.0
Zn	34.0	15.0	13.0	16.0
Zr	219.0	154.0	120.0	220.0

Note: X indicates between 1 and 10; X_0 indicates between 10 and 100

* average sandstone, Krauskopf 1983

Table 9.13 Trace element contents (in ppm) of shales

Trace elements	Present study average shale	Comparable shale bedrocks 1*	2*	3*
Ba	544	600	580	580
Ce	72	70		59
Co	13	20	20	19
Cr	111	100	100	90
Cu	20	50	57	45
Ga	36	25		19
La	43			92
Ni	17	80	95	68
Pb	68	20	20	20
Rb	54	140		140
Sr	449	400	450	300
Th	14	12		12
U	4	3.5		3.7
Y	35	35	80	26
Zn	14	90		95
Zr	288	180		160

* Data from:
1 average shales, Krauskopf 1983
2 average shales, Krauskopf 1967
3 average shales, Turekian & Wedepohl 1961

Table 9.14 Comparison between trace element contents (in ppm) of carbonate bedrocks in the NW Glasgow area and average carbonates of Krauskopf (1983).

Trace elements	Present study, average limestone	Comparable carbonate
Ba	296.5	10.0
Ce	36.5	11.5
Co	16.0	0.1
Cr	43.0	11.0
Cu	12.0	4.0
Ga	9.0	4.0
La	19.0	na
Ni	26.5	20.0
Pb	25.5	9.0
Rb	11.5	3.0
Sr	470.0	610.0
Th	2.0	1.7
U	3.5	2.2
Y	12.5	30.0
Zn	31.5	20.0
Zr	93.0	19.0

Note: na denotes data not available

Table 9.15 Comparison between trace element contents (in ppm) of basic igneous bedrocks in the NW Glasgow area and comparable basic igneous bedrocks.

Trace elements	Present study		Comparable basic igneous bedrocks			
	Basalt	Dolerite	1	2	3	4
Ba	557	429	474	215	300	330
Ce	93	52	na	na	na	48
Co	66	40	37	39	45	48
Cr	122	68	148	111	200	170
Cu	62	93	109	na	100	87
Ga	28	23	20	21	18	17
La	49	26	na	na	na	15
Ni	124	49	46	60	160	130
Pb	9	15	na	na	na	6
Rb	22	17	9	48	45	30
Sr	747	587	400	313	440	465
Th	5	3	na	na	na	4
U	2	2	na	na	na	1
Y	28	25	41	25	20	21
Zn	131	83	na	na	na	105
Zr	326	129	104	95	110	140

Note: na denotes data not available

Data collected from:
1 Northern Ireland Tertiary basalts (Prinz 1967)
2 Scottish Tertiary tholeiitic basalts (Prinz 1967)
3 Average world basalt (Vinogradov 1962)
4 Average basaltic rocks (Turekian & Wedepohl 1961)

Table 9.16 Modal composition (wt %) of shale bedrocks.

Mineral	Present study	1	2
Quartz	27.2	20	26
Plagioclase	13.5	8	11
K-feldspar	2.3		
Chlorite	50.2	59	48
Mica	6.8		
Fe oxides	-	3	5
Others	-	10	10

1 Average shales, Yaalon 1962; data from Krynine 1948.

2 Average shale, Clarke 1924.

Table 9.17 NW Glasgow area. Analyses of trace element contents (in ppm) of bedrock, Red till and Grey till samples.

	Ba	Ce	Co	Cr	Cu	Ga	La	Ni	Pb	Rb	Sr	Th	U	Y	Zn	Zr
Carboniferous sandstone	300	39	5	53	2.4	8	19	8	19	14	38	3.6	2.6	17	34	219
Carboniferous conglomerate	47	20	0	23	1	4	8	1	6	4	13	0	2	7	15	154
Upper O.R.S. sandstone	287	24	1	41	1.5	3.5	14	1	6	36	38	1	1.5	8	13	120
Carboniferous shale	544	72	13	111	20	36	43	17	68	54	449	14	4	35	14	288
Carboniferous limestone	296	36.5	16	43	12	9	19	26.5	29.5	11.5	470	2	3.5	12.5	31.5	93
Basalt	557	93	66	122	62	28	49	124	9	22	747	5	2	28	131	326
Dolerite	429	52	40	68	93	23	26	49	15	17	587	3	2	25	83	129
Average of twenty Red till samples	425	64	12.6	111	14.2	13.5	35.3	31.1	14.6	53.6	116	6.5	2.3	23.9	59.5	257
Average of nineteen Grey till samples	436	73	14.2	112	14.6	16.4	39.4	36.8	16	67	140	7.6	2.4	25	64	248

PART III

TILLS OF NORTHERN AYRSHIRE

CHAPTER 10

GRAIN-SIZE ANALYSIS OF TILLS OF NORTHERN AYRSHIRE

10.1 Introduction

This chapter presents data on the grain-size characteristics of the matrix of 67 samples of till and associated Quaternary deposits that were collected in Northern Ayrshire. The basis on which sampling sites were chosen is explained in Chapters 1.1 and 4.2.1, and the principles underlying grain-size analysis of tills are discussed in Chapter 5.1.1.

10.2 Grain-size analysis data

The results of the mechanical analyses are shown in Tables 10.1 to 10.3. Cumulative curves of the sand to clay fractions were drawn on arithmetic probability paper (Figs. 10.1 to 10.12) using the phi scale (Krumbein 1938). The statistical grain-size parameters, mean size (Mz), inclusive graphic standard deviation (σ_I), inclusive graphic skewness (Sk_I) and inclusive graphic kurtosis (K_G), were determined from the cumulative curves by the graphical method of percentile intercepts (Folk & Ward 1957). Such grain-size parameters are mutually independent and can be applied to normal as well as non-normal distributions (Landim & Frakes 1968).

In order to visualise more easily the average percentage values in Tables 10.4 and 10.5, these values have also been plotted as histograms (Figs 10.13 to 10.16). Grain-size descriptions are based on Picard's (1971) ternary diagram for sand, silt and clay (Figs 10.17a to 10.19b). The grain-size parameters, Mz, σ_I, Sk_I and K_G, have been tabulated in Table 10.3. Sampled stratigraphical sections and the results of the grain-size analyses are discussed separately for each site.

10.3 Discussion of the grain-size analysis data

Greenock Mains site

10.3.1 Field data

At Greenock Mains the sampled exposures occur in cuts made by Greenock Water. The samples were collected at Locations 2 and 6. The stratigraphical successions at the two Locations are:

Location 2, NS 6369 2780 and NS 6363 2779, Figures 10.20 and 10.21

4	Soil		1m
3	Upper till		5m
2	Sand and gravel	up to	18m
1	Lower "shelly till"	up to	1.5m

Location 6, NS 6331 2768, Figures 10.20 and 10.22

4	Soil	1m
3	Upper till	6m
2	Sand and gravel	4m
1	Lower shelly till	7m

Seven samples of the Upper till were collected at Location 2 from a very high cliff face that proved dangerous to negotiate. Because the cliff face at Location 6 was even steeper and more dangerous, the Upper till was not sampled at that Location.

Briefly, field descriptions of the three "till" units are as follows:

1) The Upper till at Location 2 has a red-brown sandy matrix, with clasts mainly of sandstone (mainly buff-coloured, but some dull red in colour), shale and siltstone, and occasional igneous rocks.
2) The Lower "shelly till" at Location 2 has a dark grey clayey silt matrix, with very rare small clasts of quartzitic composition. A very faint horizontal lamination appeared to be present in this deposit.
3) The Lower shelly till at Location 6 has a dark grey silty clay matrix, with clasts of buff-coloured sandstone, shale, igneous and Highland metamorphic rocks.

10.3.2 Cumulative curves

Figures 10.1 and 10.2 illustrate the cumulative curves for the samples from Greenock Mains. In Figure 10.1, it may be seen that the curves are divisible into two groups. The first, represented by the seven uppermost curves, includes only samples of the Upper till at Location 2. The second group comprises the lowermost three curves, which depart from the general trend of the first group. The curves representing the Lower shelly till at Location 6 (Fig. 10.2) constitute a narrow band in which most of the curves are approximately parallel. It may be seen from Figures 10.1 and 10.2 that there is a strong suggestion of three different types of deposit at Greenock Mains and, when the data are arranged in a triangular diagram (Fig. 10.17b), this division stands out more clearly.

10.3.3 Grain-size distribution: sand-silt-clay composition

The following can be observed from Table 10.5 and Figures 10.13, 10.15 and 10.17b:

1) At Location 2, the matrix of the Lower "shelly till", on average, has 6.08% sand, 78.12% silt and 15.80% clay. This deposit is

bimodal, with a dominant peak in the medium silt (5ø - 6ø) and a subsidiary peak in the very fine silt grade (7ø - 8ø) (Fig. 10.13). It should be noted in particular that the relatively large amount of silt-sized material is finer than 5ø (Fig. 10.13).

2) At Location 2, the Upper till, on average, has 58.08% sand, 32.17% silt and 9.57% clay, with a modal class in the fine sand grade. The samples examined from this till vary between silty sand and sandy mud (Fig.10.17b).

3) At Location 6, the Lower shelly till, on average, has 53.06% sand, 41.50% silt and 5.40% clay, with a modal class in the fine sand grade (2ø - 3ø)(Fig. 10.13). The Lower shelly till samples at this Location are dominantly silty sand to sandy mud (Fig. 10.17b).

10.3.4 Variation of grain-size parameters

The distribution of the grain-size parameters, Mz σ_I, Sk_I and K_G, for each sampled deposit at Greenock Mains is shown in Figures 10.23 to 10.26. In Table 10.6, the ranges, mean values and standard deviations for the grain-size parameters are given.

Mean size (Mz)

The average mean sizes, Mz, are 6.78ø (fine-grained silt) for the Lower "shelly till" at Location 2, 4.14ø (coarse-grained silt) for the Upper till at Location 2 and 4.17ø (coarse-grained silt) for the Lower shelly till at Location 6. Mz values for the Lower "shelly till" at Location 2 range from 6.77 to 7.67ø (fine to very fine-grained silt) and for the Upper till at Location 2 from 3.67 to 4.56ø (very fine-grained sand to coarse-grained silt), whilst those for the Lower shelly till at Location 6 range from 3.93 to 4.67ø (very fine-grained sand to coarse-grained silt). In Figure 10.23 it may be seen that Mz values for the Lower "shelly till" at Location 2 are of appreciably finer grade than those for both the Upper till at Location 2 and Lower shelly till at Location 6.

Inclusive graphic standard deviation (σ_I)

The mean sorting values, σ_I, are respectively 1.7ø, 2.71ø and 2.43ø for the Lower "shelly till" at Location 2, the Upper till at Location 2 and the Lower shelly till at Location 6. σ_I values for the Lower "shelly till" at Location 2 are $1.51 < \sigma_I < 1.82$, and for the Upper till at Location 2 are $2.53 < \sigma_I < 3.02$, whilst those for the Lower shelly till at Location 6 are $2.28 < \sigma_I < 2.53$. The sorting changes from poorly sorted for the Lower "shelly till" at Location 2 to very poorly sorted for both the Upper till at Location 2 and the Lower shelly till at Location 6.

Inclusive graphic skewness (Sk_I)

At Location 2, skewness (Sk_I) varies between 0.02 and 0.25 (average = 0.10), nearly symmetrical to fine skewed, for the Lower "shelly till", whereas for the Upper till skewness varies from 0.17 to 0.39 (average = 0.29), fine skewed to strongly fine skewed. Skewness values for the Lower shelly till at Location 6 range from 0.06 to 0.24 (average = 0.16), nearly symmetrical to fine skewed.

Inclusive graphic kurtosis (K_G)

The Lower "shelly till" samples at Location 2 range from mesokurtic to leptokurtic ($1.01 < K_G < 1.31$; Fig. 10.26). The K_G values for the Upper till at Location 2 range from mesokurtic to platykurtic ($0.72 < K_G < 1.02$), whereas all the Lower shelly till samples at Location 6 are platykurtic ($0.80 < K_G < 0.91$). Average K_G values are, respectively, 1.17, 0.84 and 0.86.

10.3.5 Vertical variation in the sand-silt-clay composition and the grain-size parameters

Figures 10.27 to 10.29 show the vertical variations in sand-silt-clay percentages and grain-size parameters, Mz, σ_I, Sk_I and K_G, in the three deposits examined at Greenock Mains.

The sand-silt-clay composition and the grain-size parameters of the Lower "shelly till" at Location 2 (Fig. 10.27) cannot be studied satisfactorily in a vertical sense because only three samples were collected due to the limited exposed thickness (1.5m) of this deposit.

In contrast, in the Upper till at Location 2 (Fig. 10.28), there are large differences between samples. In particular, the samples between 3 and 4m depth are more sandy and less silty and clayey than those from above and below. This probably indicates that the Upper till at this location is not uniform in composition. The greater sand content in the lowermost till samples may be due to incorporation of material from the underlying sand and gravel unit. In general, the mean size (Mz) shows coarsening upwards; there is a change from coarse silt in the lower part of the section to very fine sand in the upper part. Sorting (σ_I) shows improvement as the mean size shows coarsening. Skewness (Sk_I) and kurtosis (K_G) show obvious oscillations, and no clear trends.

At Location 6, the Lower shelly till (Fig. 10.29) exhibits a gradual upward depletion in silt and clay content, with a corresponding increase in the sand content. This probably results from partial leaching of the silt and clay by weathering. The mean size (Mz) gradually increases in phi units downwards (i.e. it fines downwards). The sorting (σ_I) generally shows a slight improvement downwards. The skewness (Sk_I) changes from fine-skewed in the uppermost four samples to nearly symmetrical in the lowermost three samples. Although most of the samples are platykurtic, kurtosis (K_G)

generally decreases downwards.

Merkland Burn site

10.3.6 Field data

The section sampled at this site is exposed in a deep stream-cut produced by the Merkland Burn, a tributary of the River Ayr. The stratigraphy at this exposure is:

Location 8, NS 5908 2716, Figures 10.20 and 10.30

5	Upper red till		5m	
4	Sand and gravel		1m	
3	Shelly till	up to	6.5m	
2	Sand and gravel		0.5m	
1	Lower red till		1.5m	(base not seen)

At this site, the exposed cliff face was very steep and dangerous. Although an extending ladder was used, it was considered that conditions were too dangerous for the collection of more than one sample from the Upper red till. For the same reasons, the top 2.0 - 2.5m of the shelly till was not sampled.

Briefly, field descriptions of the three till units are as follows:

1) Both the Upper and Lower red tills have a red-brown sandy matrix, with clasts of sandstone (mainly dull red in colour) and igneous rocks.

2) The shelly till has a brownish-grey silty matrix, with clasts mainly of buff- and dull-red-coloured sandstone, and a few igneous and Highland metamorphic rocks.

10.3.7 Cumulative curves

The cumulative curves for the shelly till at this site are shown in Figure 10.3 and those representing both Upper and Lower red tills are shown in Figure 10.4. The curves for each type of till in each figure constitute a narrow band in which most of the curves are parallel. However, the shelly till samples form fairly straight line cumulative curves (Fig. 10.3), which suggests that the source rock may have influenced the grain-size distribution of the shelly till. If a monomineralic rock type predominates in till, the cumulative curve of its grain-size distribution does not approximate to a straight line. If, however, several bimodal distribution curves are superimposed one upon another, the resulting curve becomes more or less straight (Dreimanis & Vagners 1971a, 247).

10.3.8 Grain-size distribution: sand-silt-clay composition

The following can be observed from Table 10.5 and Figures 10.13, 10.15 and 10.18a:

1) The Lower red till, on average, has 63.45% sand, 29.05% silt and 7.5% clay, with a distinct modal class in the fine grade (2ø - 3ø) (Fig. 10.13). The one sample of Upper red till has 68.09% sand, 22.30% silt and 9.61% clay, with a distinct modal class in the fine sand grade (2ø - 3ø)(Fig. 10.13). All the samples from both Lower and Upper red tills are silty sand (Fig. 10.18a).
2) The shelly till, on average, has 53.48% sand, 41.01% silt and 5.51% clay, with a broad modal class in the fine and very fine sand grades (2ø - 4ø). Most of the shelly till samples are silty sands. One sample is silty mud (Fig. 10.18a).

10.3.9 Variation of grain-size parameters

The distribution of the grain-size parameters, Mz, σ_I, Sk_I and K_G, for each till unit at the Merkland Burn site is shown in Figures 10.23 to 10.26.

Mean size (Mz)

Mean size values (Mz) for the Lower red till range from 3.83ø to 4.07ø (very fine-grained sand to coarse-grained silt) and from 3.90ø to 4.33ø (very fine-grained sand to coarse-grained silt) for the shelly till. The average mean sizes are 3.73ø (very fine-grained sand) for the Upper red till, 3.83ø (very fine-grained sand) for the Lower red till and 4.12ø (coarse-grained silt) for the shelly till. To some degree the mean size therefore records the difference between the shelly till on the one hand and the two red tills, Upper and Lower, on the other.

Inclusive graphic standard deviation (σ_I)

All the samples of the three tills are very poorly sorted. The average sorting values, σ_I, are respectively 2.70ø, 2.64ø and, 2.45ø for the Upper red till, the Lower red till and the shelly till. σ_I values for the Lower red till are $2.55 < \sigma_I < 2.73$, whilst those for the shelly till are $2.35 < \sigma_I < 2.53$.

Inclusive graphic skewness (Sk_I)

Skewness values for the Lower red till matrix indicate that most of the samples have fine skewed to strongly fine skewed distribution ($0.25 < Sk_I < 0.39$). The single sample of the Upper red till has a strongly fine skewed distribution ($Sk_I = 0.46$), whilst the shelly till samples have a nearly symmetrical to fine skewed distribution ($0.06 < Sk_I < 0.21$) The average Sk_I values are 0.34 and 0.16 for the Lower red till and the shelly till respectively.

Inclusive graphic kurtosis (K_G)

The Lower red till samples are platykurtic to mesokurtic ($0.84 < K_G < 1.11$). The single sample of the Upper red till is mesokurtic ($K_G = 1.01$), whereas most of the shelly till samples are platykurtic ($0.67 < K_G < 0.90$). The average K_G values are 0.96 and 0.88 for the Lower red till and shelly till respectively.

10.3.10 Vertical variation in the sand-silt-clay composition and the grain-size parameters

Figures 10.31 shows the vertical variation in the sand-silt-clay composition and the grain-size parameters, Mz, σ_I, Sk_I and K_G, in the matrices of the Lower red till and shelly till at the Merkland Burn site.

The results for the three samples of Lower red till indicate that the uppermost and middle samples have higher sand content and corresponding lower silt and clay content than the lowermost sample. This probably indicates that the upper part of the Lower till has been leached. The mean size (Mz) shows coarsening downwards. The sorting value (σ_I) generally shows that the upper and middle samples are better sorted than the lowermost one. The skewness value (Sk_I) generally increases upwards, changing from fine skewed in the lowermost sample to strongly fine skewed in the middle and upper samples. Kurtosis (K_G) generally increases upwards, changing from platykurtic in the lowermost sample to mesokurtic in the middle and upper samples.

Due to the dangerous nature of the cliff section, the samples of shelly till at Merkland Burn, Location 8, were collected at levels lower than 8.0m below the top of the cliff (Fig. 10.30). The samples from between 9.5 and 10.5m depth are more sandy and less silty than the samples above and below this zone. This probably indicates that the shelly till at this location is not uniform in grain size. The mean size (Mz) generally shows coarsening downwards, changing from coarse-grained silt in the uppermost samples to very fine-grained sand in the lowermost sample. However, sorting (σ_I) shows a slight improvement upwards, although the uppermost samples are still poorly sorted. The vertical distributions of skewness (Sk_I) and kurtosis (K_G) are irregular and do not show any clear trends.

Sorn Mains site

10.3.11 Field data

The exposures sampled at Sorn Mains occur in cuts made by the Burn o' Need, a tributary of the River Ayr. The samples were collected at three Locations close to each other, 5-1, 5-2 and 5-3. The stratigraphical successions at the three Locations are:

Location 5-1, NS 5369 2802, Figures 10.32a and 10.33

2	Soil	0.5m	
1	Shelly till	at least 3m	(base not seen)

Location 5-2, NS 5371 2793, Figures 10.32a and 10.34

2	Soil	up to 1m	
1	Shelly till	up to 15m	(base not seen)

Location 5-3, NS 5385 2815, Figures 10.32a and 10.35

3	Sand and gravel	1.5m	
2	Grey till	1.0m	
1	Red till	at least 0.5m	(base not seen)

Briefly, field descriptions of the till units are as follows:

1) The shelly till at Locations 5-1 and 5-2 has a grey silty matrix, with clasts mainly of buff-coloured sandstone and shale, with a small quantity of red sandstone and smaller quantity of Highland metamorphic rocks.

2) The upper till at Location 5-3 has a grey sandy silt matrix, with numerous clasts of basic igneous rocks, buff-coloured sandstone and shale.

3) The lower till at Location 5-3 has a red sandy matrix, with fewer clasts than the overlying grey till. The clasts are mainly of red sandstone. The contact between the two tills is sharp.

10.3.12 Cumulative curves

The curves for the shelly till at Locations 5-1 and 5-2 (Figs. 10.5 and 10.6) show that at each Location the curves constitute a narrow band in which most of the curves are parallel. Also, the curves for the grey till and the red till at Location 5-3 (Fig. 10.7) are nearly parallel.

10.3.13 Grain-size distribution: sand-silt-clay composition

From Table 10.5 and Figures 10.13 , 10.15 and 10.18b the following observations may be recorded:

1) At Location 5-1, the shelly till, on average, has 46.98% sand, 44.79% silt and 8.24% clay, with a principal modal class in the fine sand grade (2ø - 3ø)(Fig. 10.13). The samples vary from silty sand to sandy mud (Fig. 10.18b).

2) At Location 5-2, the shelly till, on average, has 43.71% sand, 49.95% silt and 6.34% clay, with a principal modal class in the fine sand grade (2ø - 3ø), and subsidiary modes in the coarse silt (4ø = 5ø) and very fine silt grades (7ø - 8ø)(Fig.10.13). The

samples vary from sandy and silty mud to, mainly, sandy silt (Fig. 10.18b).

3) At Location 5-3, the single sample from the grey till has 43.88% sand, 48.92% silt and 7.20% clay, with a broad modal class in the fine sand and very fine sand grades (2ø - 4ø)(Fig. 10.13). The single sample of red till is slightly coarser in grade than the grey till sample. It has 47.57% sand, 45.18% silt and 7.25% clay, with a distinct modal class in the fine sand grade (2ø - 3ø)(Fig. 10.13). The grey till sample is silty mud, whereas the red till sample is sandy mud (Fig. 10.18b).

10.3.14 Variation of the grain-size parameters

The distribution of the grain-size parameters, Mz, σ_I, Sk_I and K_G, for each of the tills at Sorn Mains is shown in Table 10.6 and Figures 10.23 to 10.26.

Mean size (Mz)

Samples from the shelly till at Location 5-1 are mainly of coarse silt size, with mean size values (Mz) ranging between 4.40ø and 4.80ø, with an average of 4.59ø (coarse-grained silt). Also, the shelly till samples at Location 5-2 are dominantly of coarse silt size, with mean size (Mz) values ranging between 4.43ø and 4.60ø, and an average of 4.54ø (coarse-grained silt). On the other hand, at Location 5-3, mean size (Mz) values of the single sample of grey till and the single sample of red till are, respectively, 4.60ø and 4.53ø (coarse-grained silt).

Inclusive graphic standard deviation (σ_I)

According to the sorting classification introduced by Folk & Ward (1957), all the analysed till samples from Sorn Mains are very poorly sorted ($2 < \sigma_I < 4$)(Fig. 10.24). The shelly till samples at Location 5-2 are relatively better sorted ($2.22 < \sigma_I < 2.61$, average = 2.44ø) than the shelly till samples at Location 5-1, which have values of $2.41 < \sigma_I < 2.67$, with an average of 2.51ø. σ_I values are 2.55ø and 2.46ø respectively for the single samples of grey and red tills at Location 5-3.

Inclusive graphic skewness (Sk_I)

Skewness values (Sk_I) for the shelly till samples from Location 5-1 range from nearly symmetrical to fine skewed distribution ($0.03 < Sk_I < 0.24$), with an average of 0.12 (fine skewed), whereas most of the shelly till samples at Location 5-2 are nearly symmetrical ($-0.01 < Sk_I < 0.11$), with an average of 0.05 (nearly symmetrical). At Location 5-3, the grey till sample has a nearly symmetrical distribution ($Sk_I = -0.02$), whilst the red till sample has a fine skewed distribution ($Sk_I = 0.12$).

Inclusive graphic kurtosis (K_G)

All the samples of till examined from the three Locations at Sorn Mains are platykurtic ($0.67 < K_G < 0.90$)(Fig. 10.26). At Location 5-1, the K_G values for the shelly till samples range between 0.74 and 0.83, with an average of 0.80, whereas at Location 5-2 the K_G values for the shelly till samples range between 0.74 and 0.88, with an average of 0.80. At Location 5-3, the sample of grey till has K_G value of 0.79, whilst the sample of red till has K_G value of 0.82.

10.3.15 Vertical variation in sand-silt-clay composition and grain-size parameters

At Location 5-1, the shelly till exhibits a gradual upward depletion in silt and clay content, with a corresponding increase in sand content (Fig. 10.36). The mean size (Mz in phi units) increases downwards from 4.40 to 4.80ø (i.e. coarsening upwards). The sorting (σ_I) shows obvious oscillations and no clear trend of upward improvement. Skewness (Sk_I) changes from nearly symmetrical in the lower samples to fine skewed in the uppermost two samples. Kurtosis (K_G) does not show any clear trends.

The shelly till at Location 5-2 (Fig. 10.37) has been leached, which accounts for the gradual downward increase of the clay content. The uppermost sample contains higher silt and lower sand contents than the samples below it. This suggests that perhaps the till was originally finer-grained at the top. The more general downward decrease in sand content is accompanied by an increase of the mean size (Mz) in phi units (i.e. fining downwards) and slight improvement of the sorting (Fig. 10.37). Both skewness and kurtosis show no clear trends, there being obvious oscillations between high and low values.

Sourlie site

10.3.16 Field data

At Sourlie (Fig. 10.38), a multiple succession of stratified Quaternary deposits, underlain and overlain by thick deposits of till, was exposed in a very large excavation in 1986. This site is of especial interest because the inter-till deposits represent an interstadial episode in Middle Devensian times (Jardine & Dickson 1987).

The stratigraphical successions at the Sourlie site was as follows:

6	Upper grey till	up to 12+m
5	Pink-brown shelly till	up to 3.5m
4	Local pockets of sand and organic-rich clay and silt	up to 1.5m
3	Sand and gravel	up to 9m
2	Lower grey till	up to 7.5m
1	Bedrock	

Briefly, field descriptions of the three till units are as follows:

1) The upper grey till has a dark grey sandy clay to silty clay matrix, with clasts of (local) sedimentary rocks (shale and sandstone) and farther-travelled basic igneous rocks.
2) The shelly till has a pink-brown sandy silt matrix, with a mixture of clasts of local and far-travelled sedimentary, igneous and metamorphic rocks, together with occasional fragments and rare complete valves of marine molluscs.
3) The Lower grey till has a dark grey sandy clay to silty clay matrix, with clasts of (mainly) shale and sandstone.

Samples of the three tills were collected from vertical faces at Location 3 (Lower grey till, NS 3372 4147; Upper grey till, NS 3364 4148) and Location 13 (junction of Upper grey till and pink-brown shelly till, NS 3361 4147)(Fig. 10.38).

10.3.17 Cumulative curves

Grain-size cumulative curves are presented in Figures 10.8 to 10.10. Both Upper and Lower grey tills at Location 3 have almost identical cumulative curves. The curves for the two tills have irregular size distributions. At Location 13, the Upper grey till is separated from the underlying pink-brown shelly till by a sharp boundary. It should be noted from Figure 10.10 that the curves for the two tills at this Location are separated into two groups, between which there is (little or) no overlap. The three upper curves represent only samples from the shelly till and the three lower curves represent only samples from the Upper grey till.

10.3.18 Grain-size distribution: sand-silt-clay composition

From Table 10.5 and Figures 10.14, 10.16 and 10.19a the following observations may be recorded:

1) At Location 3, the Upper grey till, on average, has 42.95% sand, 44.74% silt and 12.30% clay, with a distinct modal class in the very fine silt grade (7ø - 8ø) and secondary mode in the fine sand grade (2ø - 3ø)(Fig. 10.14). The Lower grey till, on average, has 44.53% sand, 44.20% silt and 11.26% clay, with a principal modal class in the fine sand grade (2ø - 3ø) and a subsidiary mode in the very fine silt grade (7ø - 8ø)(Fig. 10.14). Both Upper and Lower grey till samples vary from sandy mud to silty mud (Fig. 10.19a).
2) At Location 13, the Upper grey till, on average, has 36.90% sand, 45.97% silt and 17.13% clay, with a broad modal class in the very fine silt and clay fractions (7ø to > 8ø)(Fig. 10.14). The shelly till, on average, has 53.78% sand, 37.81% silt and 8.41% clay, with a distinct modal class in the fine sand grade (2ø - 3ø)(Fig. 10.14). All the Upper grey till samples are silty mud, whereas all the shelly till samples are silty sand (Fig. 10.19a).

10.3.19 Variations of grain-size parameters

The distribution of the grain-size parameters, Mz, σ_I, Sk_I and K_G, for the tills at Sourlie are shown in Table 10.6 and Figures 10.23 to 10.26.

Mean size (Mz)

At Location 3, the Upper grey till samples are of coarse silt to medium silt size, with mean size value (Mz) ranging between 4.06 and 5.10ø, and with an average of 4.83ø (coarse-grained silt). The Lower grey till samples at the same Location are mainly of coarse silt size, with mean size values (Mz) ranging between 4.50 and 5.00ø, and with an average of 4.73ø (coarse-grained silt).

At Location 13, the Upper grey till samples are mainly of medium silt size, with mean size values (Mz) ranging between 5.13 and 5.43ø, and with an average of 5.28ø (medium-grained silt), whereas the shelly till samples at that Location are mainly of coarse silt size, with mean size values (Mz) ranging between 4.16 and 4.28ø, and with an average of 4.21ø (coarse-grained silt).

Inclusive graphic standard deviation (σ_I)

Generally, all the till samples at Sourlie are very poorly sorted ($2 < \sigma_I < 4$). At Location 3, the average sorting values are: Upper grey till, 2.71ø; Lower grey till, 2.64ø. At Location 13, the average sorting values are: Upper grey till, 2.94ø; shelly till, 2.50ø. Clearly, the shelly till is better sorted than both the grey tills.

Inclusive graphic skewness (Sk_I)

Average skewness values (Sk_I) for the various tills at Sourlie show significant differences between the Upper and Lower grey tills at Location 3 and between the Upper grey till and the shelly till at Location 13 (Table 10.6). The average skewness values at Location 3 are 0.01 (nearly symmetrical) and 0.11 (fine skewed) for the Upper and Lower grey tills respectively, whereas at Location 13 the average values for the skewness are -0.19 (coarse skewed) and 0.25 (fine skewed) for the Upper grey till and shelly till respectively. The differences in skewness between the Upper grey, Lower grey and shelly tills at Sourlie may be explained by the nature of the tills. The Upper grey till is mainly silty mud and the Lower grey till is mainly sandy mud, whereas the shelly till is dominantly silty sand.

Inclusive graphic kurtosis (K_G)

At Location 13, the Upper grey till and the shelly till have similar average kurtosis (K_G) values (K_G = 0.80, platykurtic). Similarly, at Location 3 average kurtosis values show no significant differences between the Upper and Lower grey tills; both are platykurtic (average values, 0.79 and 0.75, respectively).

10.3.20 Vertical variations in the sand-silt-clay composition and grain-size parameters.

Figures 10.39, 10.40 and 10.41 show the vertical variations in the sand-silt-clay composition and in the grain-size parameters for the tills at Sourlie. Values are plotted against the stratigraphical positions of the samples.

At Location 3, the Upper grey till exhibits a gradual decrease in the sand content downwards, with a corresponding increase in the silt and clay content. The mean size (Mz) increases downwards in phi units (i.e. fining downwards) changing from coarse silt in the uppermost four samples to medium silt in the lowermost two samples. Sorting (σ_I) shows a slight improvement upwards. Skewness (Sk_I) decreases downwards and changes from nearly symmetrical to fine skewed in the lowermost sample. Kurtosis (K_G) shows a slight increase downwards.

The Lower grey till at Location 3 (Fig. 10.40) shows a downward increase in the sand content, with a corresponding decrease in the silt and clay content. The mean size (Mz) shows coarsening downwards. Sorting (σ_I) shows a slight improvement downwards. The skewness (Sk_I) increases downwards, changing from nearly symmetrical to coarse skewed. Kurtosis (K_G) shows a general increase downwards.

In the Upper grey till and shelly till at Location 13 (Fig. 10.41), the sand content shows a sharp increase downwards from the Upper grey till to the shelly till, with a corresponding decrease in silt and clay content. Mean size (Mz) shows coarsening downwards in the Upper grey till, and changes sharply from medium silt in the Upper grey till to coarse silt in the shelly till. Sorting (σ_I) shows a slight improvement from the Upper grey till to the shelly till. Skewness (Sk_I) changes from negatively skewed in the Upper grey till to positively skewed in the shelly till. Kurtosis (K_G) does not show any clear trends.

<u>Tayburn site</u>

10.3.21 Field data

At Tayburn, the sampled exposures occur in cuts made by Hareshawmuir Water. Till samples were collected at two Locations, 5B and 7B. At this Site there are two superimposed till units. The upper till, grey in colour, is separated from the lower, red till by a sharp boundary. The stratigraphical successions at the two locations are as follows:

Location 5B, NS 5107 4345, Figures 10.32b and 10.42

3	Soil	0.5m	
2	Grey till	2.0m	
1	Red till	up to 2.0m	(base not seen)

Location 7B, NS 5095 4333, Figures 10.32b and 10.43

3	Soil	0.5m	
2	Grey till	5.5m	
1	Red till	at least 2.5m	(base not seen)

Briefly, field descriptions of the two till units are as follows:

1) The upper till has a dark grey silty matrix, with numerous cobble- and pebble-sized clasts of sedimentary rocks, mainly buff-coloured sandstone, and smaller quantities of basic igneous rocks.

2) The lower till has a dark-brown to red sandy matrix, with numerous pebble-sized clasts mainly of basic igneous rocks and red sandstone, together with a few fragments of limestone. This till has a washed appearance.

10.3.22 Cumulative curves

Figures 10.11 and 10.12 show the grain-size cumulative curves for the grey till and the red till at Tayburn In Figure 10.11 it is clear that the curve for the single sample of red till at Location 7B is separated from the four curves for the red till at Location 5B. However, there is an overlap between the cumulative curve for the single sample of grey till at Location 7B and the four curves for the samples of the same till at Location 5B (Fig. 10.12). Thus, there appears to be less variation in grain size within the grey till between the two locations than there is in the red till.

10.3.23 Grain-size distribution: sand-silt-clay composition

From Table 10.5 and Figures 10.14, 10.16 and 10.19b the following observations may be recorded:

1) The grey till at Location 5B, on average, has 35.77% sand, 51.26% silt and 12.98% clay. It is weakly polymodal, with a principal

mode in the very fine silt grade (7ø - 8ø), and subsidiary modes in the medium silt (5ø - 6ø) and fine sand grades (2ø - 3ø) (Fig.10.14). The single sample of grey till at Location 7B has 35.75% sand, 47.14% silt and 17.51% clay. It also has polymodal distribution (Fig. 10.14), with a principal broad mode in the very fine silt and clay grades (7ø to > 8ø), and subsidiary modes in the medium silt (5ø - 6ø) and fine sand grades (2ø - 3ø). The grey till samples at Location 5B are silty mud to sandy silt, and the single sample of grey till at Location 7B is sandy silt (Fig. 10.19b).

2) The red till at Location 5B, on average, has 48.18% sand, 41.33% silt and 10.50% clay. It has polymodal distribution (Fig. 10.14), with a principal mode in the fine sand grade (2ø - 3ø), and secondary modes in the medium silt (5ø - 6ø) and very fine silt grades (7ø - 8ø). The single sample of the red till from Location 7B has 37.64% sand, 46.04% silt and 16.32% clay, with a distinct modal class in the very fine silt grade (7ø - 8ø) (Fig.10.14). All four red till samples at Location 5B are sandy mud (Fig. 10.19b), whilst the single sample at Location 7B is silty mud (Fig.10.19b).

10.3.24 Variations of grain-size parameters

The distribution of the grain-size parameters, Mz, σ_I, Sk_I and K_G, for the tills at Tayburn are shown in Table 10.6 and Figures 10.23 to 10.26.

<u>Mean size</u> (Mz)

The grey till samples at Location 5B are of coarse silt to medium silt size (4.83ø < Mz < 5.20ø), with an average of 4.97ø (coarse-grained silt), and the single sample of grey till at Location 7B has a mean size (Mz) value of 5.3ϕ (medium-grained silt).

The red till samples at Location 5B are dominantly coarse-grained silt (4.13ϕ < Mz < 4.43ϕ), with an average of 4.31ϕ (coarse-grained silt), and the single sample of red till at Location 7B has a mean size value of 4.87ϕ (coarse-grained silt).

Inclusive graphic standard deviation (σ_I)

Although all the samples from the two tills at Tayburn are very poorly sorted (2ϕ < σ_I < 4ϕ), the (upper) grey till is much better sorted than the (lower) red till. At Location 5B, the average σ_I values are 2.73ϕ and 3.00ϕ for the grey till and red till respectively, whereas at Location 7B, σ_I values are 2.88ϕ and 3.23ϕ for the grey till and red till respectively.

Inclusive graphic skewness (Sk_I)

At Location 5B, average skewness values show significant differences between the grey and red tills. The grey till samples are nearly symmetrical to fine skewed (-0.04 < Sk_I < -0.19), with average Sk_I = -0.11, whereas all the red till samples are marginally negative and have a nearly symmetrical distribution (-0.03 < Sk_I < -0.08), with average Sk_I = 0.01. The skewness values of the grey till and red till samples at Location 7B, however, are both negative, -0.18 and -0.24 respectively. They do not differ significantly from one another.

Inclusive graphic kurtosis (K_G)

The average kurtosis values (K_G) of the grey and red tills at the two Locations, 5B and 7B, show no significant differences. All the samples are platykurtic and show consistently similar kurtosis values.

10.3.25 Vertical variation in the sand-silt-clay composition and the grain-size parameters

The vertical distribution of the sand-silt-clay percentages and the grain-size parameters in the grey and red tills at Location 5B are illustrated in Figure 10.44. From this Figure, the following may be observed:

1) The percentage of sand decreases at the base of the grey till. There is, however, an abrupt increase across the boundary between the (upper) grey till and the (lower) red till, and a gradual decrease downwards through the red till.
2) In the grey till, mean size (Mz) shows coarsening downwards, whereas in the red till mean size shows a coarsening upwards.
3) Sorting (σ_I) does not show much vertical change through each type of till. However, it shows an abrupt change from the red till to the grey till. Generally, the (upper) grey till shows better sorting than the (lower) red till.
4) The change from positively-skewed red till to negatively-skewed grey till accompanies a change in the mean size (Mz). Thus, the red till, which has a coarse mean size, is positively skewed, and the grey till, which has a finer mean size, is negatively skewed.
5) The vertical distribution of kurtosis (K_G) through each type of till, and from one till to another, is not significant.

10.4 Inter-relationships of the four grain-size parameters

In order to determine the inter-relationships between the four grain-size parameters, Mz, σ_I, Sk_I and K_G, of the tills of Northern Ayrshire, six scatter plot diagrams (Figs 10.45a to 10.46c) were constructed by co-plotting each pair of parameters (_cf._ Folk & Ward 1957).

Scatter plots for the grain-size parameters illustrate that the correlation coefficients determined for all the Northern Ayrshire "till" samples taken together are misleading as three samples consistently plot off the trends defined by the remainder of the samples (Fig. 10.47). These three samples are from the Lower "shelly till" at Greenock Mains, Location 2. For the purposes of the correlation, these samples have been omitted from the regression analysis.

10.4.1 Plot of mean size (Mz) versus sorting (σ_I) Figure 10.45a

As Folk & Ward (1957) pointed out, there is a strong relationship between mean size and sorting in sediments. For the Ayrshire samples, the plot of Mz against σ_I has a significant correlation coefficient (r = 0.4). The regression line is given by $\sigma_I = 1.73 + 0.20Mz$. Generally, this relationship shows that the smaller the mean size, the poorer the degree of sorting.

10.4.2 Plot of mean size (Mz) versus skewness (Sk_I), Figure 10.45b

Skewness is very closely related to grain size (Folk & Ward 1957). A symmetrical size curve has $Sk_I = 0$, and an increasing amount of coarse material imparts negative skewness.

In the present work, a linear correlation between Mz and Sk_I is indicated by the scatter diagram, Figure 10.45b. The regression line is given by $Sk_I = 1.61 - 0.34Mz$. The correlation coefficient is $r = -0.86$. Generally, this relationship indicates that a decrease in mean size in phi units leads to a higher proportion of fine material.

10.4.3 Plot of mean size (Mz) versus kurtosis (K_G), Figure 10.45c

Folk & Ward (1957) pointed out that a normal curve would give a value of $K_G = 1.0$ and, if the tails of the curve are better sorted than the central portion, K_G values are < 0.9 (platykurtic).

In the present work, the scatter plot diagram between Mz and K_G (Fig. 10.45c) shows that there is a significant correlation between Mz and K_G. The regression line is given by $K_G = 1.26 - 0.10Mz$. The correlation coefficient is $r = -0.58$. Generally, this relationship indicates that the smaller the mean size, the more platykurtic is the till.

10.4.4 Plot of sorting (σ_I) versus skewness (Sk_I), Figure 10.46a

Folk & Ward (1957) showed that if sorting is a function of mean size, and if skewness is a function of mean size, then sorting and skewness will have a mathematical relationship to each other.

In the present work, the studied till samples show a small range of sorting values; they are dominantly very poorly sorted. However, they show a wide range of skewness values, ranging from strongly coarse skewed to fine skewed.

A linear correlation between σ_I and Sk_I is indicated by the scatter diagram, Figure 10.46a. The regression line is given by $\sigma_I = 2.69 - 0.55Sk_I$. The correlation coefficient is $r = -0.43$. Accordingly, this correlation indicates that with increasing skewness values, sorting shows improvement.

10.4.5 Plot of sorting (σ_I) versus kurtosis (K_G), Figure 10.46b

A linear correlation between σ_I and K_G is indicated by the scatter diagram. The regression line is given by $K_G = 1.04 - 0.08 \sigma_I$. The correlation coefficient is $r = -0.23$. Accordingly, this relationship indicates that the higher the kurtosis value, the better the degree of sorting.

10.4.6 Plot of skewness (Sk_I) versus kurtosis (K_G), Figure 10.46c

In the present work, the scatter plot diagram of Sk_I against K_G shows that there is a linear correlation between these two parameters. The regression line is given by $K_G = 0.81 + 0.17Sk_I$. The correlation coefficient is $r = 0.42$. Accordingly, this correlation indicates that, with increasing K_G, Sk_I increases and high K_G values exhibit positive skewness.

10.5 Grain-size relationships between samples of the shelly till of Northern Ayrshire

Mechanical analysis of the till matrix (< 2mm) shows that there is a remarkable degree of similarity in sand, silt and clay percentages in all but three of the samples that were collected as examples of the Ayrshire shelly till, regardless of the stratigraphical or geographical positions of the samples (Fig. 10.48). The grain-size distribution of the shelly till samples from Greenock Mains Location 6, Merkland Burn Location 8, Sorn Mains Locations 5-1 and 5-2 and Sourlie Location 13 demonstrates that all of these samples have their primary mode in the fine sand grade (2ø - 3ø, Figs 10.13 and 10.14) and their mean size in the coarse-grained silt grade (4ø - 5ø, Table 10.6). Thus, on the basis of grain-size data from these five

Locations, one might postulate that there is a fair degree of homogeneity in the shelly tills of Northern Ayrshire.

The three samples that are exceptional are those that were collected from the lowermost deposit at Greenock Mains, Location 2 (Fig. 10.48). In the text above, these deposits have been termed the Lower "shelly till" but, in view of the wide difference in the mechanical composition of this deposit and that of the shelly till at the five other Locations studied, serious doubts are raised concerning the identity of this deposit as a shelly till.

10.6 Afton Lodge marine clays

For purposes of comparison, three samples of Quaternary marine clays from Afton Lodge (NS 4157 2587) were analysed. The results (Tables 10.3 and 10.5) show that these marine deposits contain, on average, 8.08% sand, 77.84% silt and 14.08% clay. These results indicate that there is a strong similarity between the marine clays at Afton Lodge and the matrix of the Lower "shelly till" at Greenock Mains, Location 2. It follows that the grain-size distribution of the Afton Lodge marine deposits differs markedly from that of the shelly till of N Ayrshire as a whole.

10.7 Colour of till in relation to mechanical composition

Several colours of till exist at the various sites in Northern Ayrshire. The colours include grey, pink-brown and red. The colours of the tills are thought to be closely related to the colours of the source rocks over which the ice moved. Generally, most of the grey tills have silty mud to sandy silt matrices, and the pink-brown and the red tills have silty sand to sandy mud matrices. This probably reflects the grain size of the source rocks. For example, the Lower grey till at Sourlie is underlain predominantly by darkcoloured Carboniferous shales and the Lower red till at the Merkland Burn site is underlain by O.R.S. and Downtonian-age sandstones, which are dominantly red in colour.

10.8 Conclusions

The most important information obtained from grain-size analysis of the tills of Northern Ayrshire is summarised below:

1) Mechanical analysis of the till matrix shows that there is a remarkable degree of uniformity in the shelly till sampled at six Locations in Northern Ayrshire, with the exception of the Lower "shelly till" at Greenock Mains, Location 2. The uniformity is probably due to a resemblance in the source material.

2) Despite slight differences in grain size between the samples of shelly till from various locations and stratigraphical horizons, certain features common to all the shelly till, except the Lower "shelly till" at Greenock Mains, Location 2, have been found. They include:

    a) Mean size (Mz) usually ranges from 3.9ø to 4.8ø.

    b) Sorting (σ_I) usually exceeds 2ø, ranging from 2.22ø to 2.67ø (very poorly sorted).

    c) Skewness (Sk_I) usually ranges from -0.01 to 0.27 (nearly symmetrical to fine skewed).

    d) Kurtosis (K_G) usually ranges from 0.74 to 0.94 (mostly platykurtic).

3) The Lower "shelly till" at Greenock Mains, Location 2, is distinctive in its relatively high silt content and average mean size (Mz) in the fine silt grade, and in its being poorly sorted and leptokurtic.

4) On the basis of mechanical composition of the till matrix, the Lower and Upper red tills at Merkland Burn are fairly similar to

each other and are distinct from the shelly till at the same exposure in having higher sand and clay contents and lower silt content than the shelly till.

5) At Tayburn, the (upper) grey and (lower) red tills show considerable variation in grain-size composition. The grey till contains 35.68% sand, 50.43% silt and 13.89% clay, whereas the red till contains 46.07% sand, 42.27% silt and 11.66% clay. Rapid change between positive and negative skewness from the (lower) red till to the (upper) grey till can be observed (Fig. 10.44).

6) At Sourlie, the Lower grey till contains higher sand and lower silt and clay contents than the Upper grey till. The Upper grey till exhibits poorer sorting than the Lower grey till. Furthermore, the Upper grey till can be distinguished by frequently having negative skewness values (nearly symmetrical to coarse skewed) in contrast with the Lower grey till, which has a tendency to positive skewness values (nearly symmetrical to fine skewed).

7) Evaluation of the effect of weathering on grain size depends largely on the assumption that the deposit concerned was originally uniform through the vertical profile and the weathered till material originally had the same grain size as the underlying non-weathered till. In the case of some of the samples from exposures in Northern Ayrshire, such as those from the Lower shelly till at Greenock Mains Location 6, the shelly till at Sorn Mains Location 5-1, the Upper grey till at Sourlie Location 3 and the (lower) red till at Tayburn Location 5B, it is clear from the study of the changes in grain size in vertical profiles that the fine material (silt and clay) tends to increase gradually downwards. This probably reflects a gradual downward leaching of the fine material during and after deposition. In the remainder

of the vertical profiles that were studied, uniformity of the deposit seems probable.

8) Folk & Ward's (1957) grain-size parameters have been calculated for all the samples investigated. To some degree, mean size (Mz) records the differences between the various types of till.

9) The "till" samples that were examined exhibit comparatively poor sorting, ranging from poorly sorted ($1 < \sigma_I < 2$) in the Lower "shelly till" at Greenock Mains, Location 2, to very poorly sorted ($2 < \sigma_I < 4$) in the remainder of the samples.

10) Most of the till samples from Northern Ayrshire (more than 90%) are platykurtic, with K_G values ranging between 0.7 and 0.9.

11) Regression analyses indicate a linear correlation between mean size and the other grain-size parameters. With increasing mean size, the sorting improves, skewness has more positive values and kurtosis decreases.

12) Sorting has negative relationships with skewness and kurtosis.

13) The sand-silt-clay distribution shows that there is a strong similarity between the marine clays at Afton Lodge and the Lower "shelly till" at Greenock Mains, Location 2. On the same evidence, there is a strong dissimilarity between these two deposits and the matrix of the shelly till of N Ayrshire as a whole.

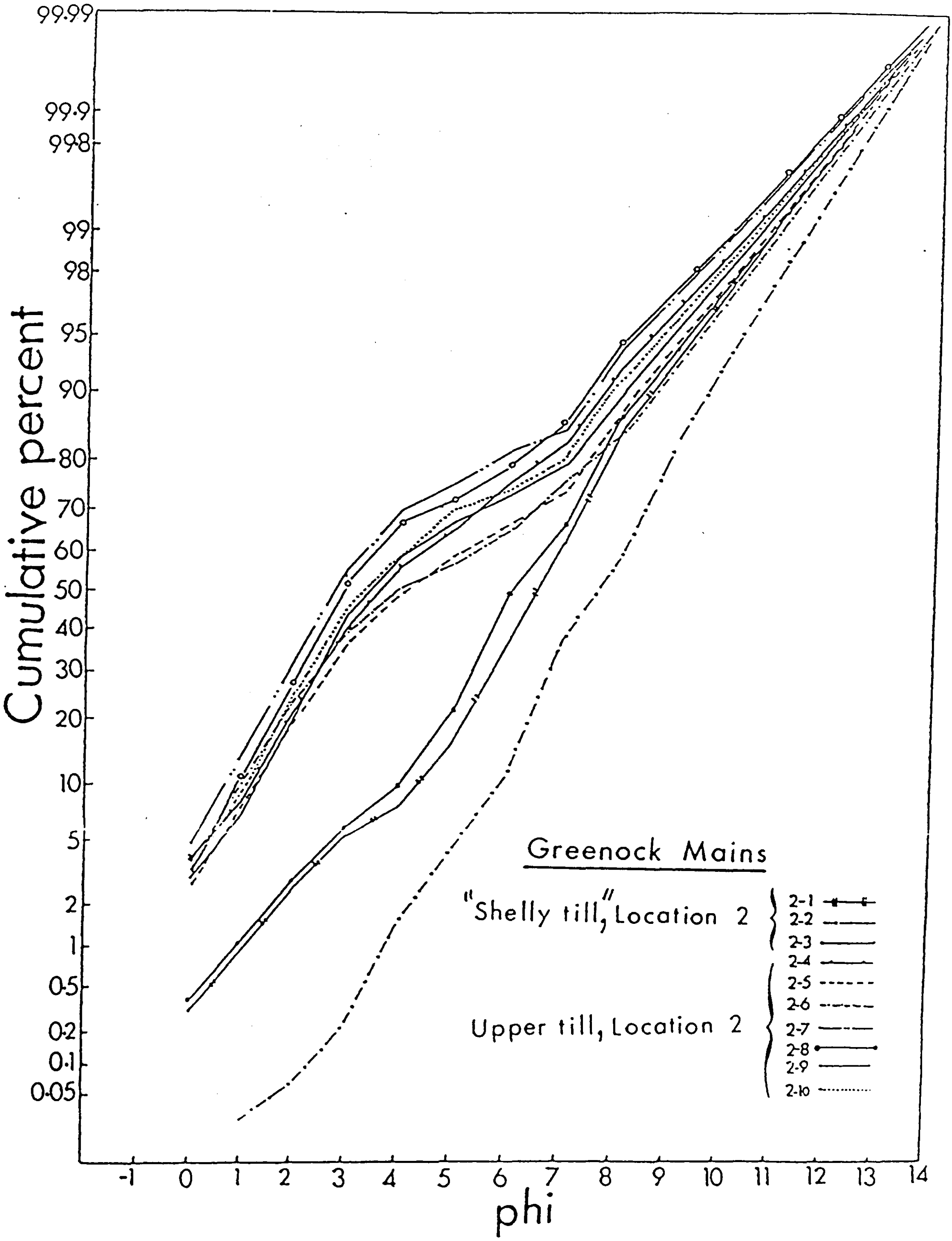


Figure 10.1 Cumulative grain-size curves for the Lower "shelly till" and Upper till samples at Greenock Mains, Location 2.

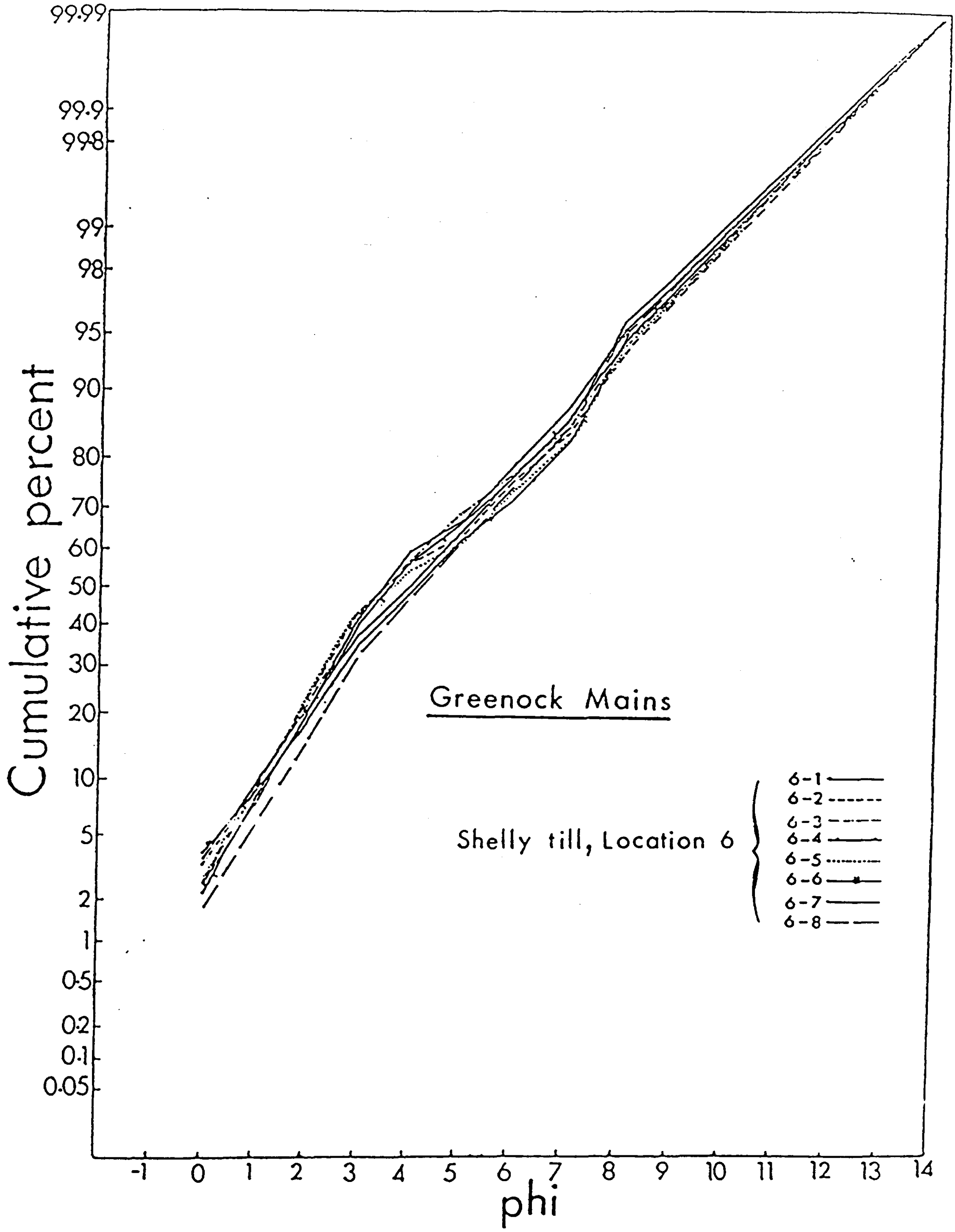


Figure 10.2 Cumulative grain-size curves for the Lower shelly till samples at Greenock Mains, Location 6.

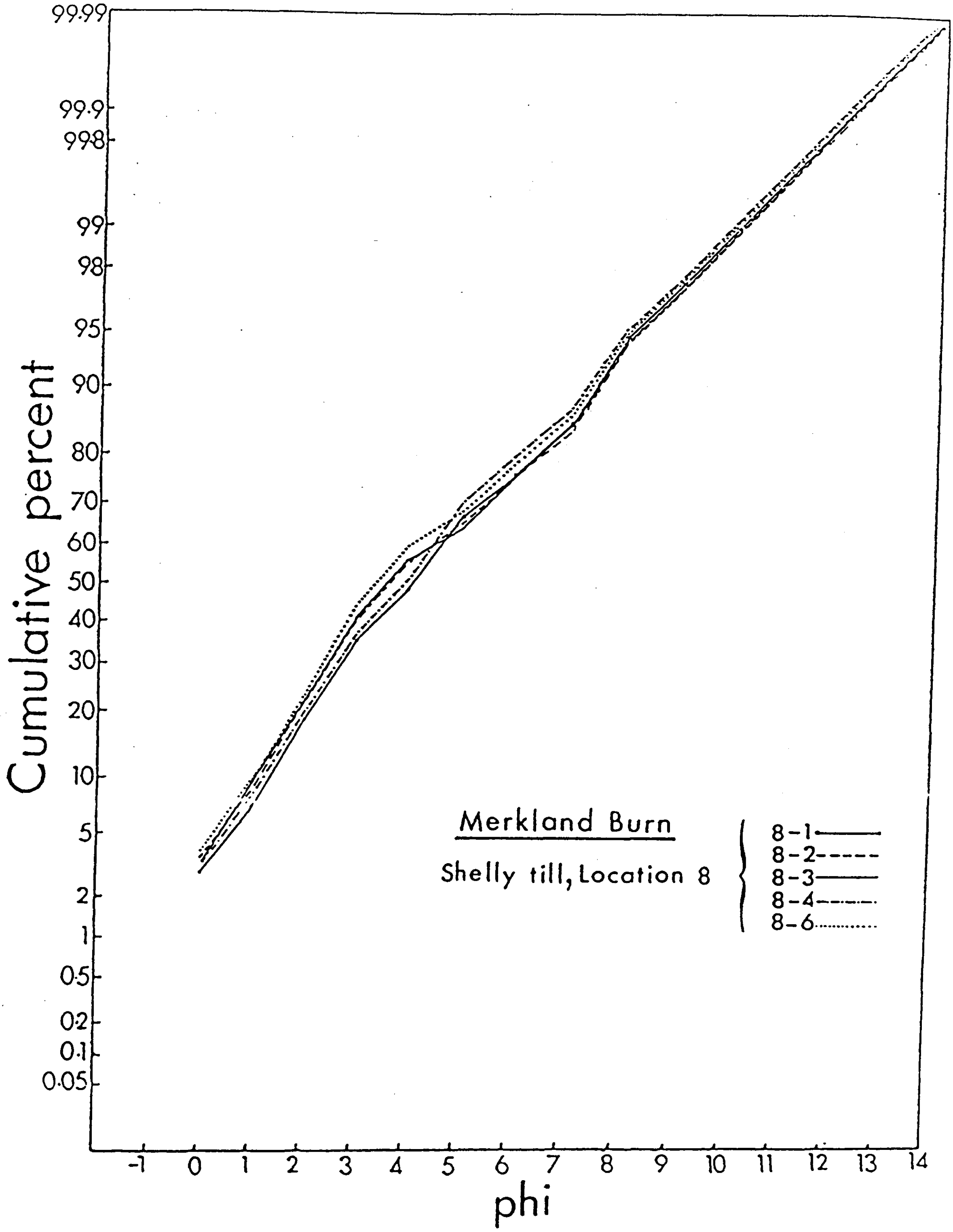


Figure 10.3 Cumulative grain-size curves for the shelly till samples at Merkland Burn, Location 8.

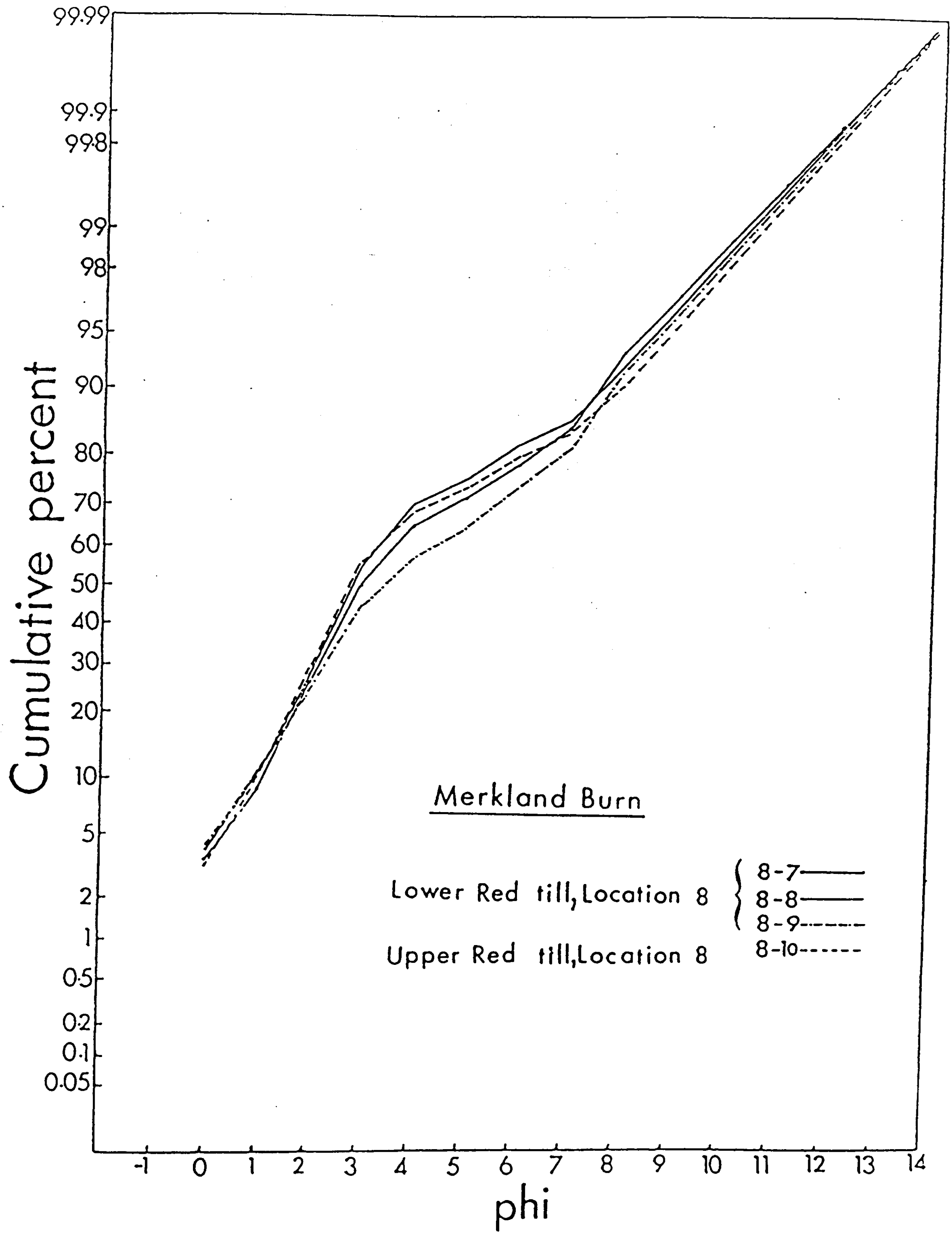


Figure 10.4 Cumulative grain-size curves for the Lower and Upper red till samples at Merkland Burn, Location 8.

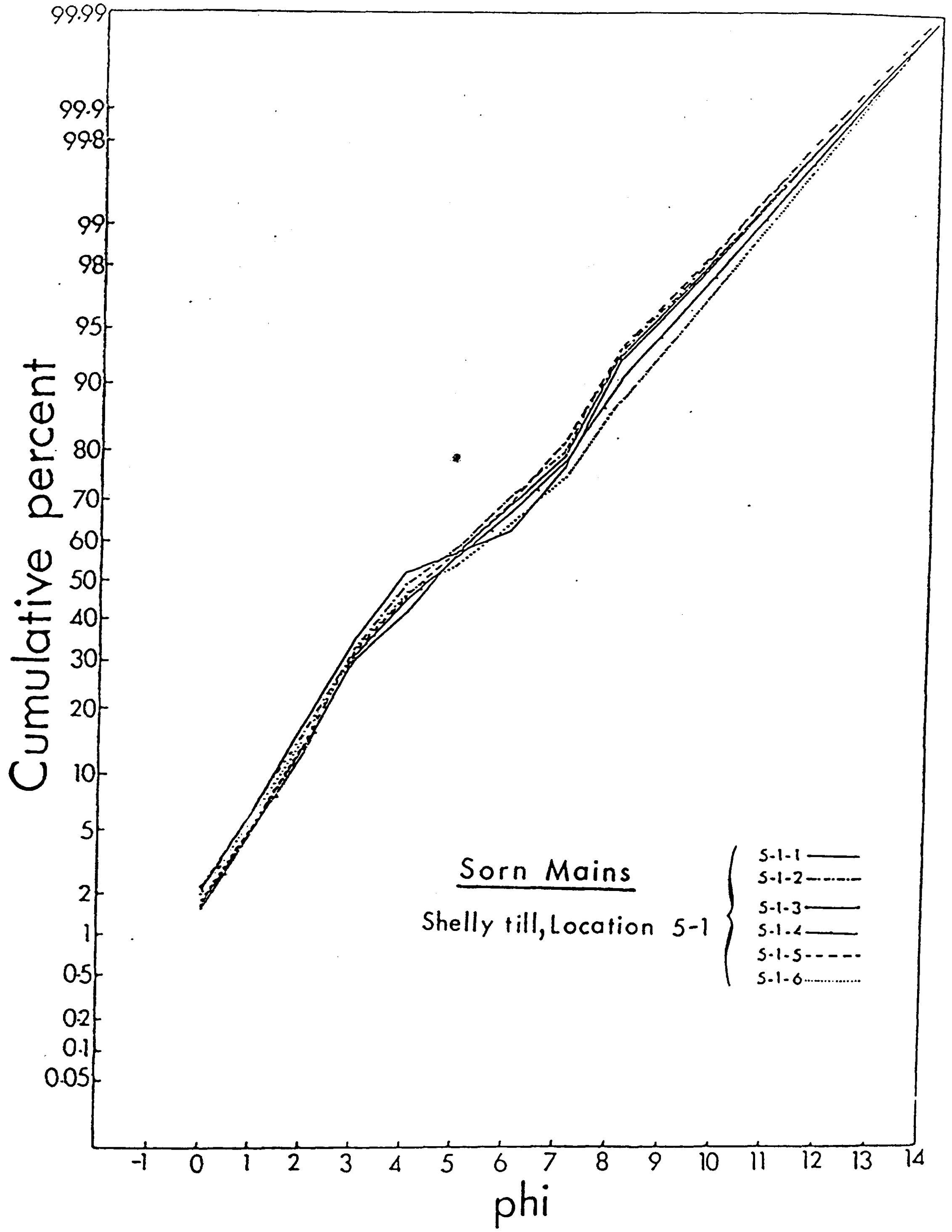


Figure 10.5 Cumulative grain-size curves for the shelly till samples at Sorn Mains, Location 5-1.

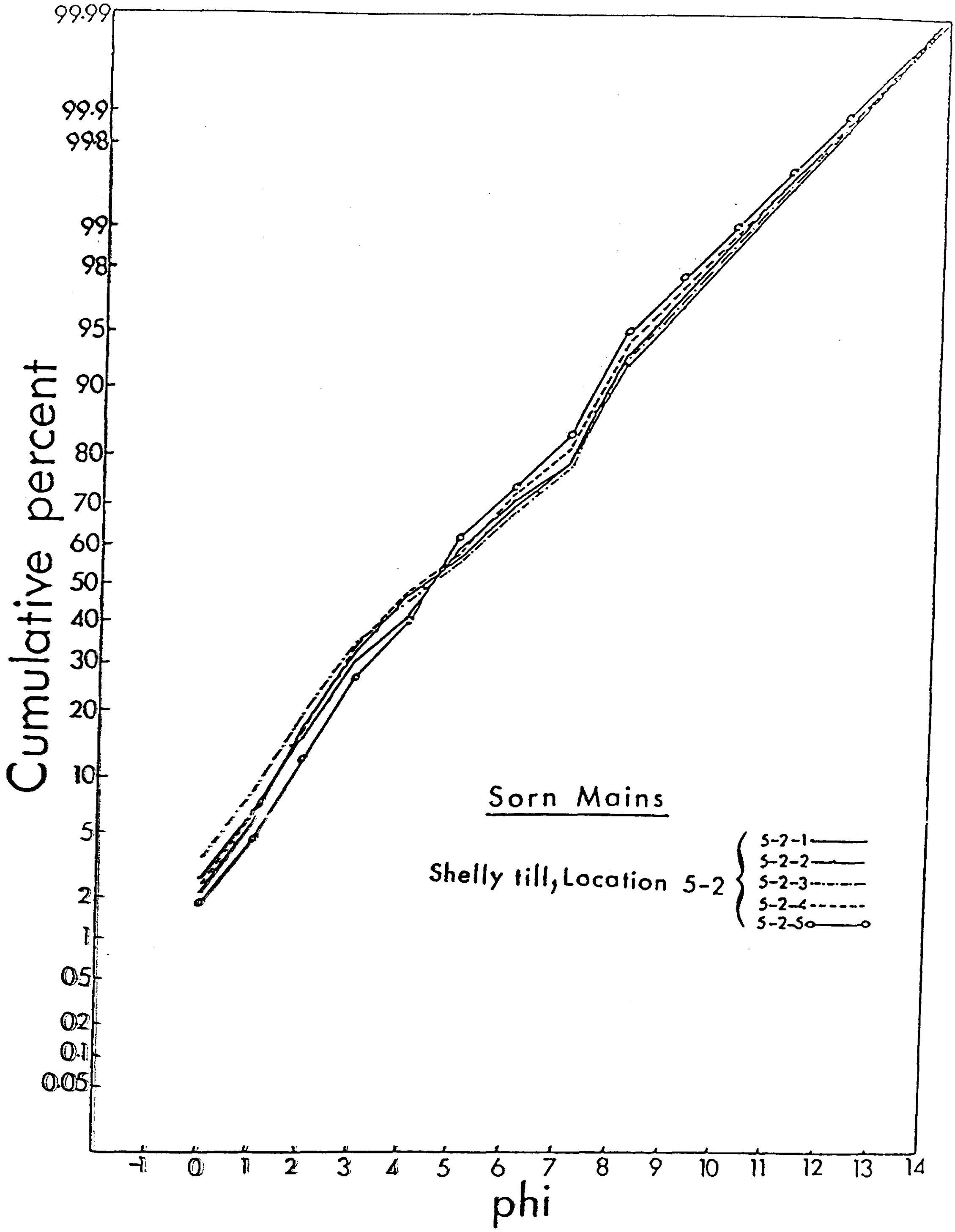


Figure 10.6 Cumulative grain-size curves for the shelly till samples at Sorn Mains, Location 5-2.

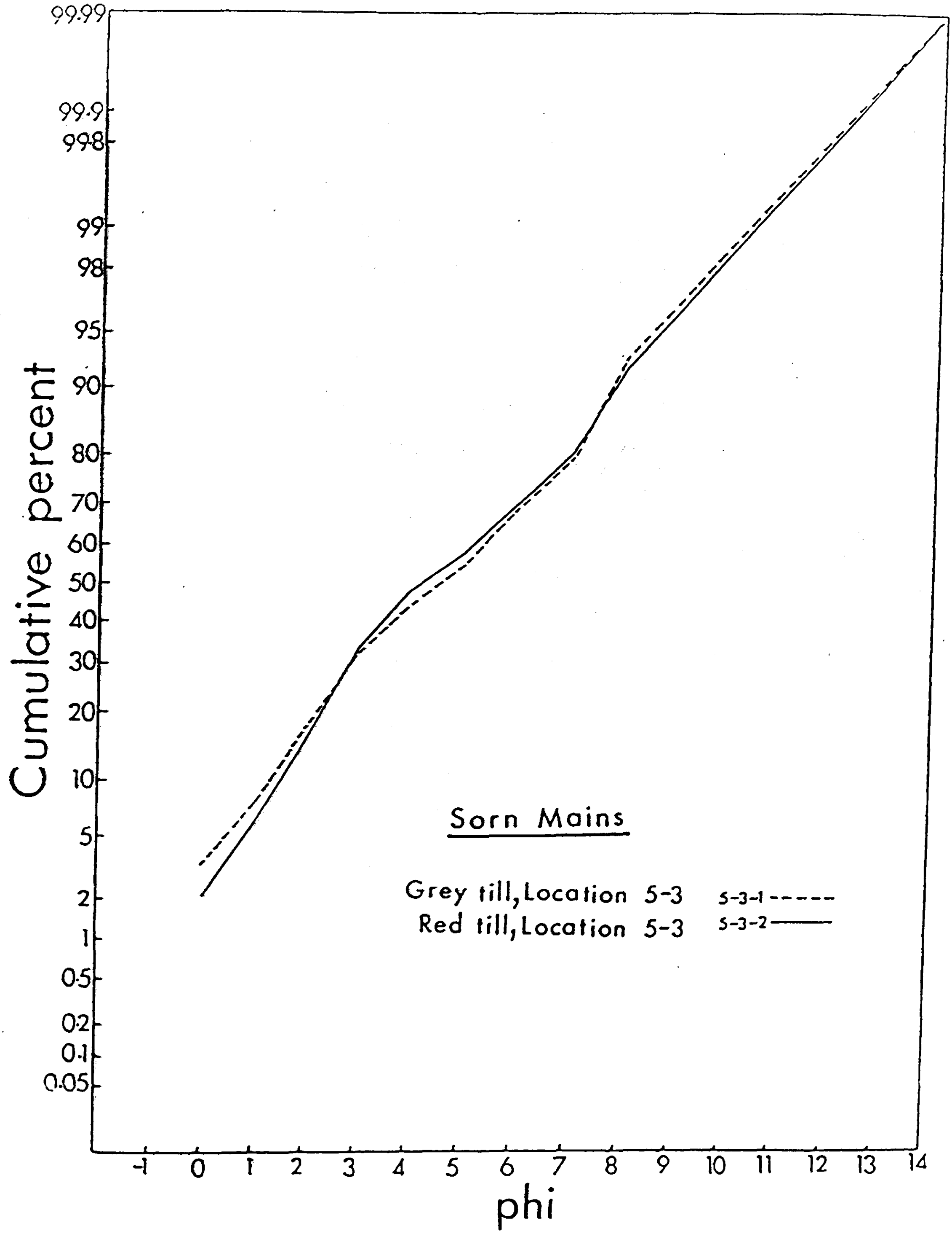


Figure 10.7 Cumulative grain-size curves for the (upper) grey till and (lower) red till at Sorn Mains, Location 5-3.

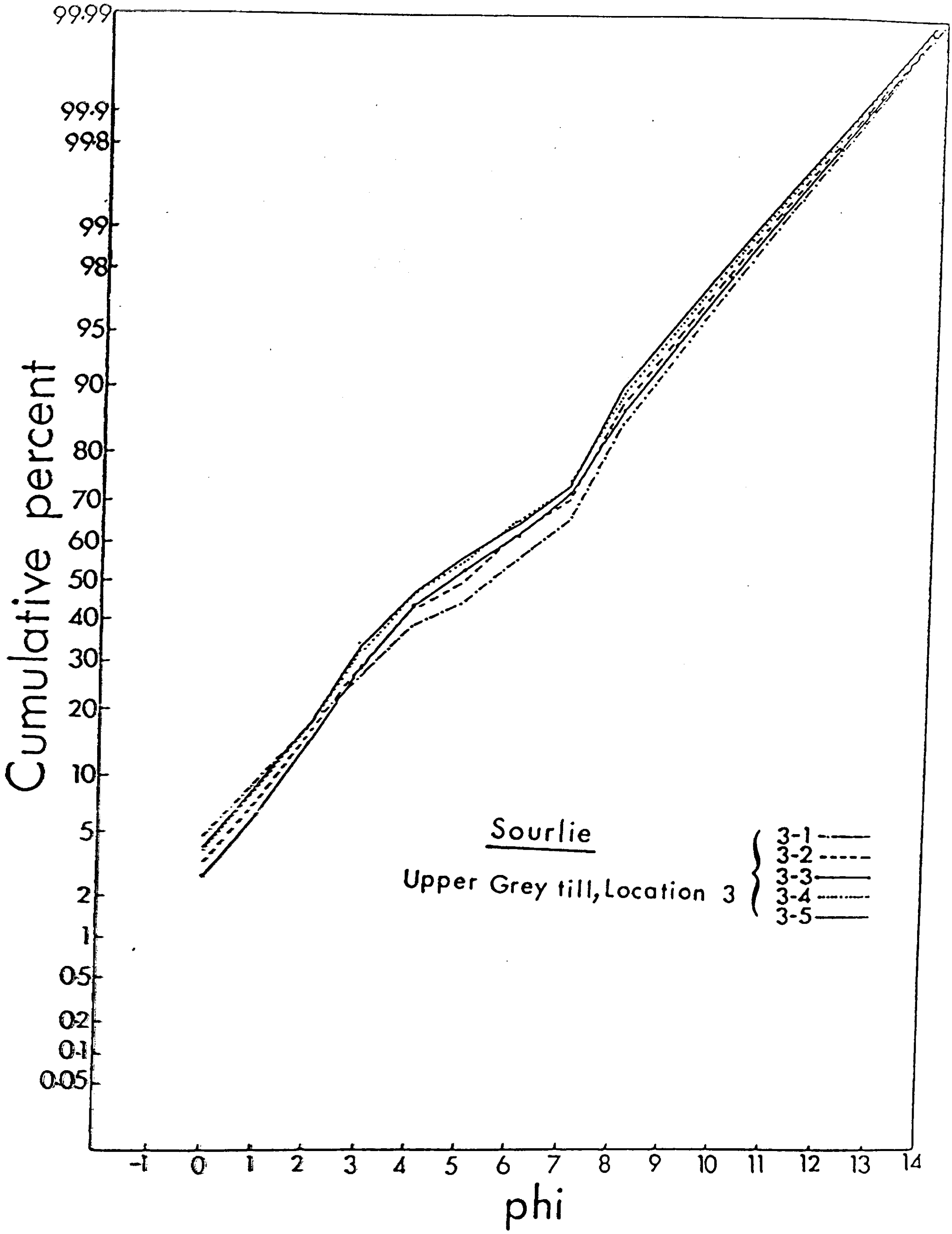


Figure 10.8 Cumulative grain-size curves for the Upper grey till samples at Sourlie, Location 3.

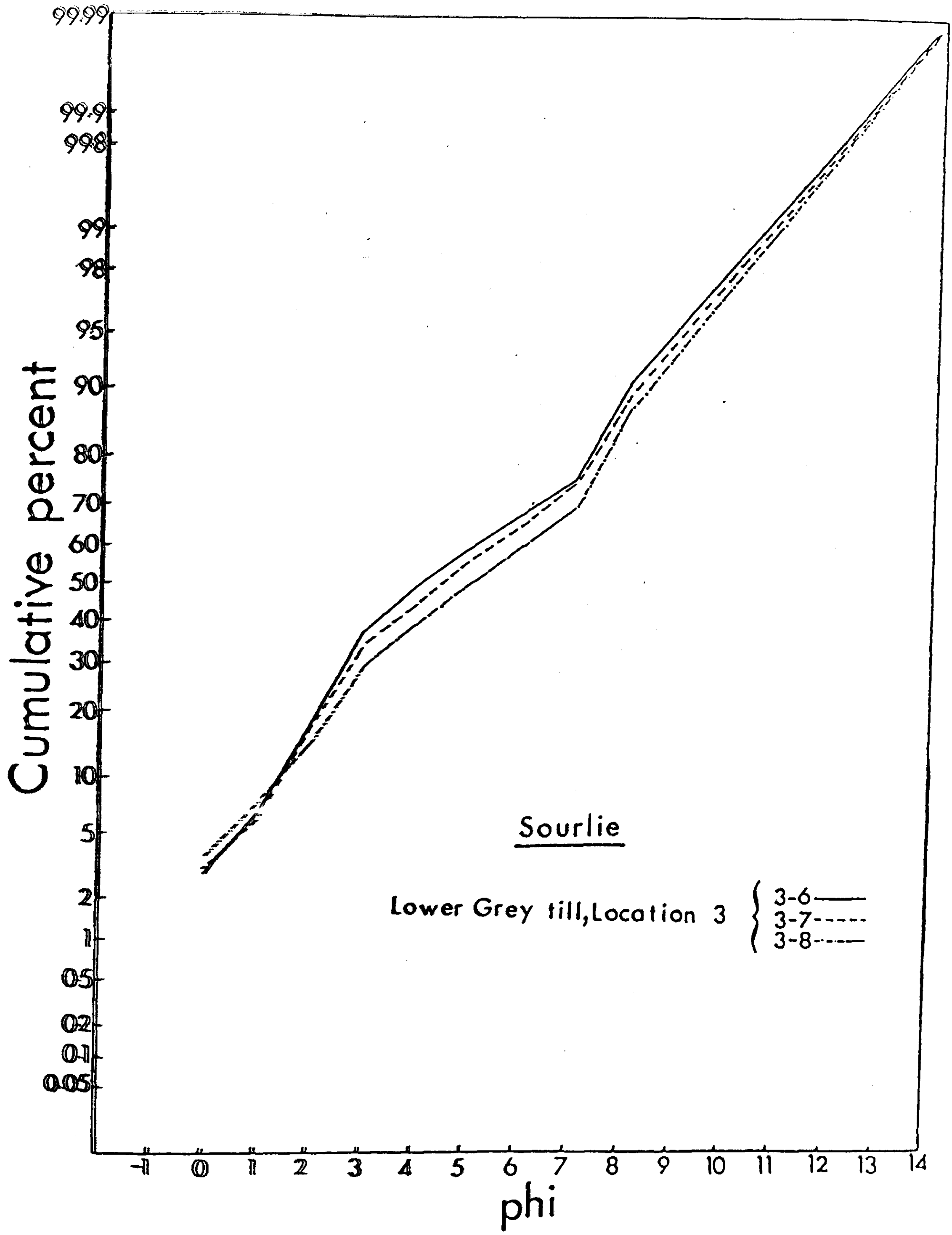


Figure 10.9 Cumulative grain-size curves for the Lower grey till samples at Sourlie, Location 3.

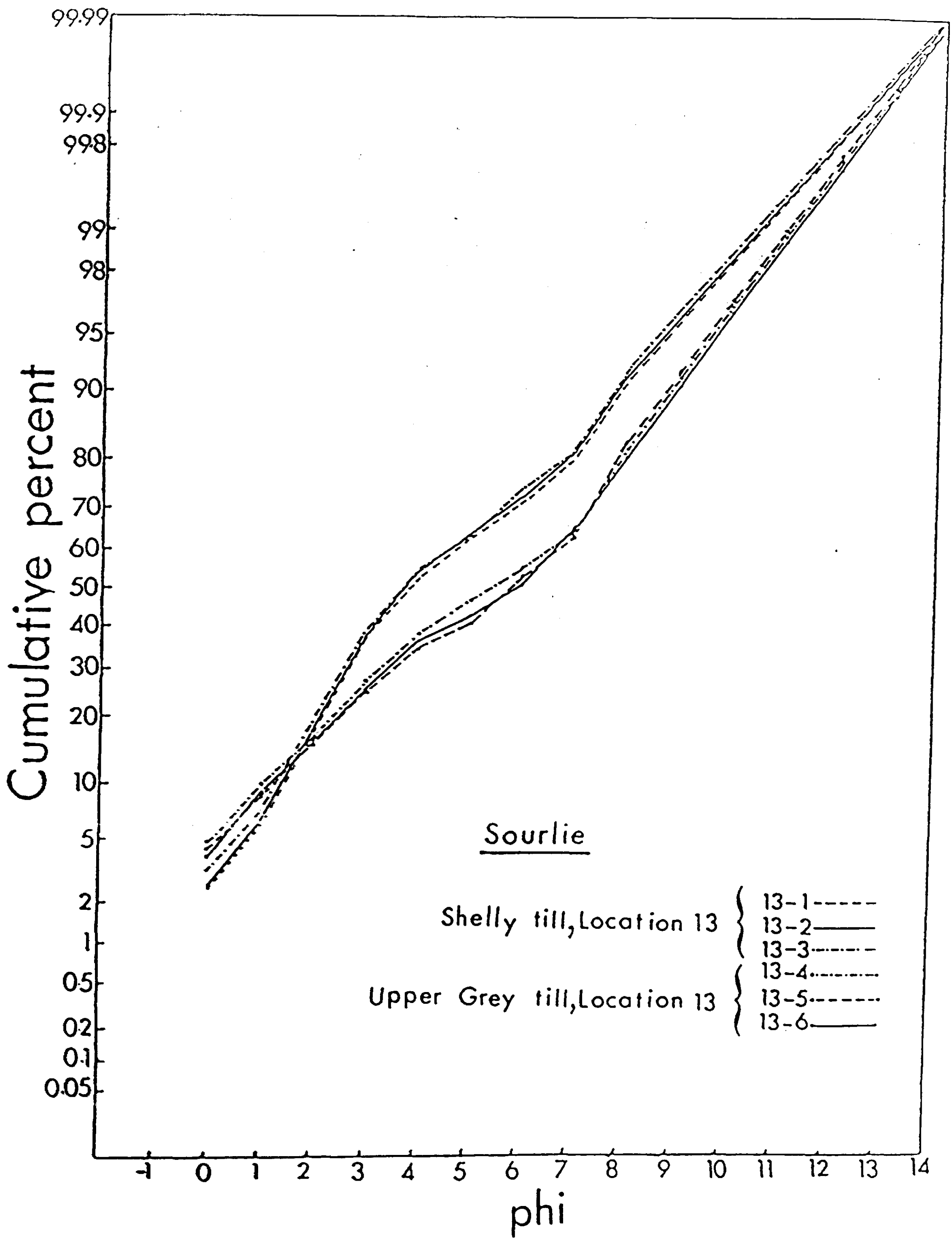


Figure 10.10 **Cumulative grain-size curves for the shelly till and Upper grey till samples at Sourlie, Location 13.**

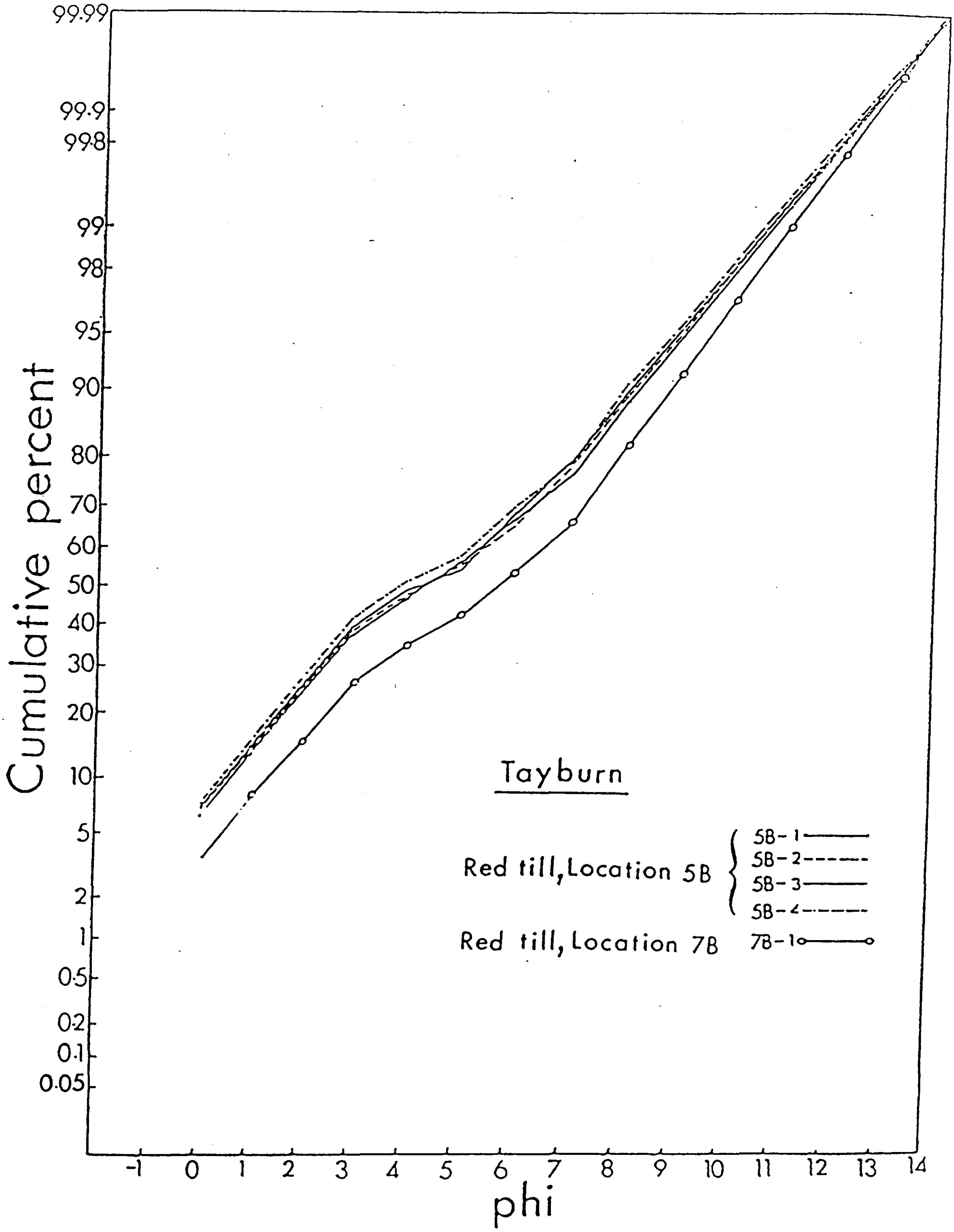


Figure 10.11 Cumulative grain-size curves for the (lower) red till samples at Tayburn, Locations 5B and 7B.

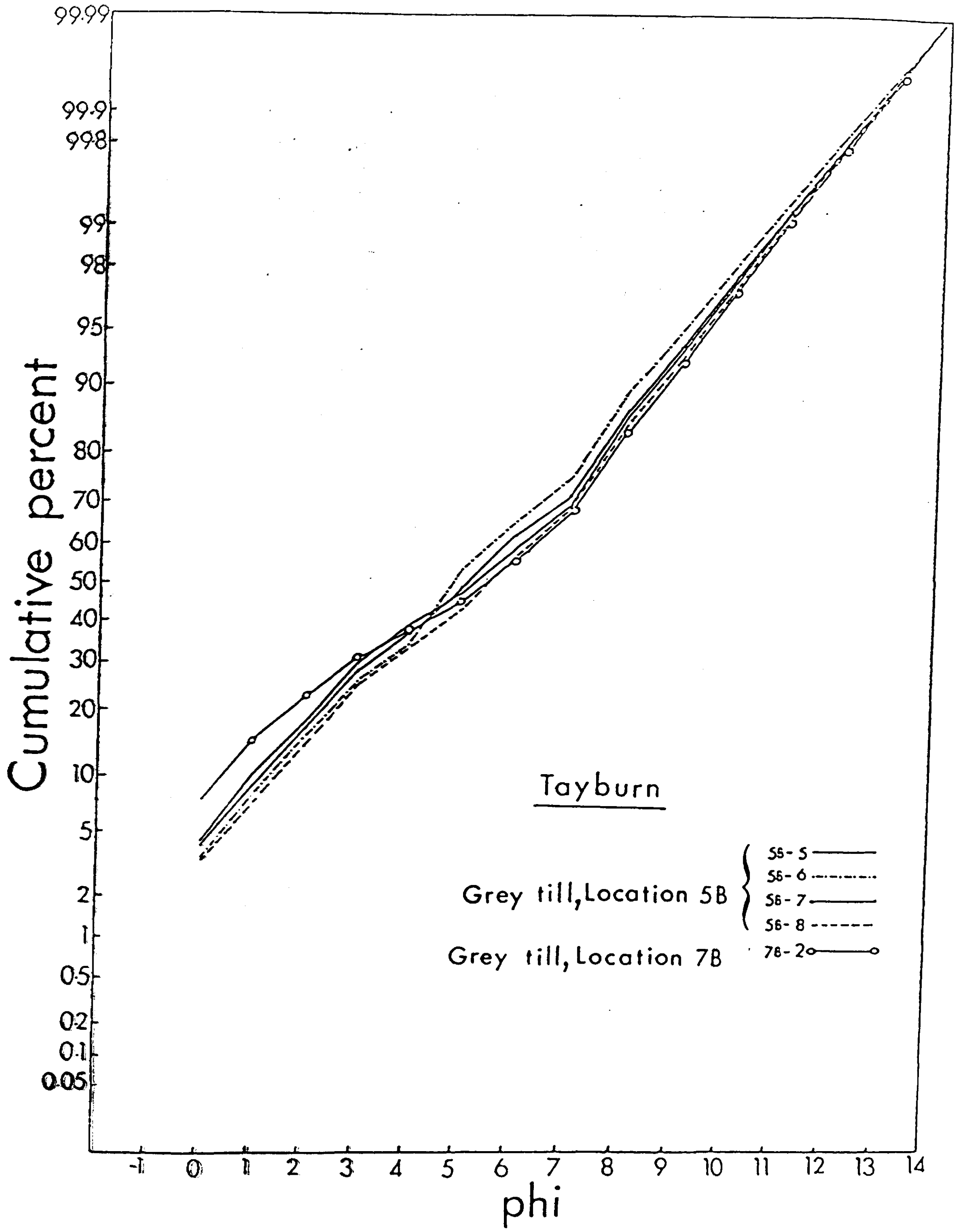


Figure 10.12 **Cumulative grain-size curves for the (upper) grey till samples at Tayburn, Locations 5B and 7B.**

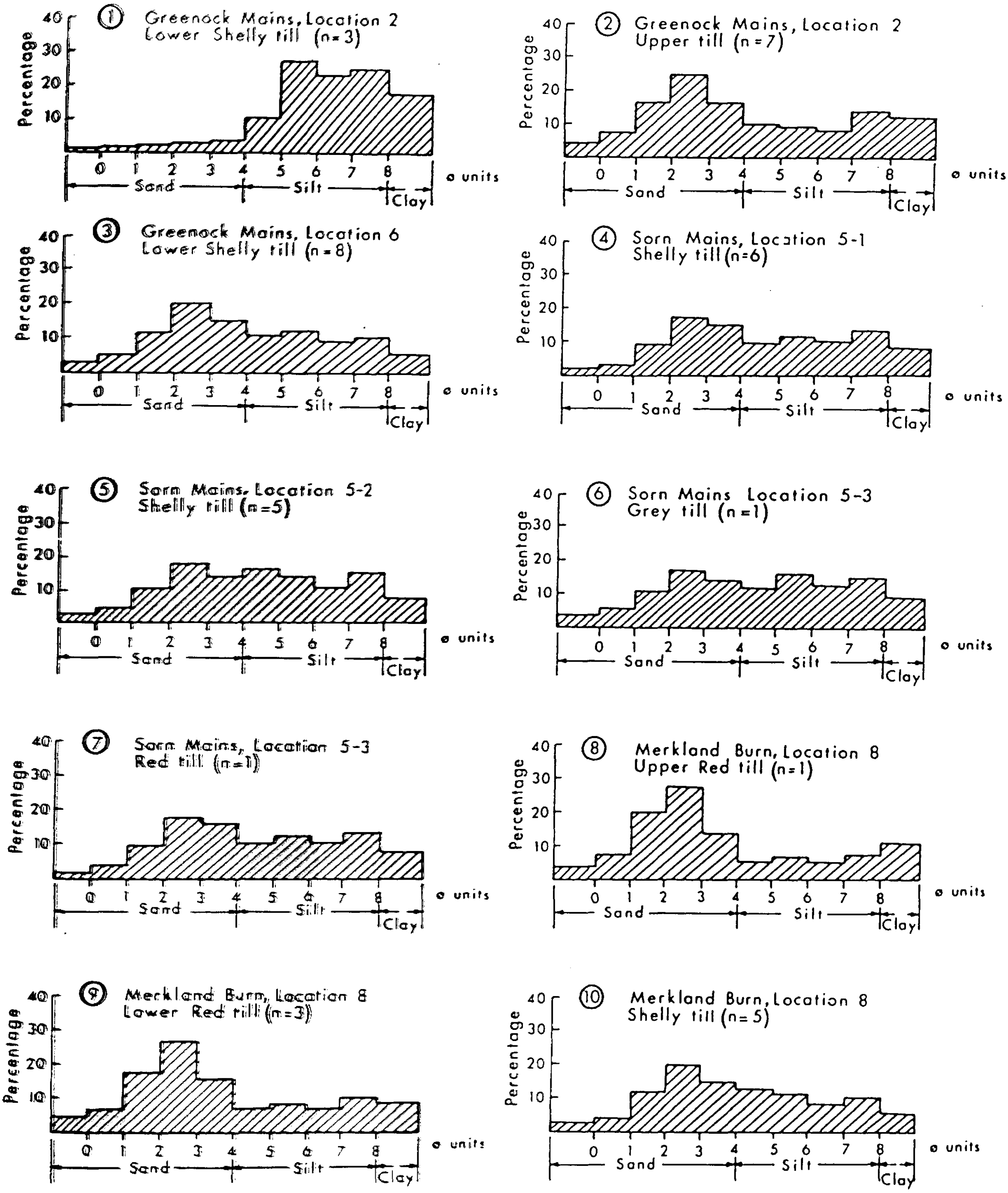


Figure 10.13 Histograms showing the average grain-size distribution by weight percent of the matrix (<2mm) in phi class intervals from -1 ø to >8 ø of till units from the Greenock Mains, Sorn Mains and Merkland Burn sites.

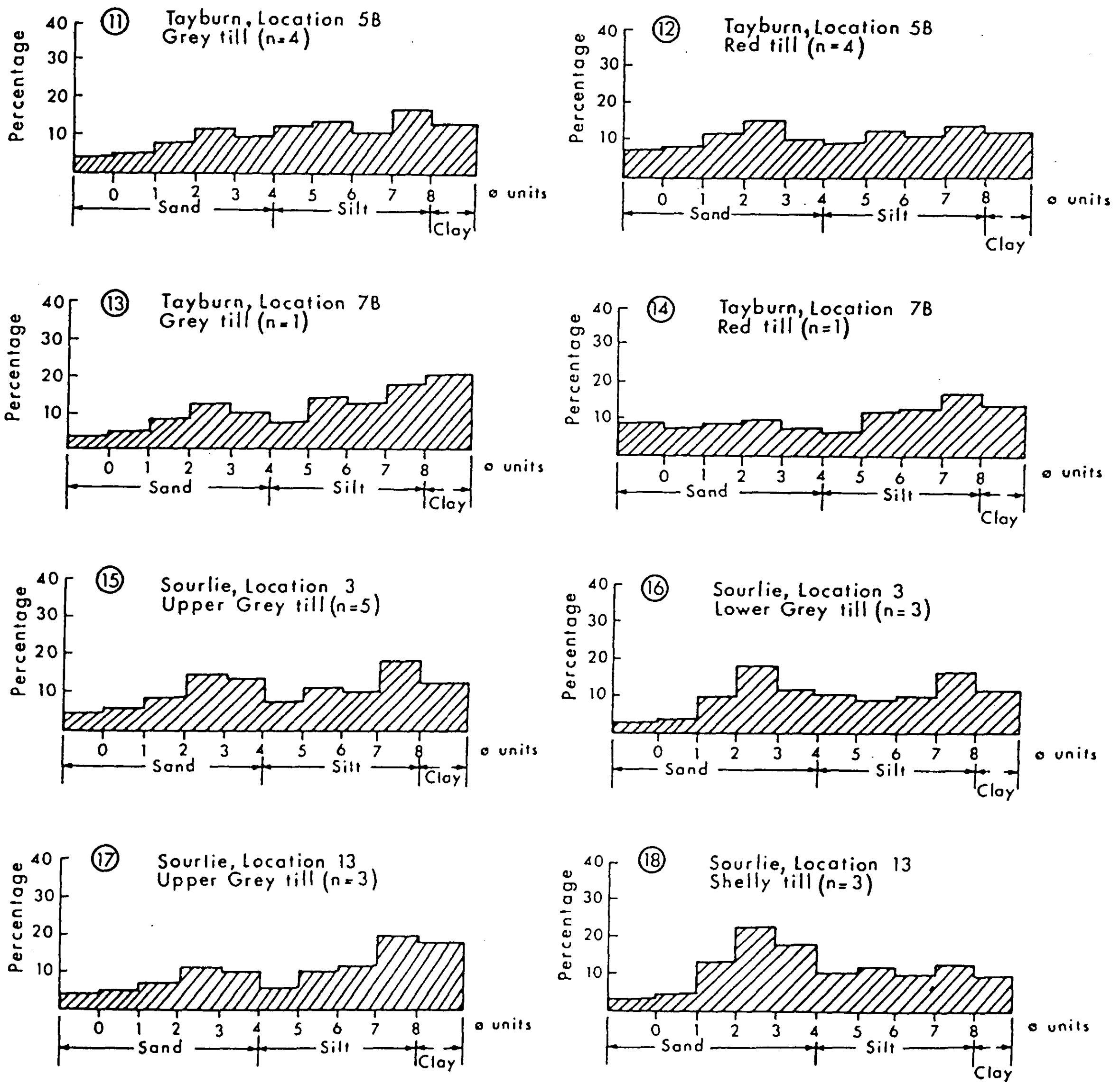


Figure 10.14 Histograms showing the average grain-size distribution by weight percent of the matrix (<2mm) in phi class intervals from -1 ø to >8 ø of till units from the Tayburn and Sourlie sites.

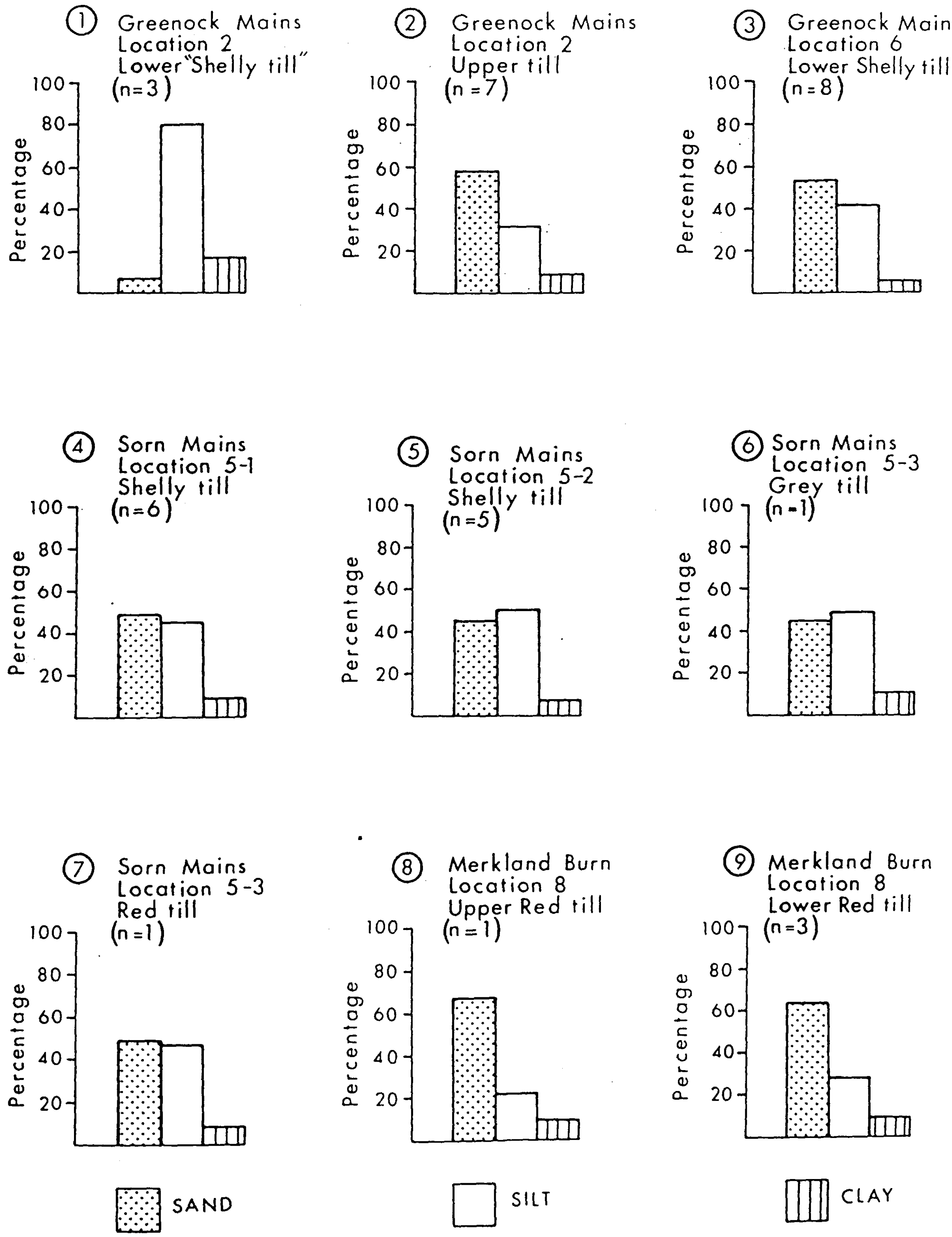


Figure 10.15 Histograms showing the average distribution of sand, silt and clay percentages of till units from the Greenock Mains, Sorn Mains and Merkland Burn sites.

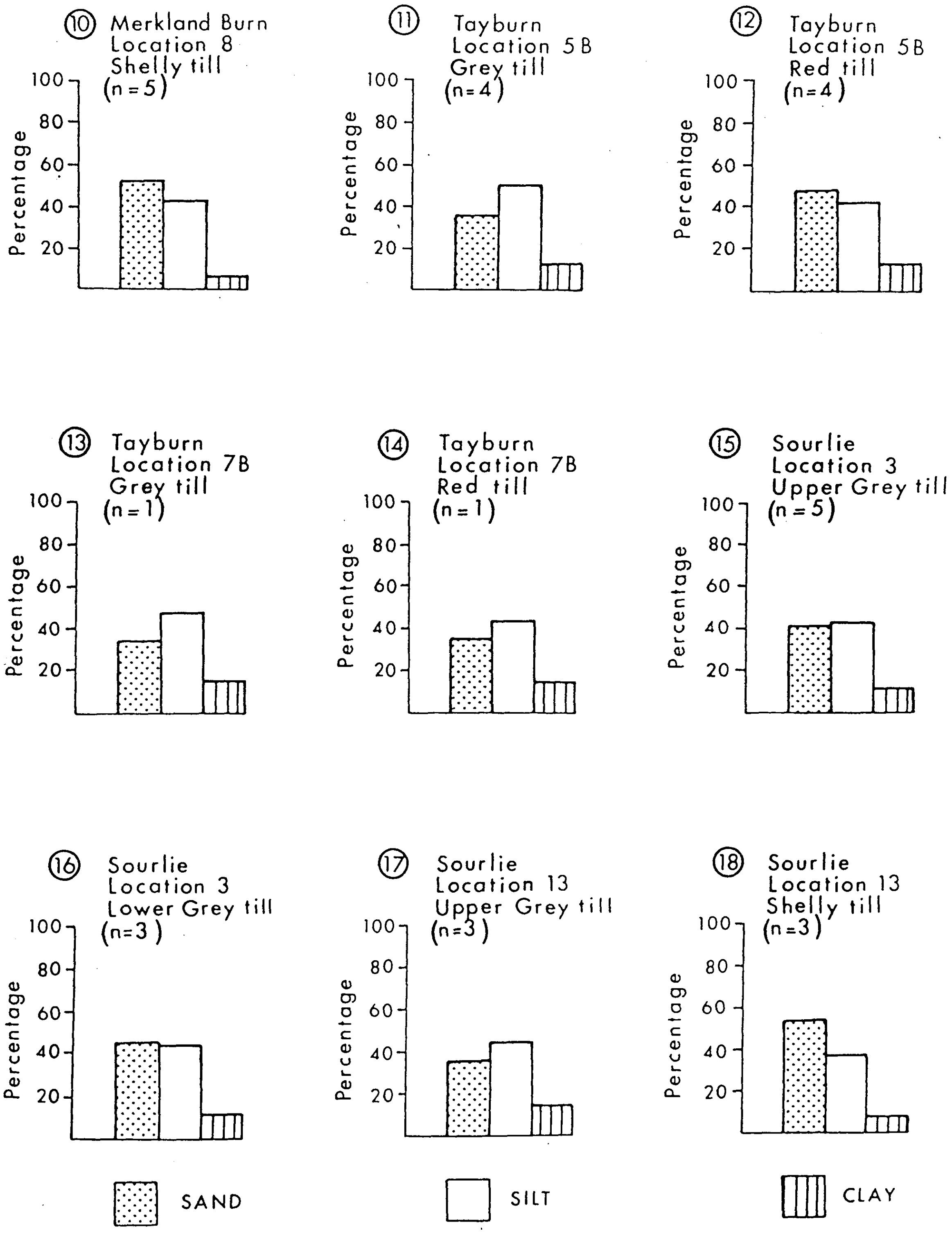


Figure 10.16 Histograms showing the average distribution of sand, silt and clay percentages of till units from the Merkland Burn, Tayburn and Sourlie sites.

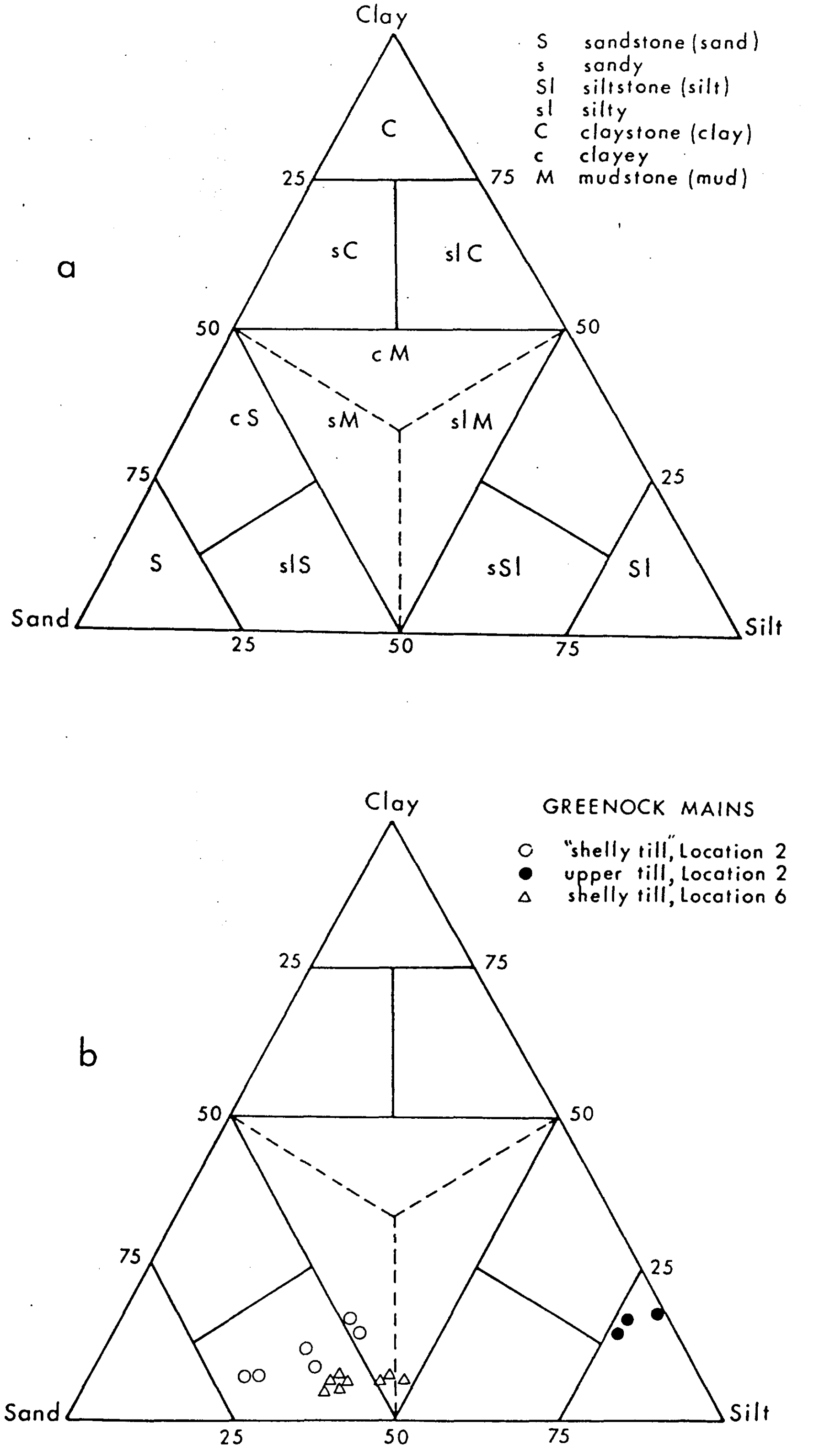
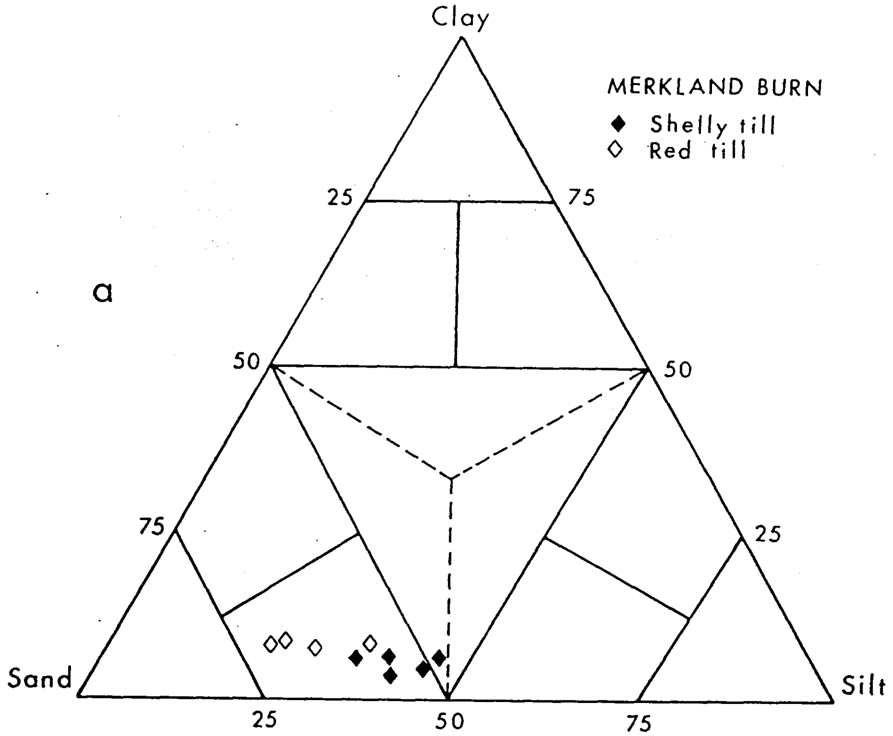


Figure 10.17 (a) Sand-silt-clay triangular diagram (after Picard 1971)
(b) Sand-silt-clay composition of the various samples collected at Greenock Mains



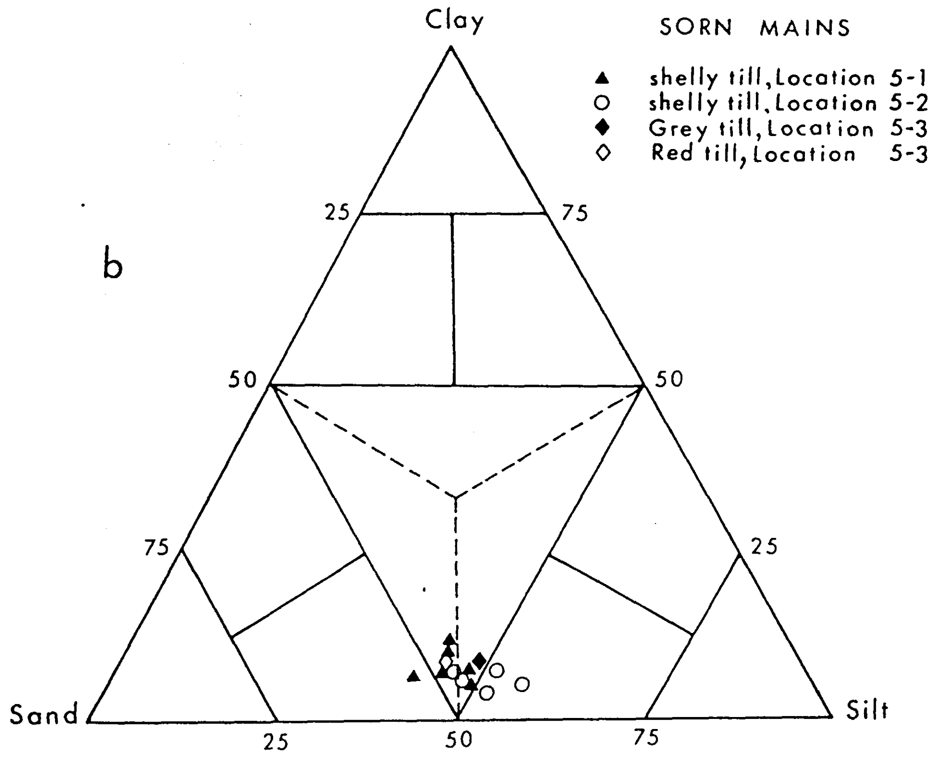
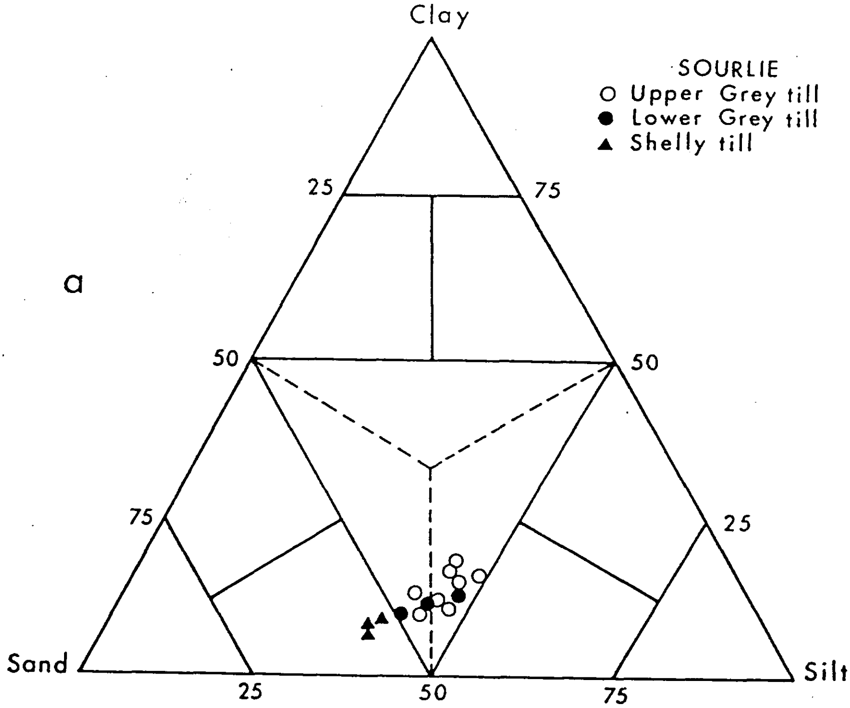


Figure 10.18 Sand-silt-clay composition of the various till samples (a) at Merkland Burn and (b) at Sorn Mains



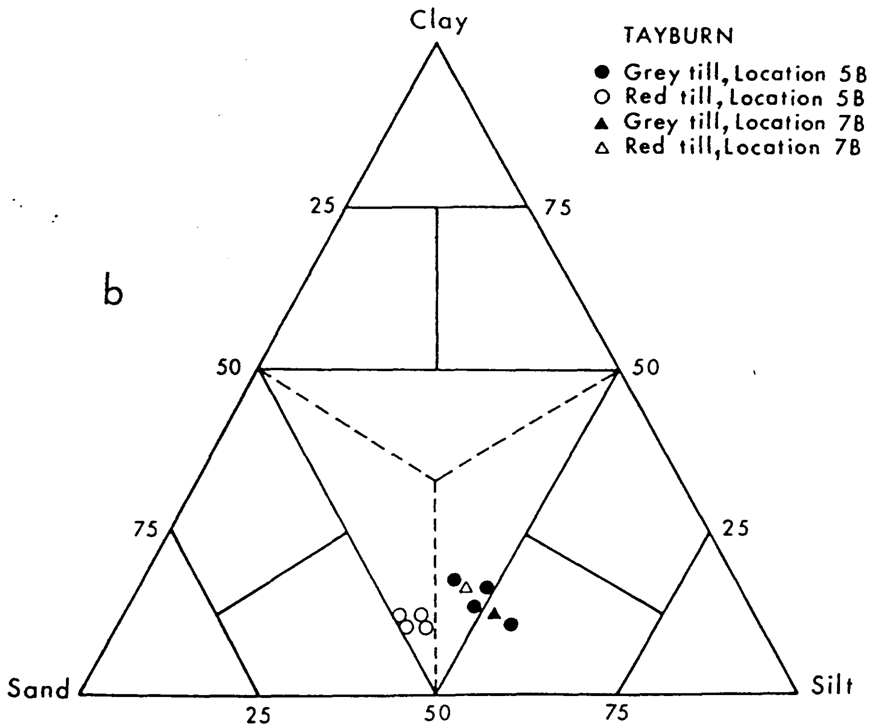


Figure 10.19 Sand-silt-clay composition of the various till samples (a) at Sourlie, and (b) at Tayburn

a

b

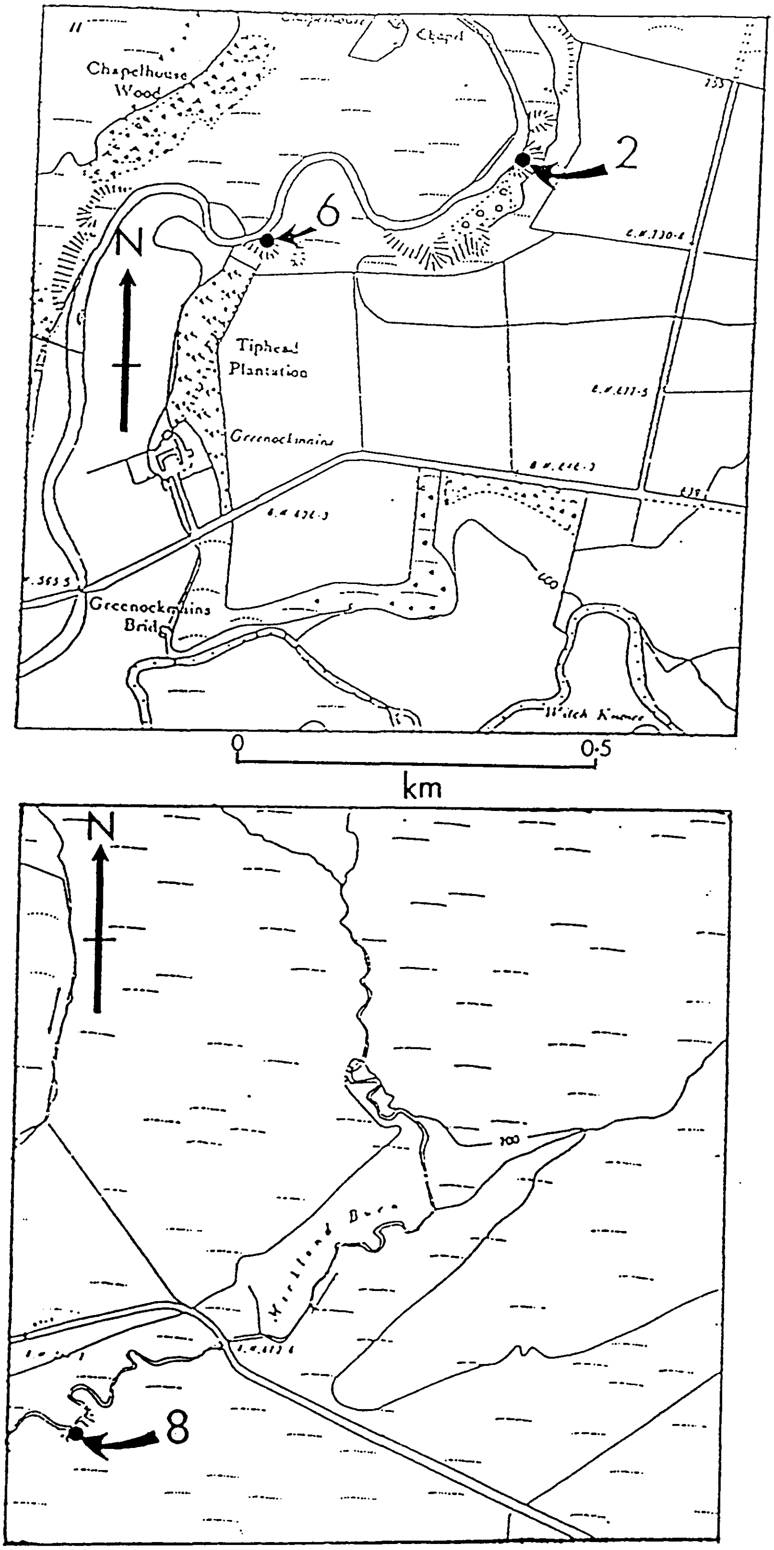


Figure 10.20 (a) Map of the Greenock Mains Site, showing the positions of Locations 2 and 6

(b) Map of the Merkland Burn Site, showing the position of Location 8

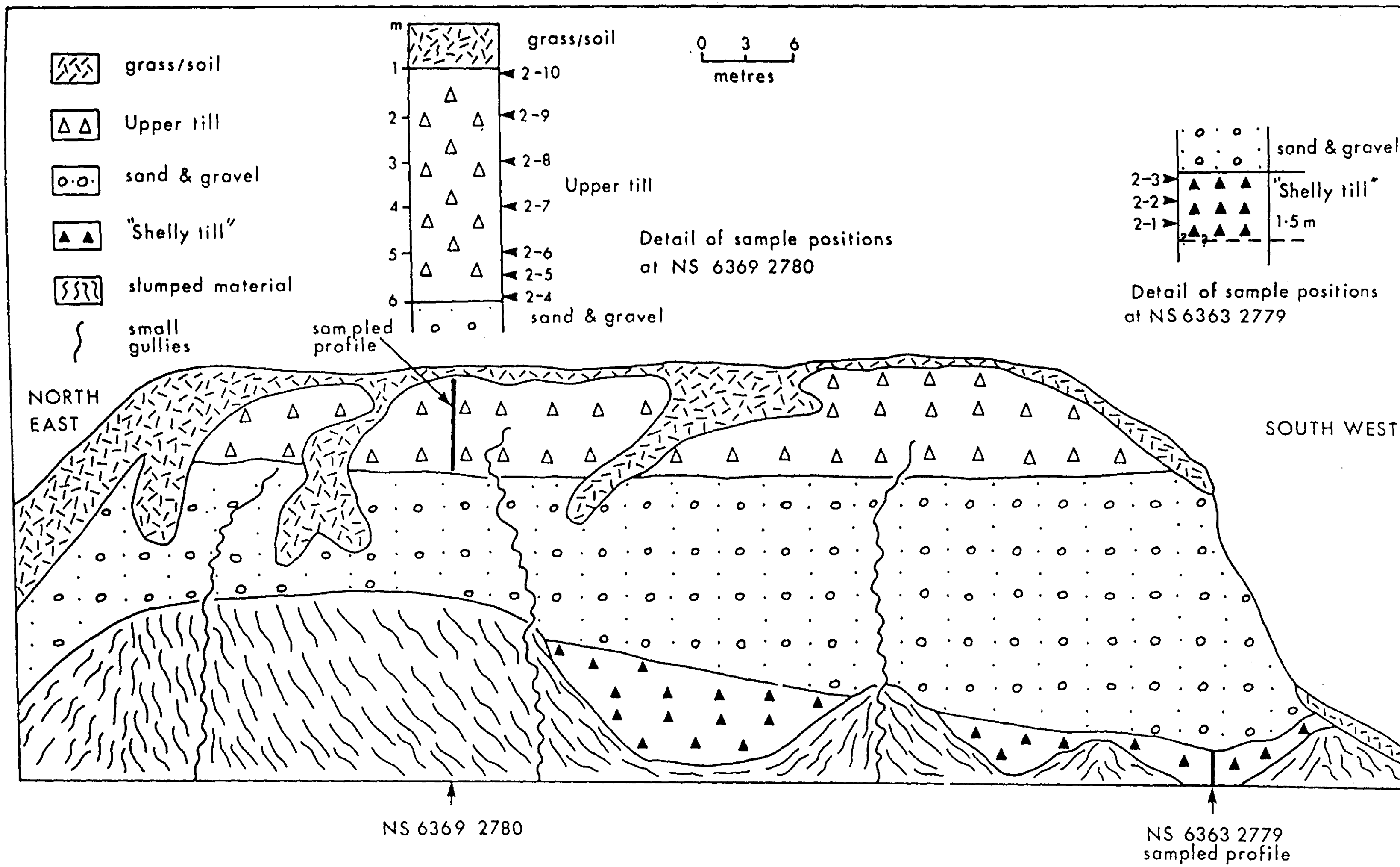


Figure 10.21 Sketch section through the deposits at Greenock Mains, Location 2, showing the stratigraphical units and sample positions within these units.

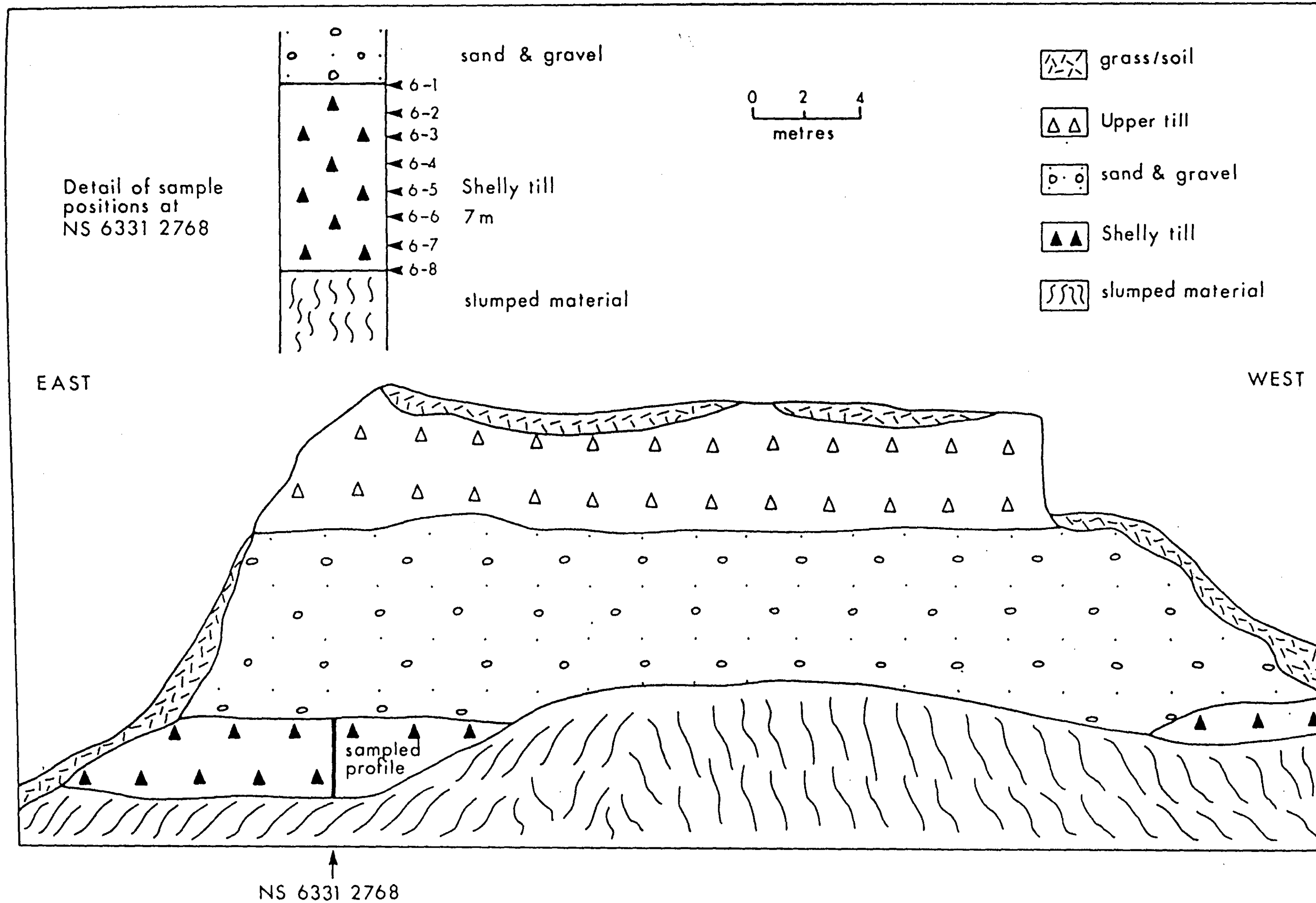


Figure 10.22 Sketch section through the deposits at Greenock Mains, Location 6, showing the stratigraphical units and sample positions within these units.

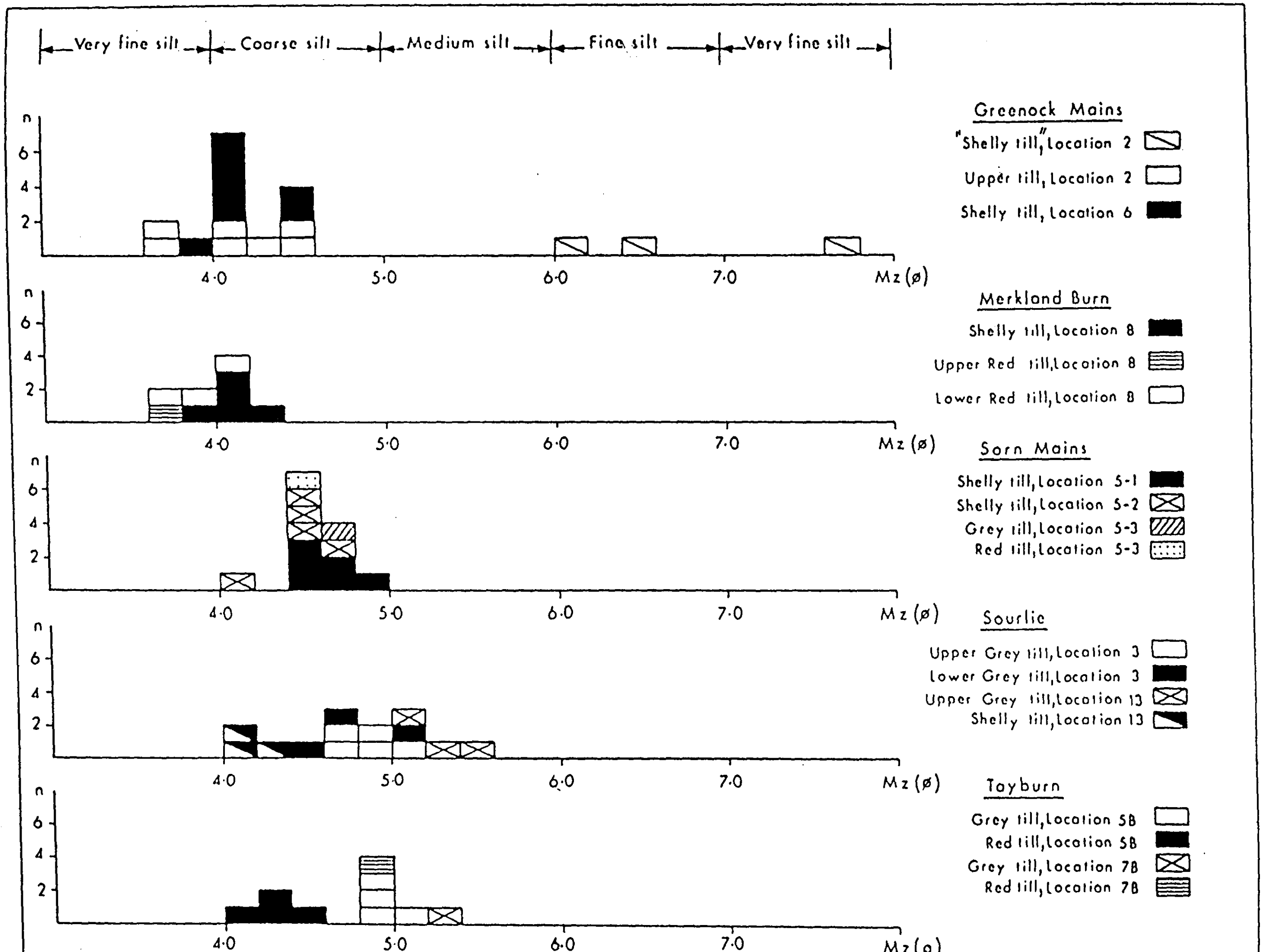


Figure 10.23 Histograms showing the distribution of Mz values (mean size) in the various till units sampled in Northern Ayrshire.

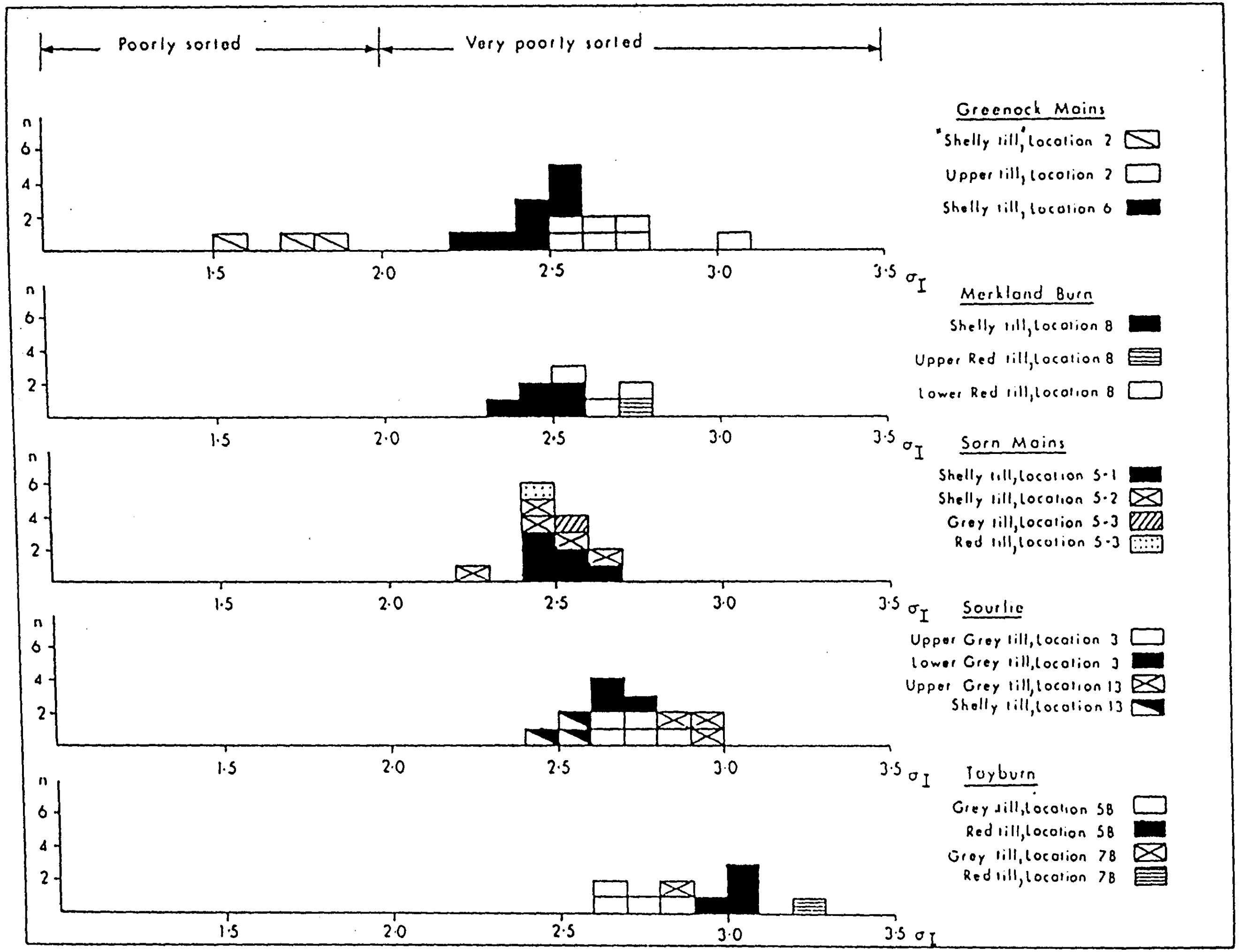


Figure 10.24 Histograms showing the distribution of σ_I values (sorting) in the various till units sampled in Northern Ayrshire.

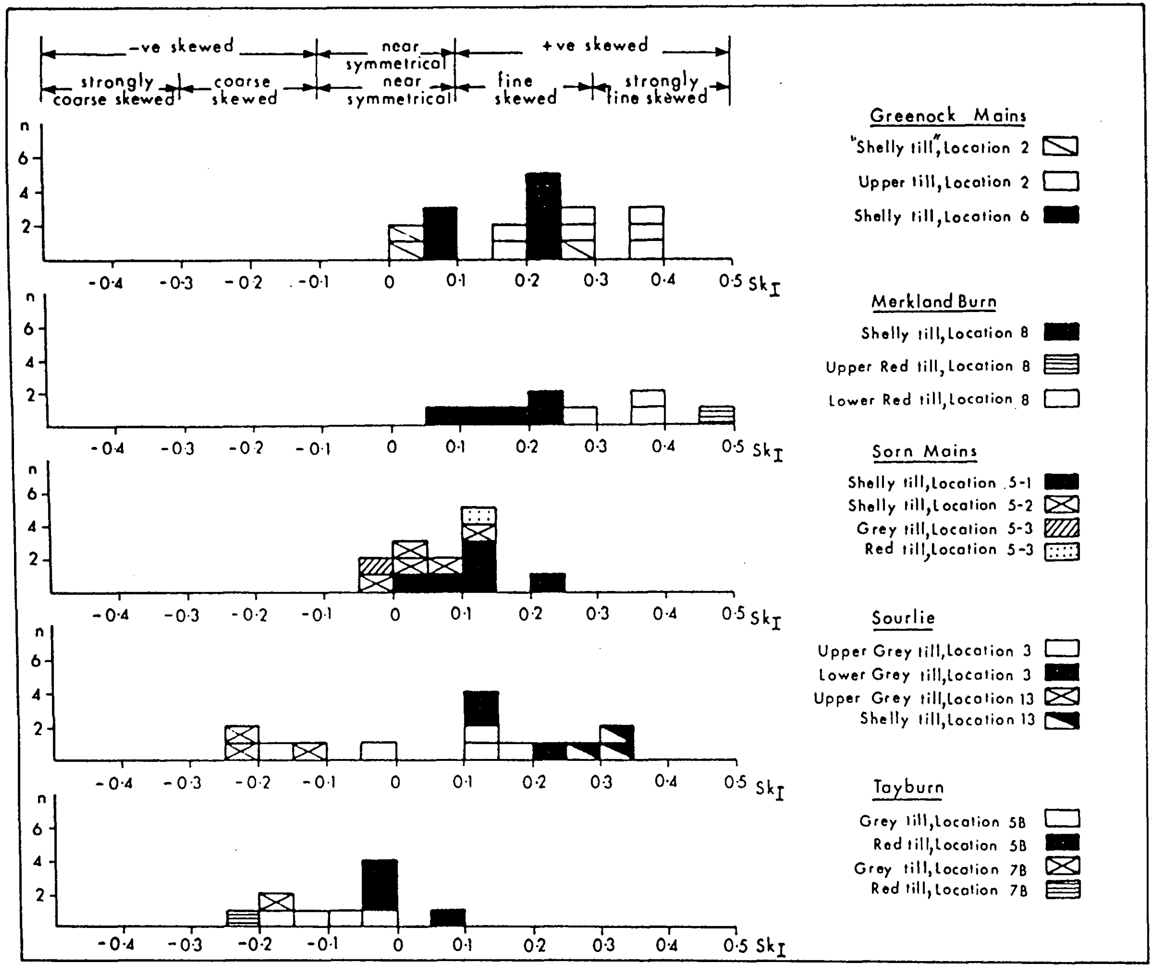


Figure 10.25 Histograms showing the distribution of Sk_I values (skewness) in the various till units sampled in Northern Ayrshire.

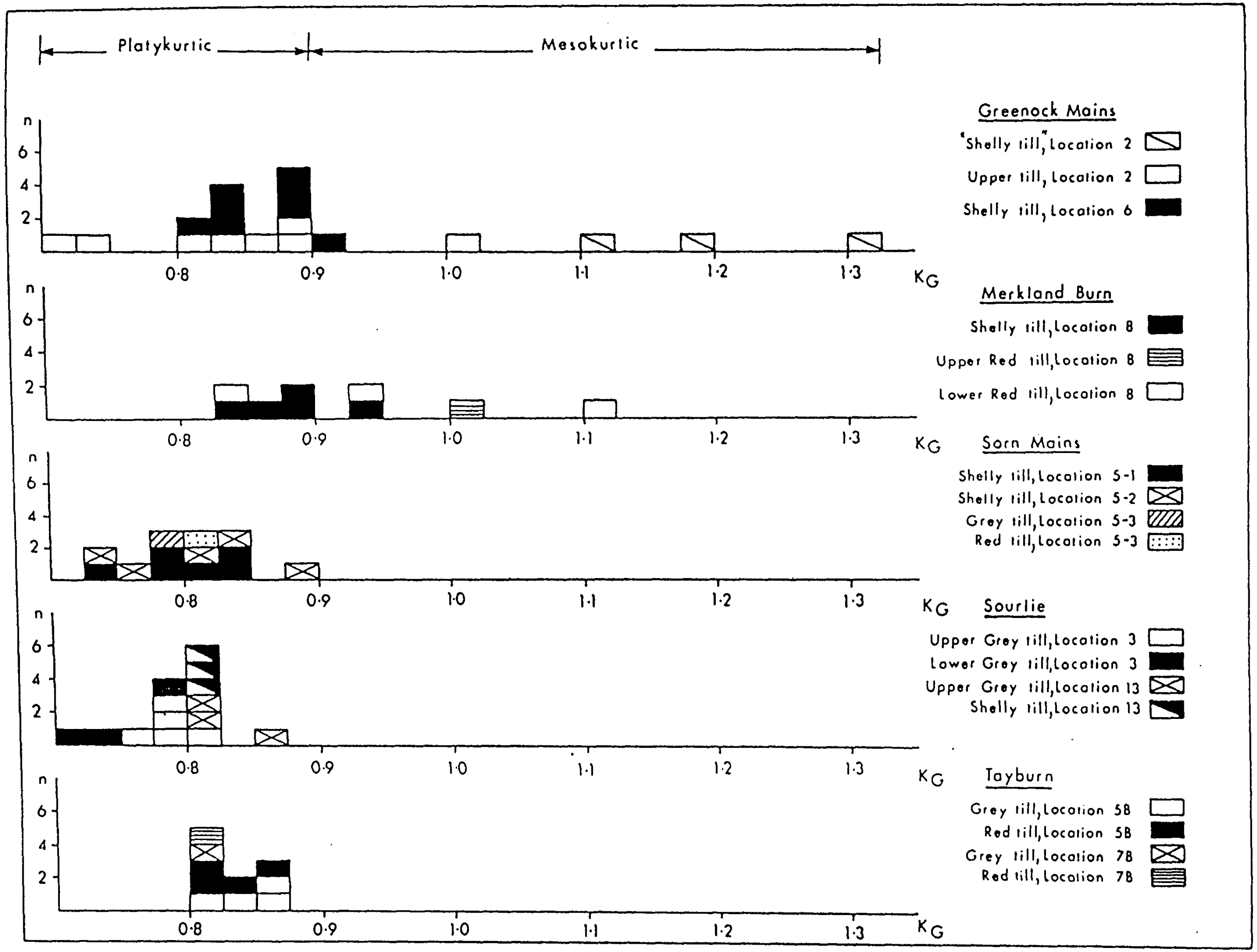


Figure 10.26 Histograms showing the distribution of K_G values (kurtosis) in the various till units sampled in Northern Ayrshire.

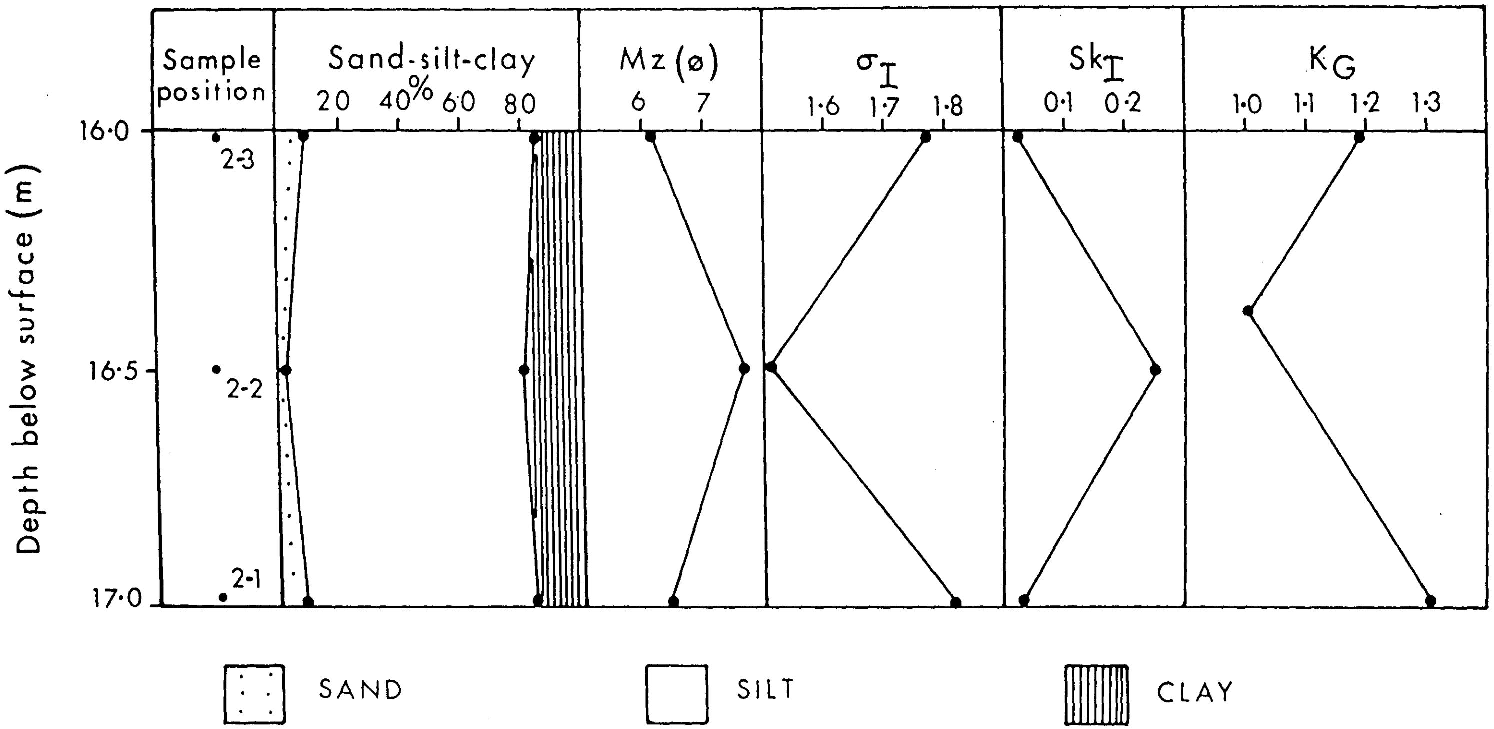


Figure 10.27 Vertical variation of sand, silt and clay percentages and grain-size parameters, Mz, σ_I, Sk_I and K_G, in the Lower "shelly till" at Greenock Mains, Location 2 (NS 6363 2779).

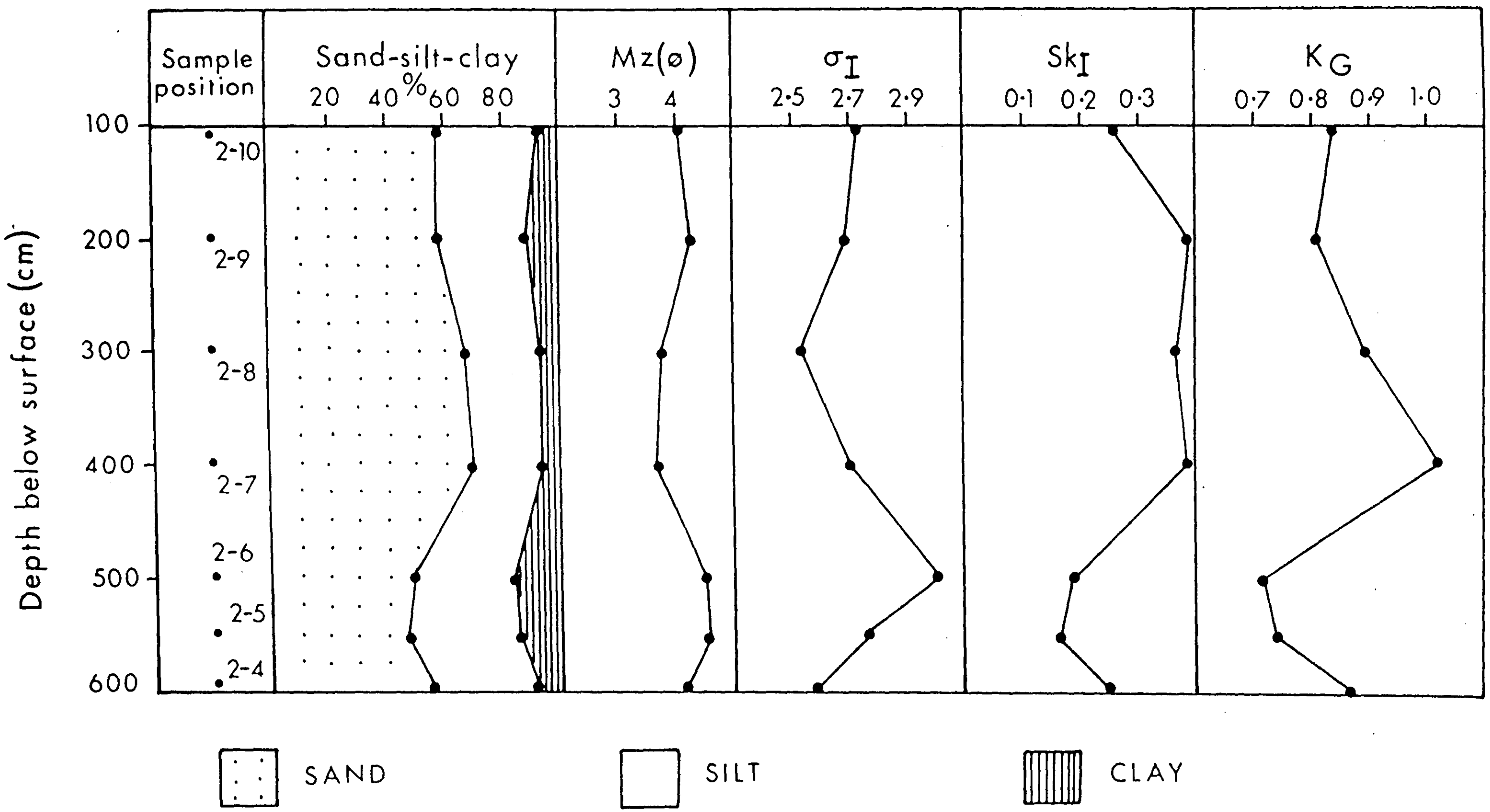


Figure 10.28 Vertical variation of sand, silt and clay percentages and grain-size parameters, Mz, σ_I, Sk_I and K_G, in the Upper till at Greenock Mains, Location 2 (NS 6369 2780).

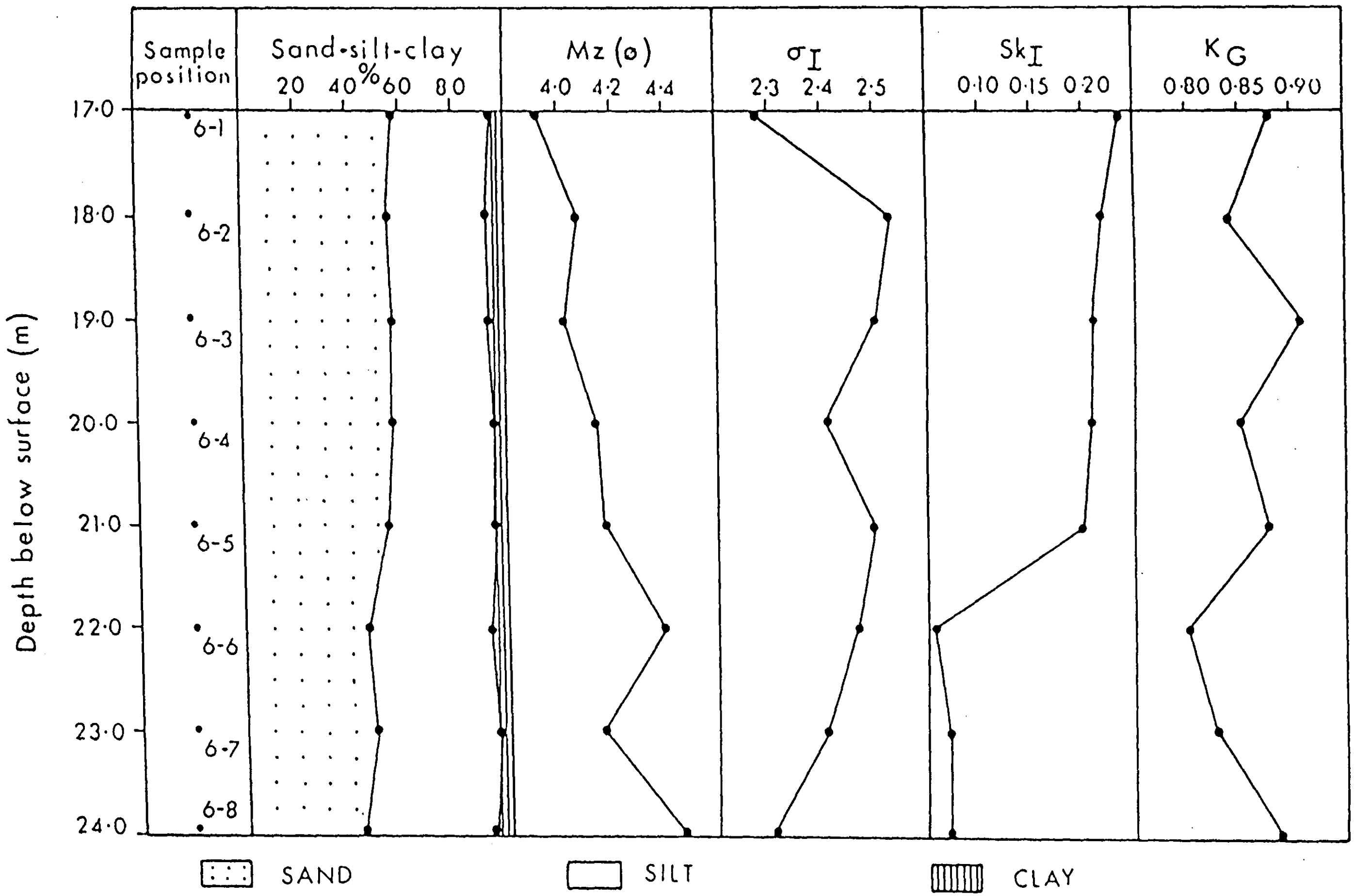


Figure 10.29 Vertical variation of sand, silt and clay percentages and grain-size parameters, Mz, σ_I, Sk_I and K_G, in the shelly till at Greenock Mains, Location 6 (NS 6331 2768).

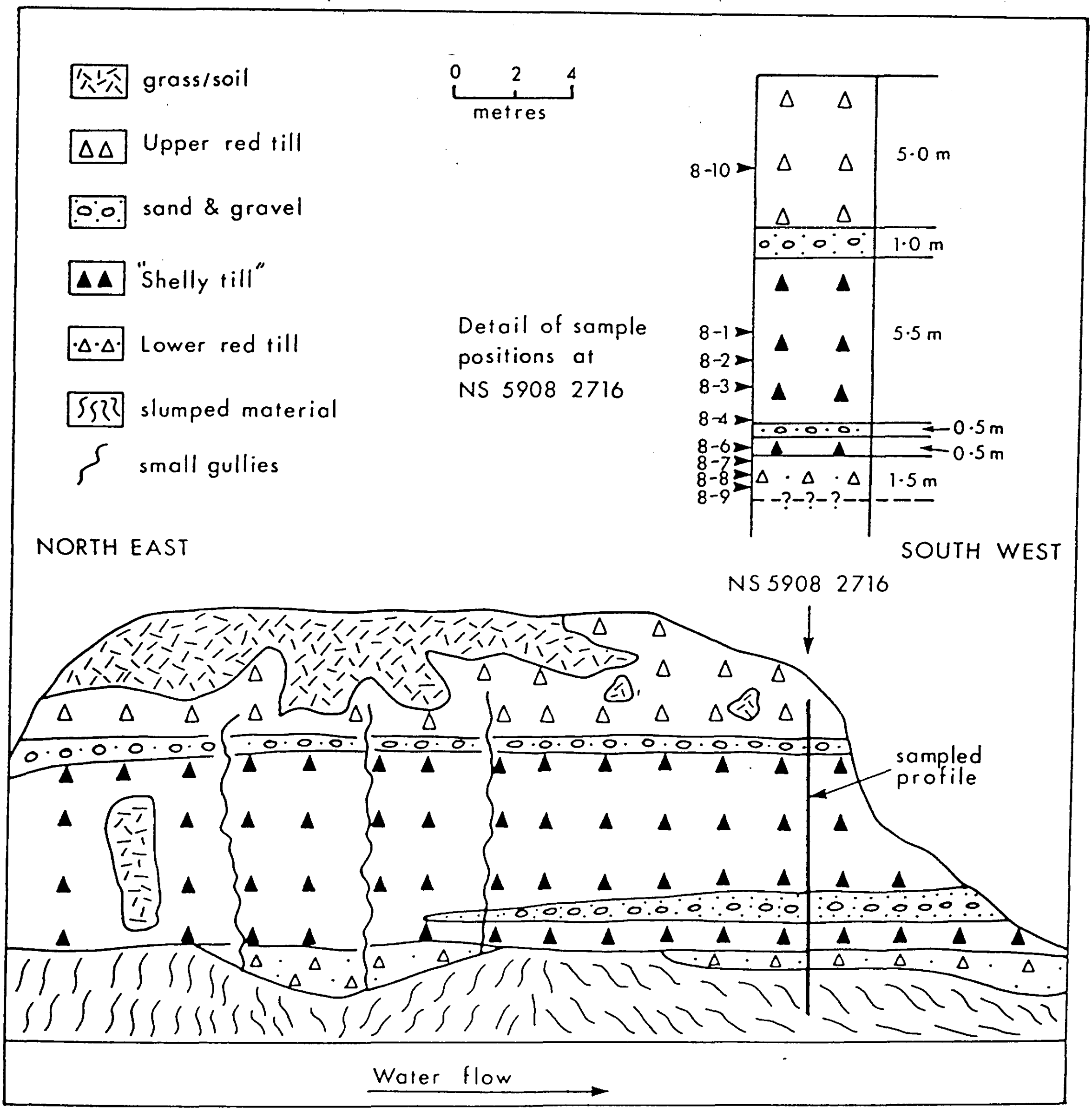


Figure 10.30 Sketch section through the deposits at Merkland Burn, Location 8, showing the stratigraphical units and sample positions within these units.

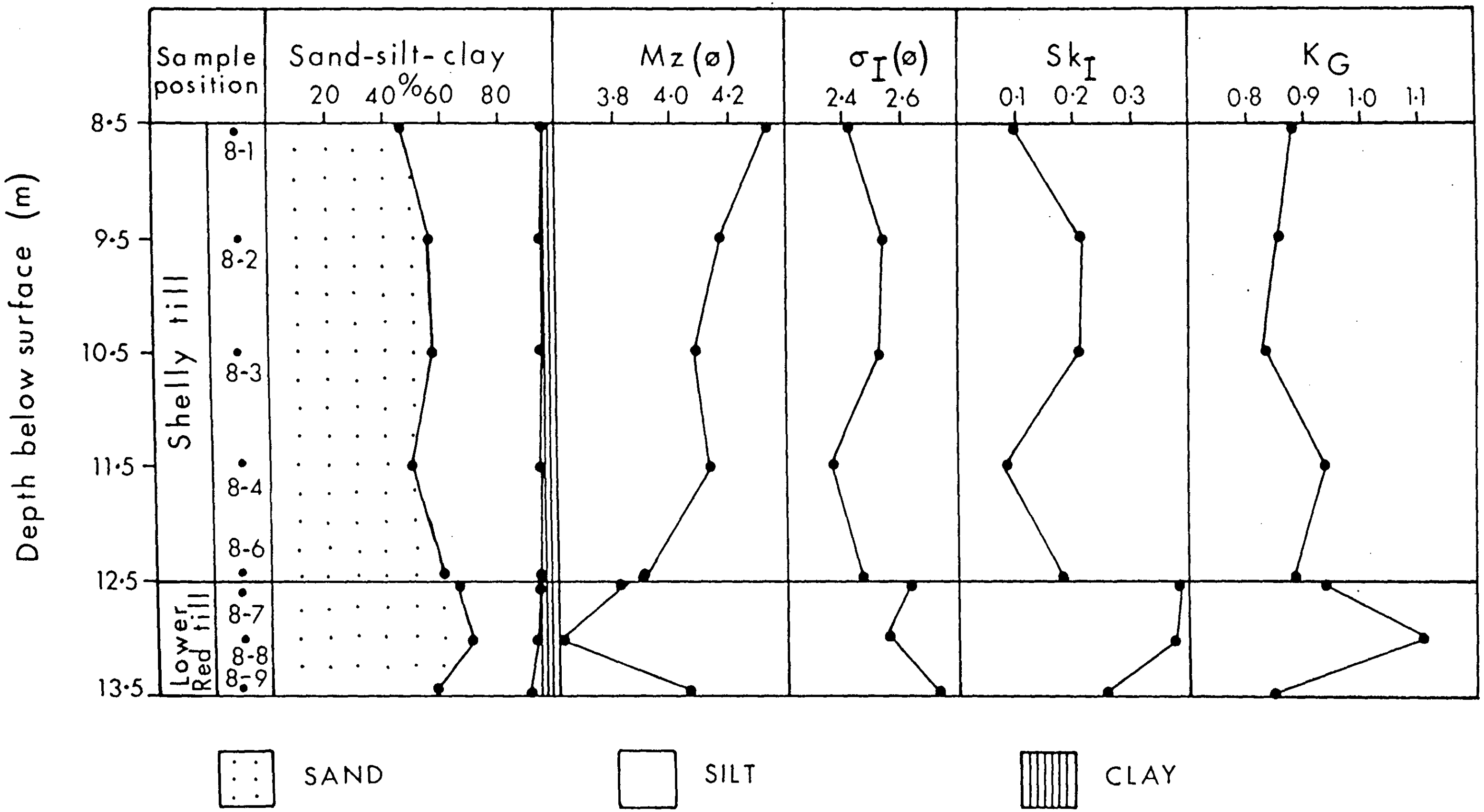
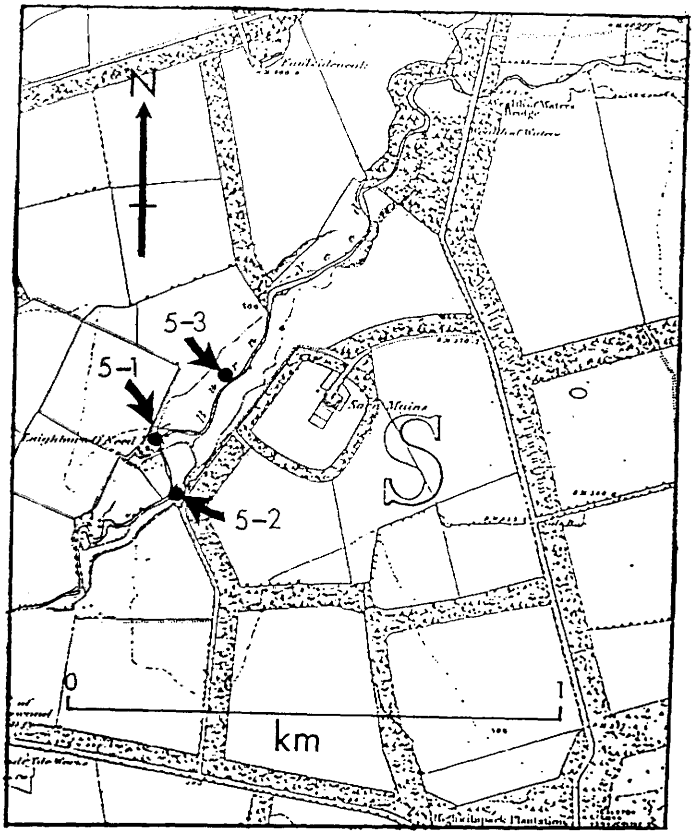


Figure 10.31 Vertical variation of sand, silt and clay percentages and grain-size parameters, Mz, σ_I, Sk_I and K_G, in the shelly till and Lower red till at Merkland Burn, Location 8 (NS 5908 2716).

a



b

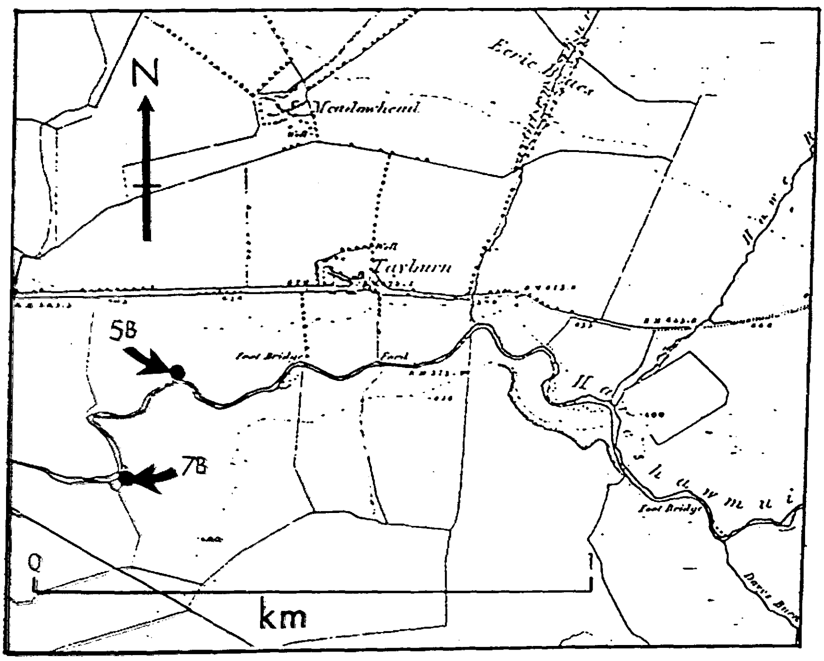


Figure 10.32 (a) Map of the Sorn Mains Site, showing the positions of Locations 5-1, 5-2 and 5-3

(b) Map of the Tayburn Site, showing the positions of Locations 5B and 7B

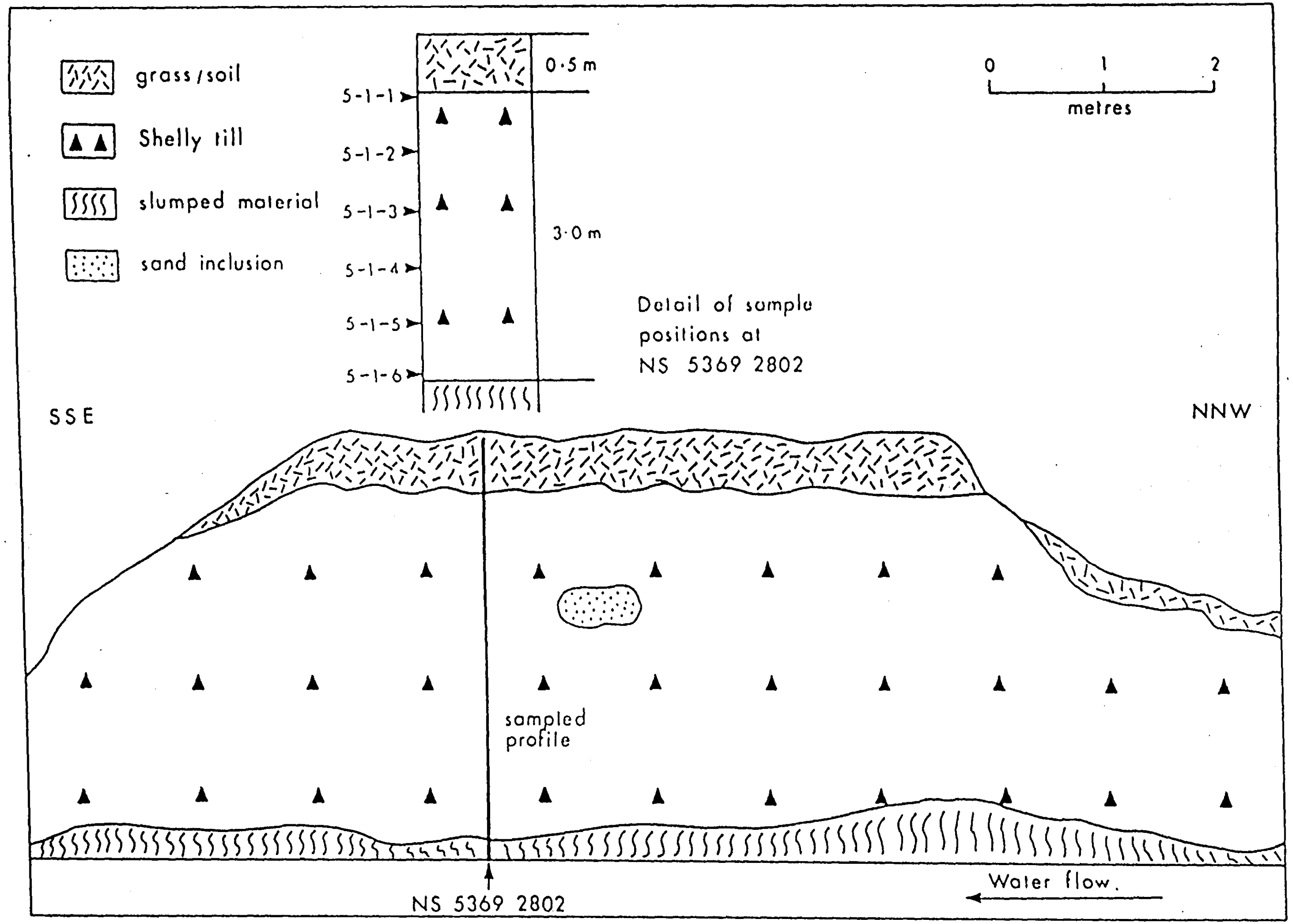


Figure 10.33 Sketch section through the exposure of shelly till at Sorn Mains, Location 5-1, showing sample positions.

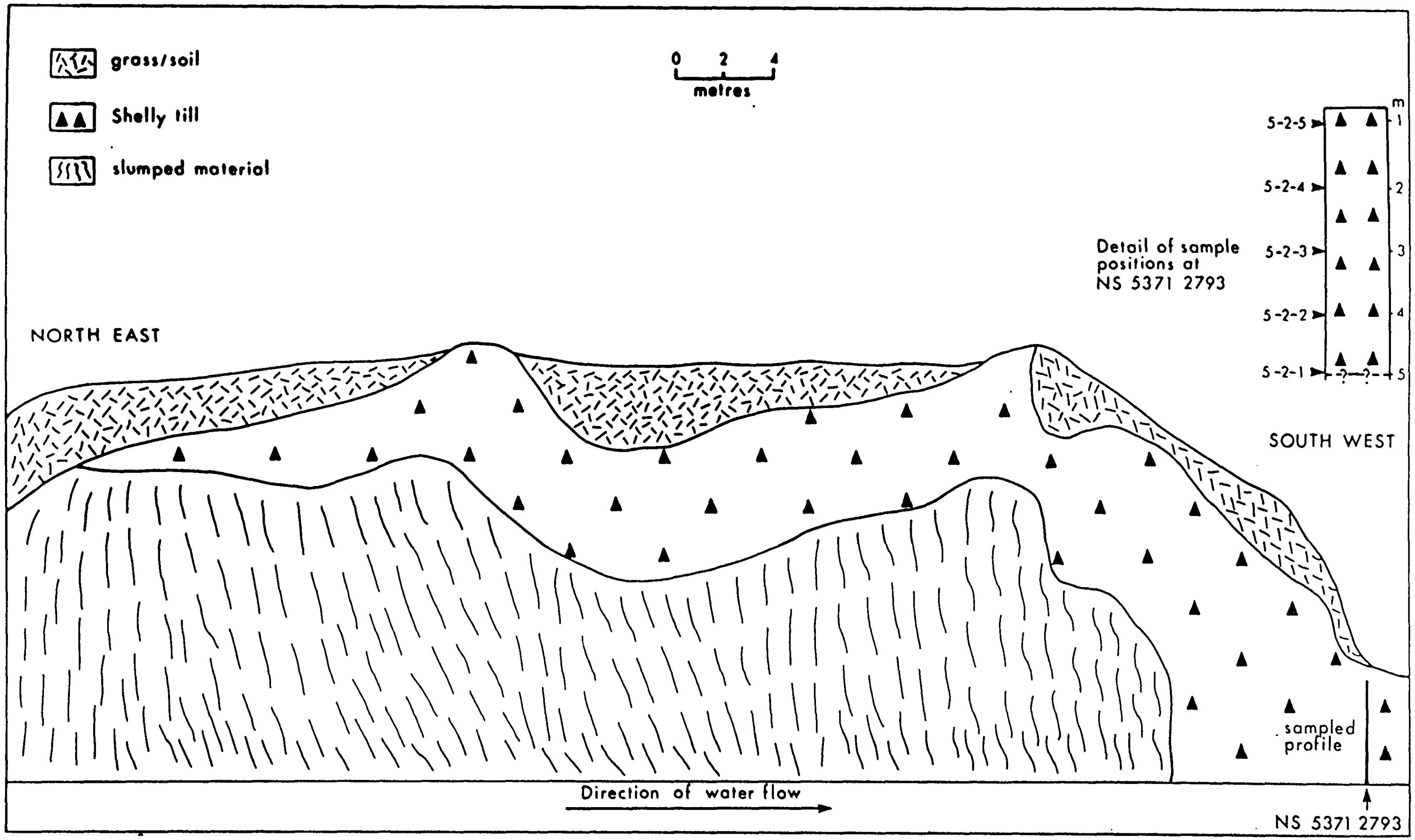


Figure 10.34 Sketch section through the exposure of shelly till at Sorn Mains, Location 5-2, showing sample positions.

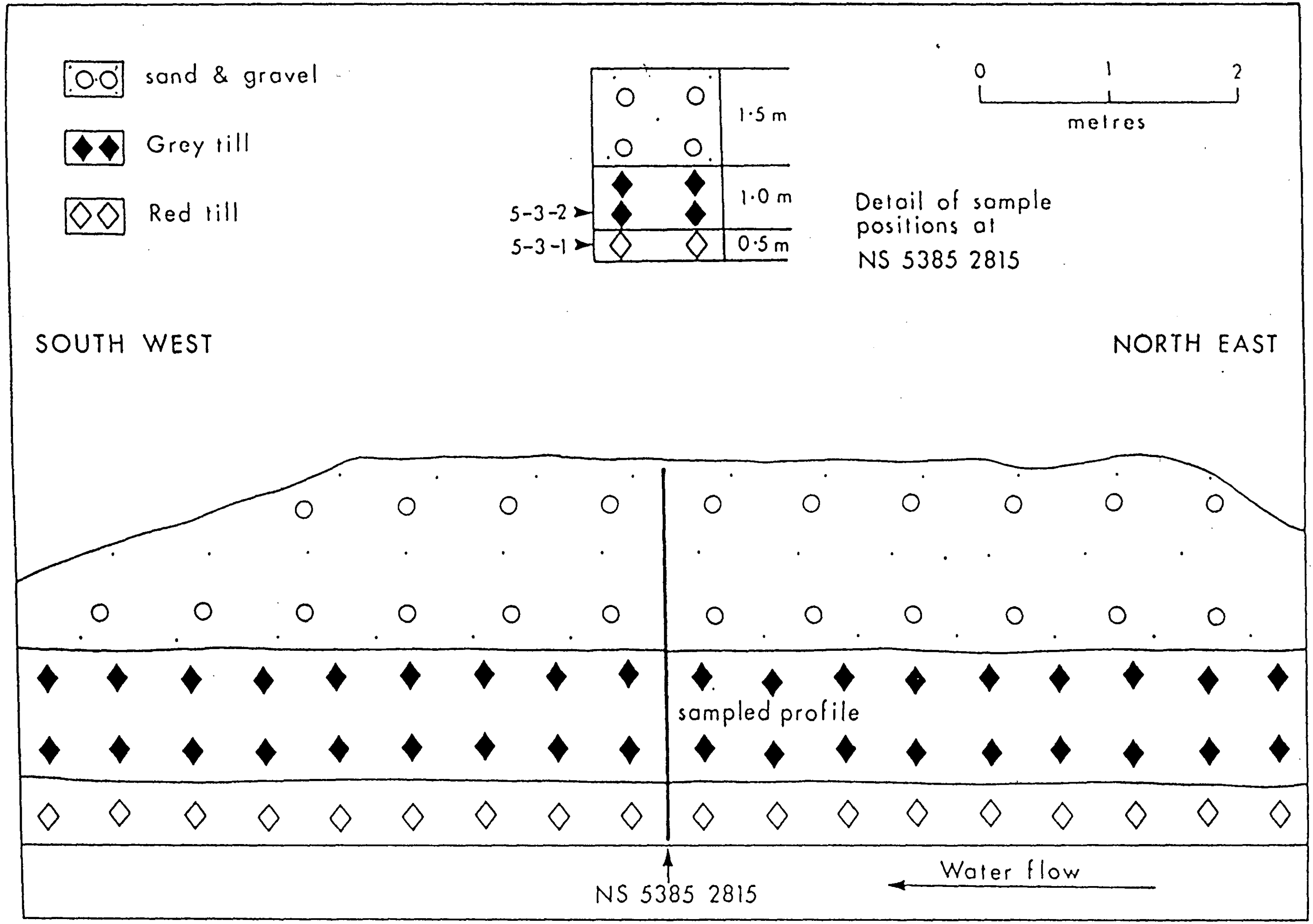


Figure 10. 35 Sketch section through the deposits at Sorn Mains, Location 5-3, showing the stratigraphical units and sample positions within these units.

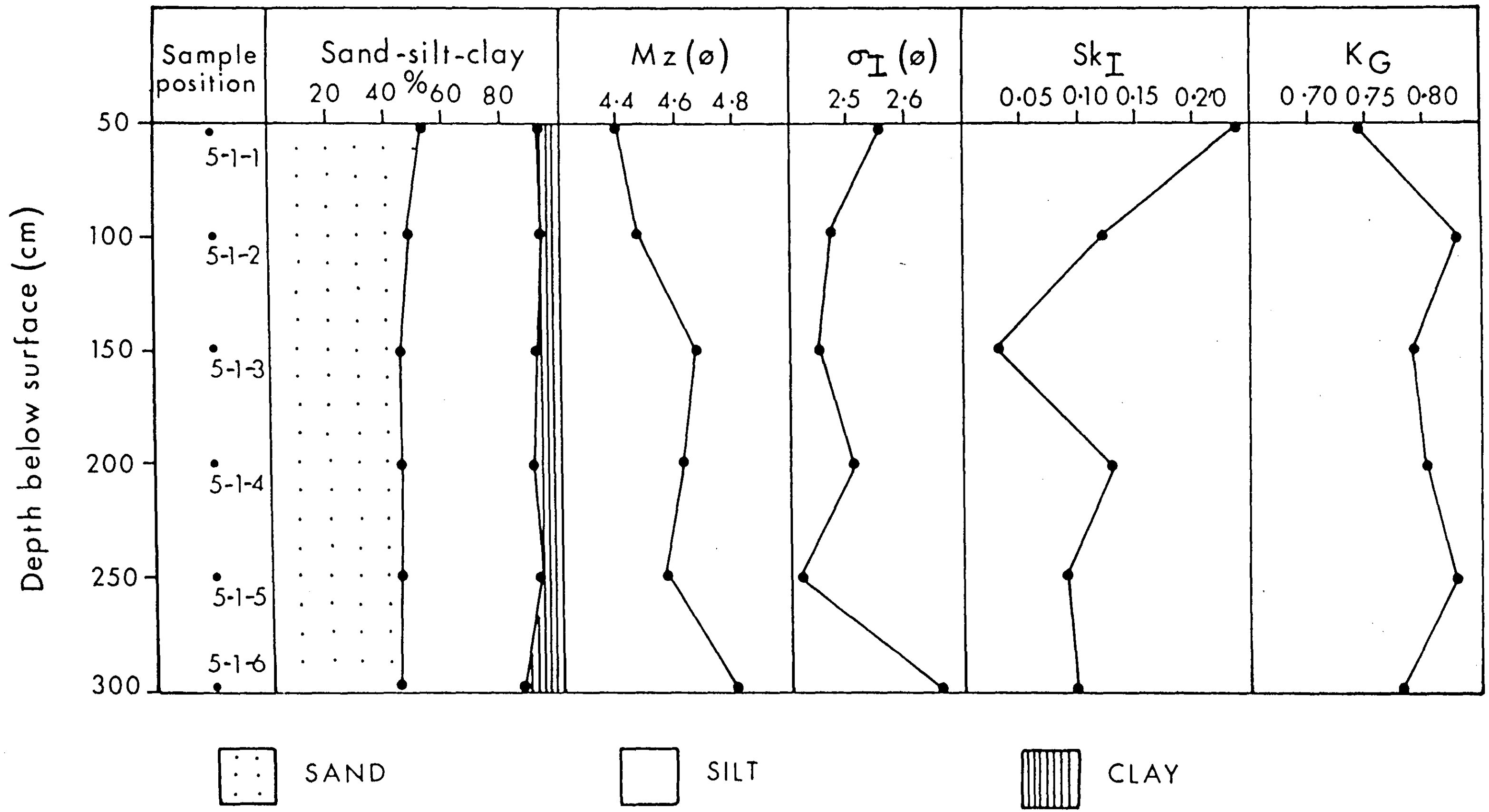


Figure 10.36 Vertical variation of sand, silt and clay percentages and grain-size parameters, Mz, σ_I, Sk_I and K_G, in the shelly till at Sorn Mains, Location 5-1 (NS 5369 2802).

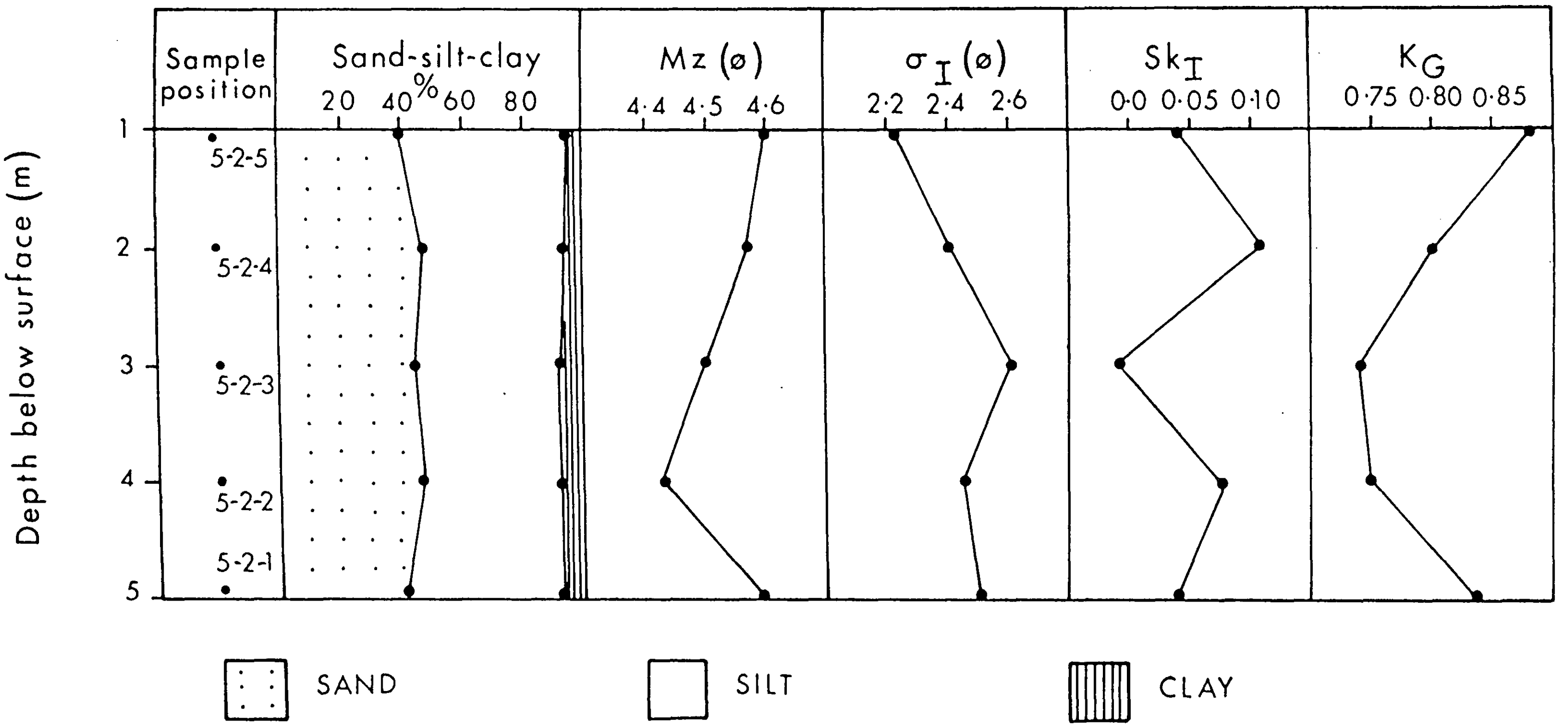


Figure 10.37 Vertical variation of sand, silt and clay percentages and grain-size parameters, Mz, σ_I, Sk_I and K_G, in the shelly till at Sorn Mains, Location 5-2 (NS 5371 2793).

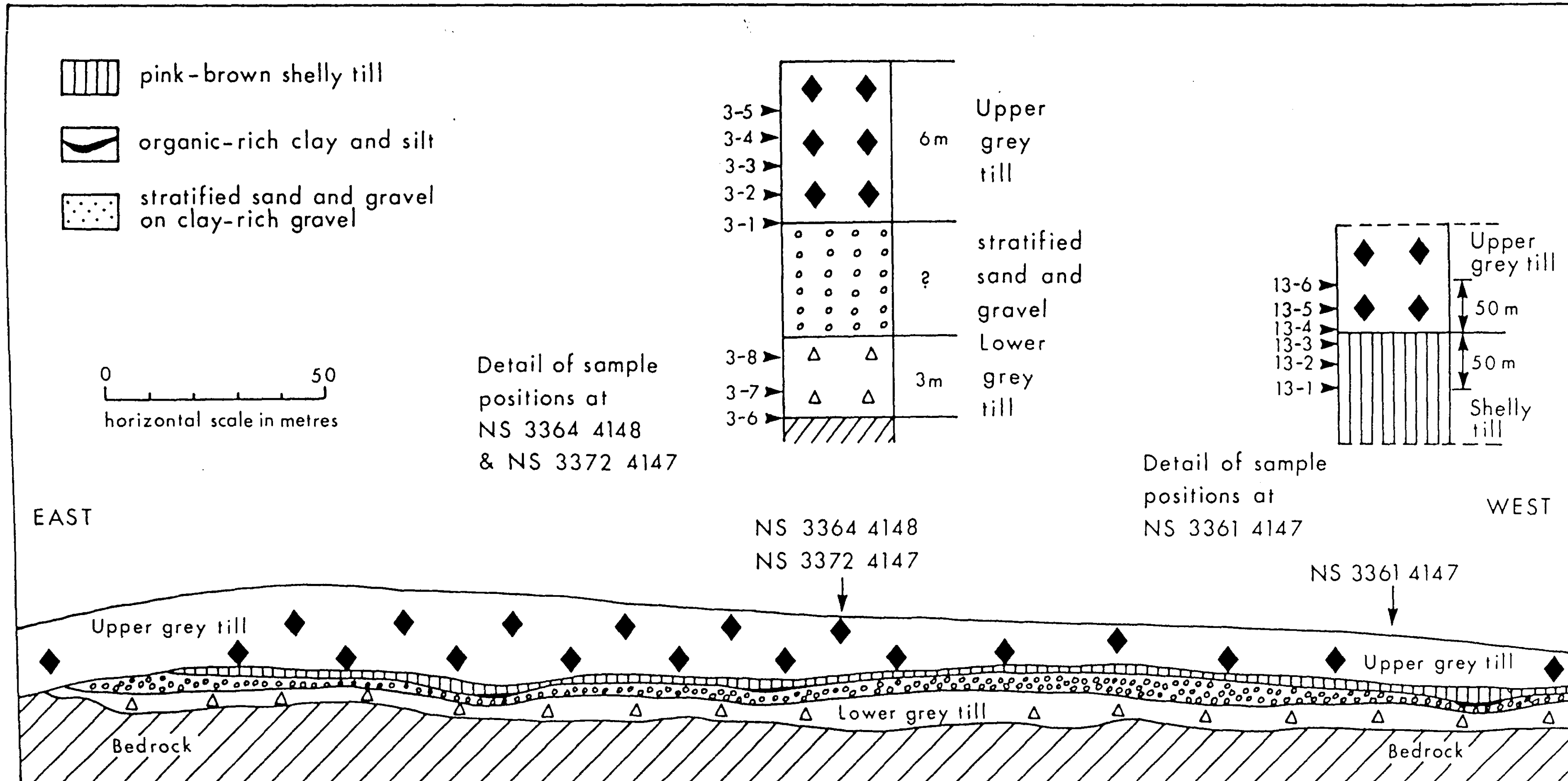


Figure 10.38 Schematic East-West vertical section through the deposits at Sourlie, showing the major stratigraphical units and sample positions within these units. Based on field measurements and observations by W. G. Jardine and P. D. W. Haughton.

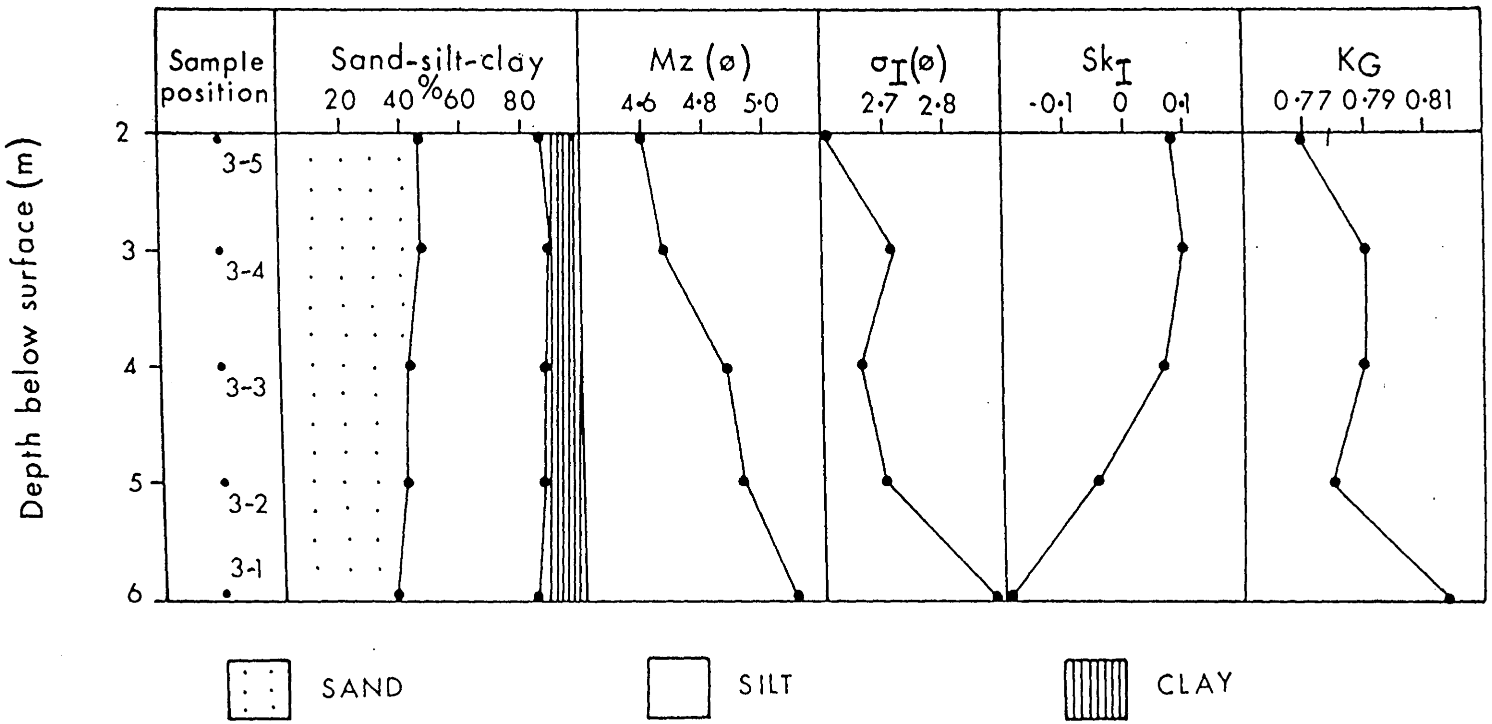


Figure 10.39 Vertical variation of sand, silt and clay percentages and grain-size parameters, Mz, σ_I, Sk_I and K_G, in the Upper grey till at Sourlie, Location 3 (NS 3364 4148).

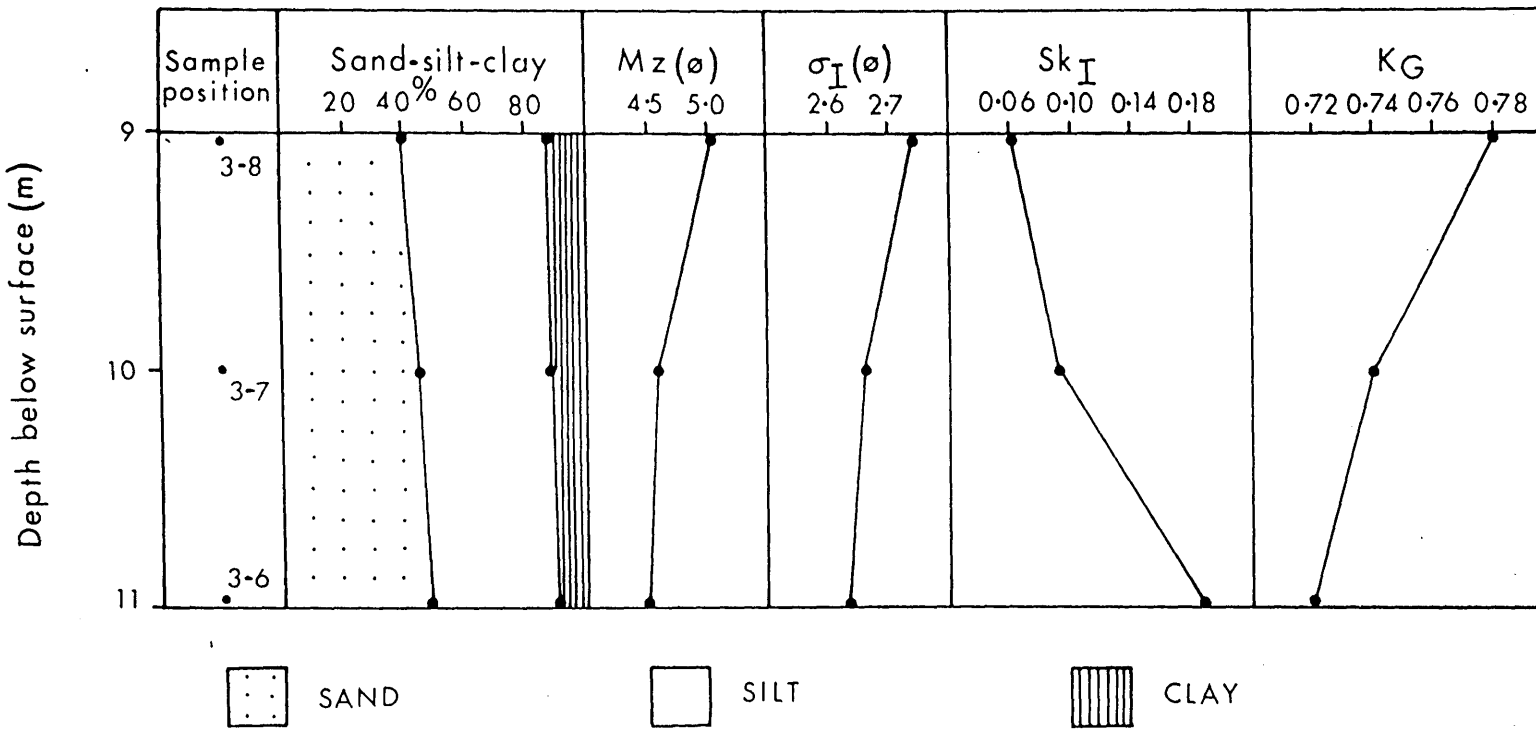


Figure 10.40 Vertical variation of sand, silt and clay percentages and grain-size parameters, Mz, σ_I, Sk_I and K_G, in the Lower grey till at Sourlie, Location 3 (NS 3372 4147).

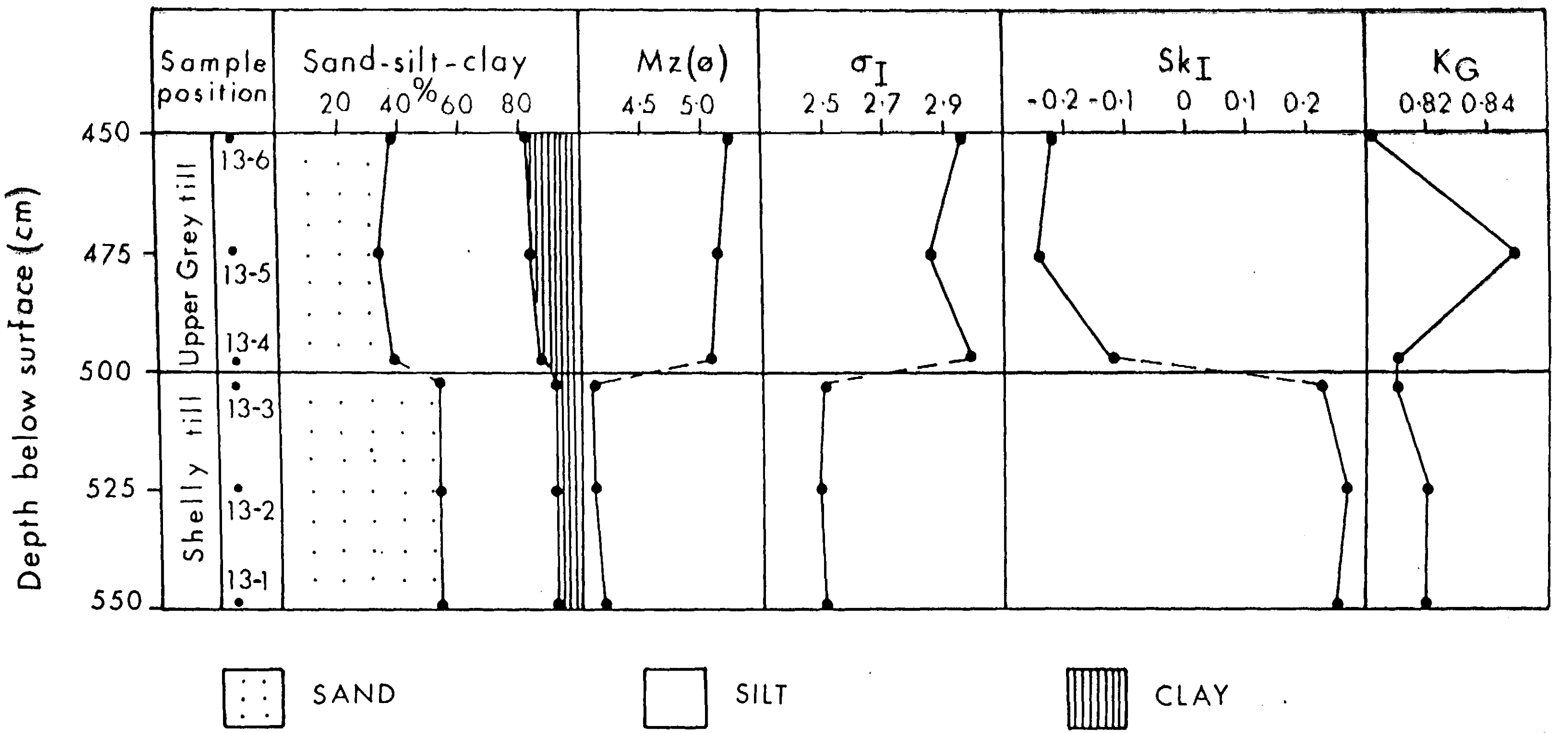


Figure 10.41 Vertical variation of sand, silt and clay percentages and grain-size parameters, Mz, σ_I, Sk_I and K_G, in the Upper grey till and shelly till at Sourlie, Location 13 (NS 3361 4147).

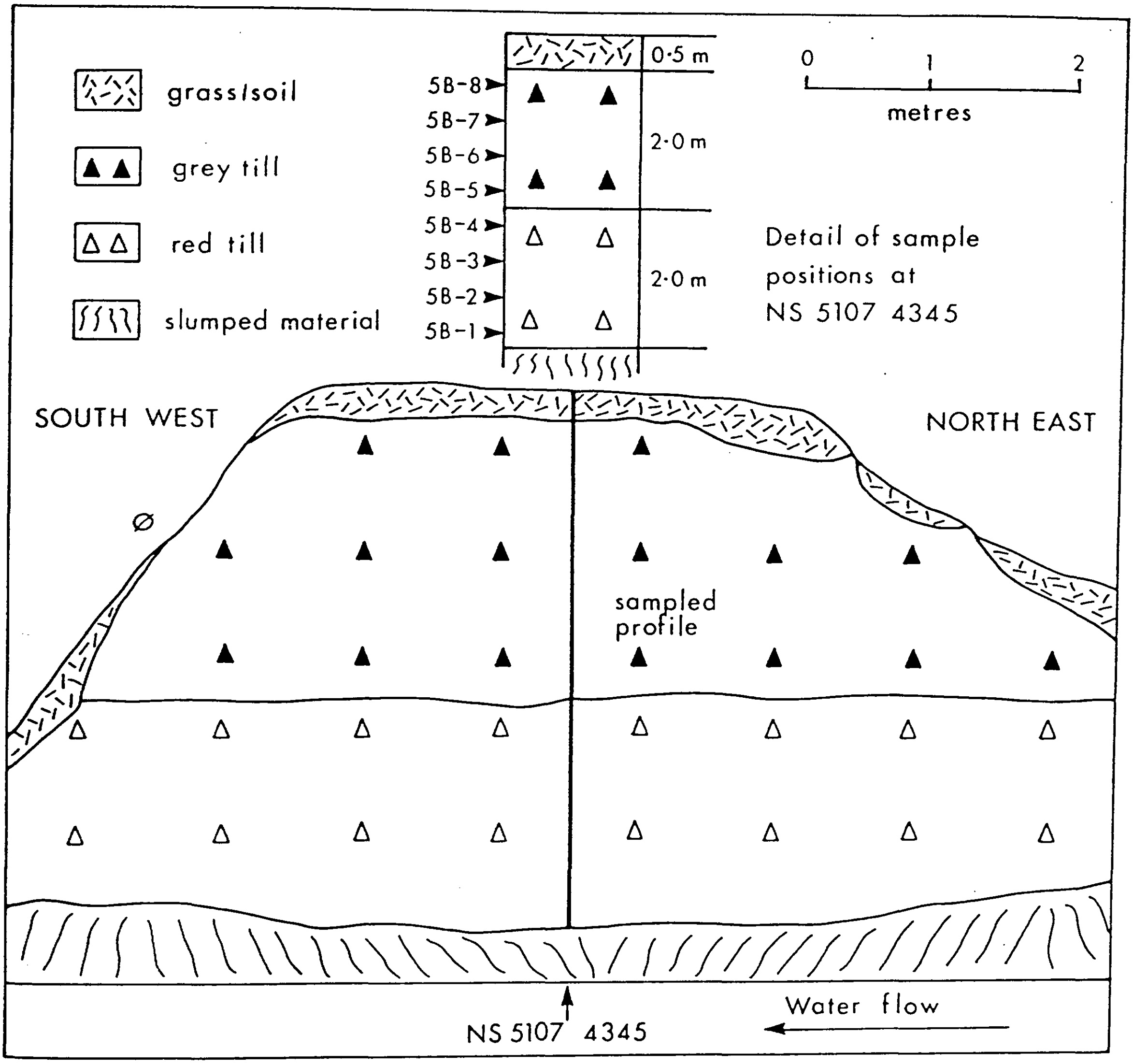


Figure 10.42 Sketch section through the deposits at Tayburn, Location 5B, showing the stratigraphical units and sample positions within these units.

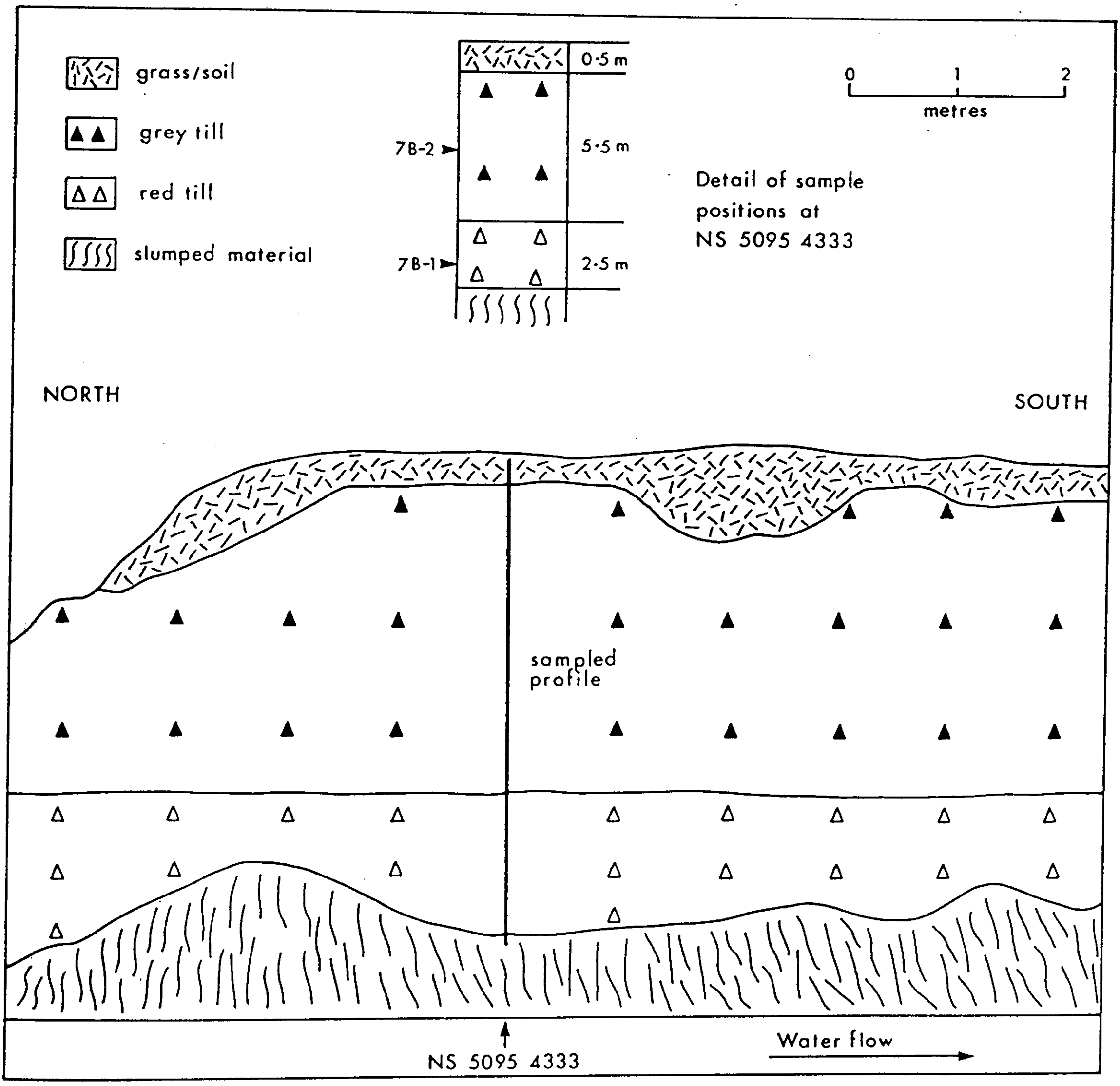


Figure 10.43 Sketch section through the deposits at Tayburn, Location 7B, showing the stratigraphical units and sample positions within these units.

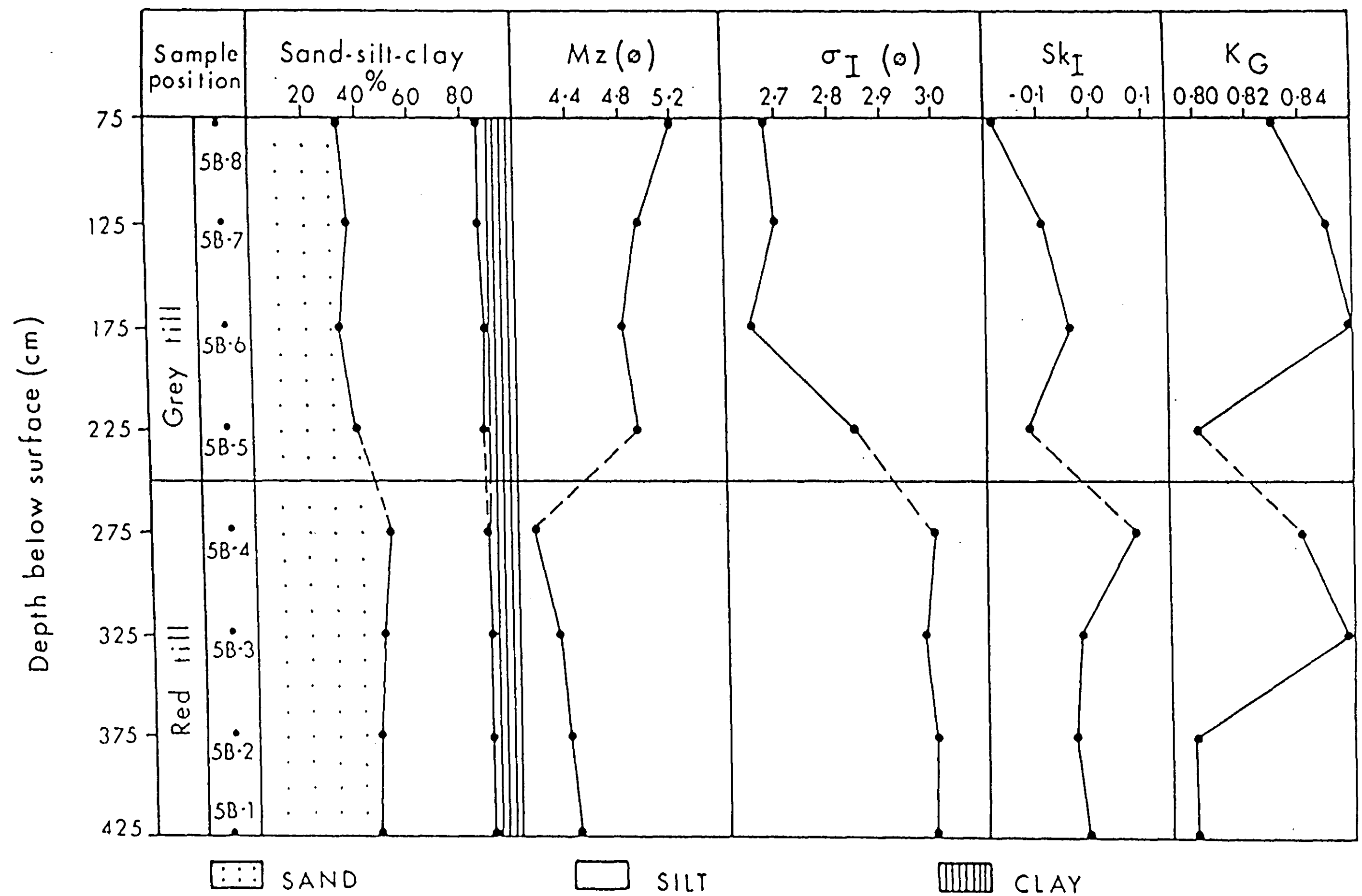


Figure 10.44 Vertical variation of sand, silt and clay percentages and grain-size parameters, Mz, σ_I, Sk_I and K_G, in the grey and red tills at Tayburn, Location 5B (NS 5095 4333).

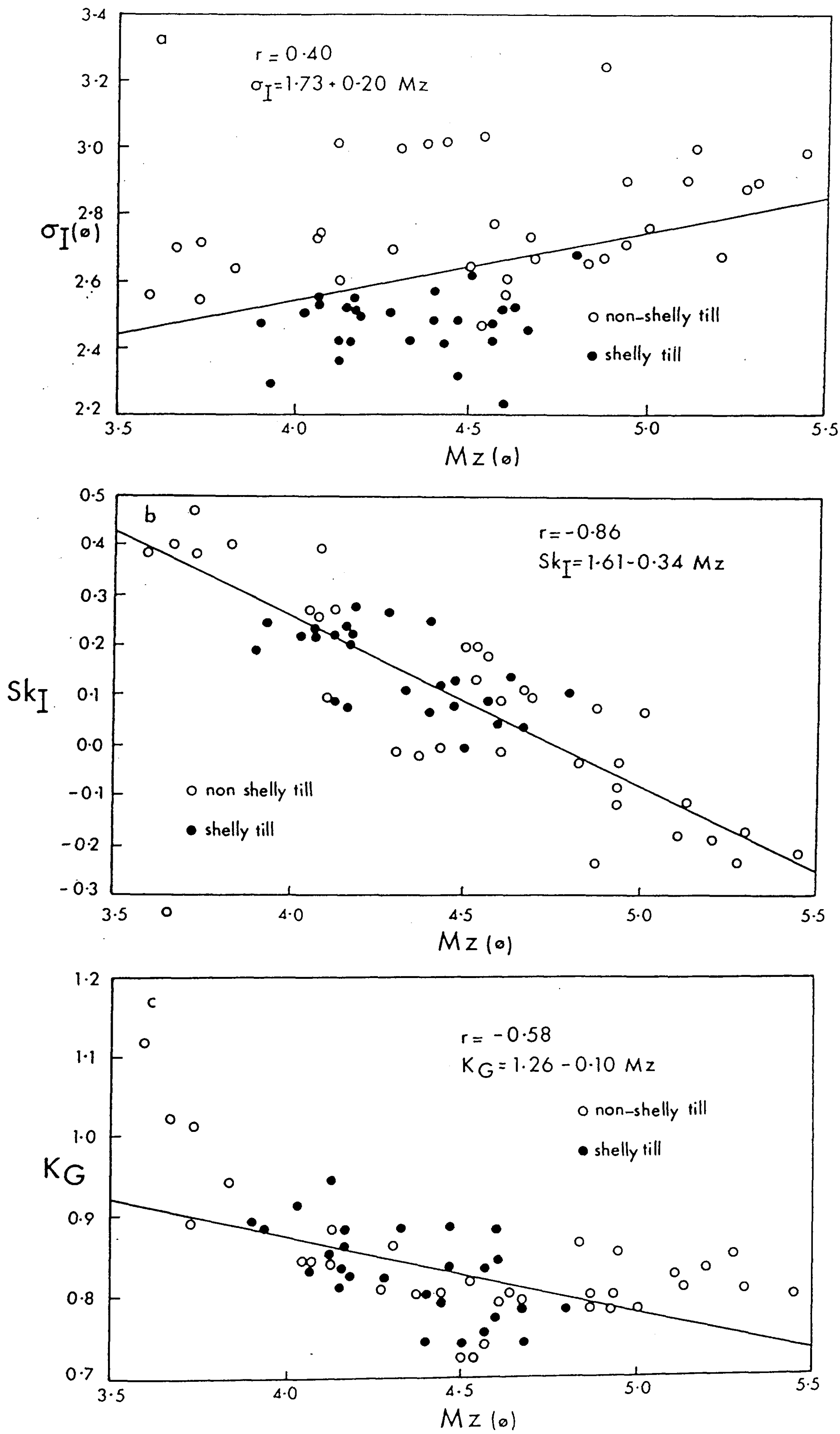


Figure 10.45 Till samples from Northern Ayrshire: scatter plots,
a mean size (Mz) versus sorting (σ_I)
b mean size (Mz) versus skewness (Sk_I)
c mean size (Mz) versus kurtosis (K_G)

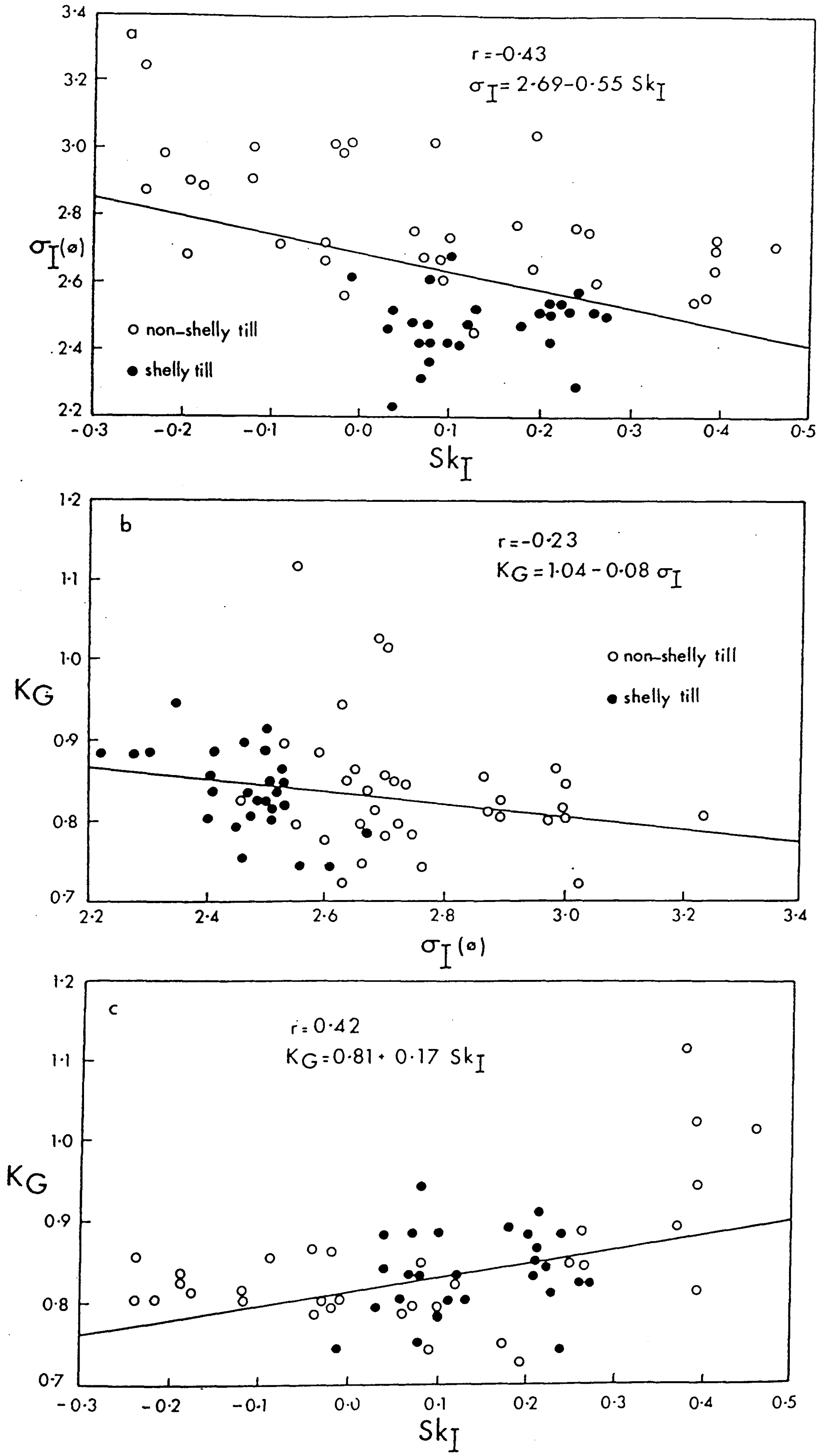


Figure 10.46 Till samples from Northern Ayrshire: scatter plots,
a skewness (Sk_I) versus sorting (σ_I)
b sorting (σ_I) versus kurtosis (K_G)
c skewness (Sk_I) versus kurtosis (K_G)

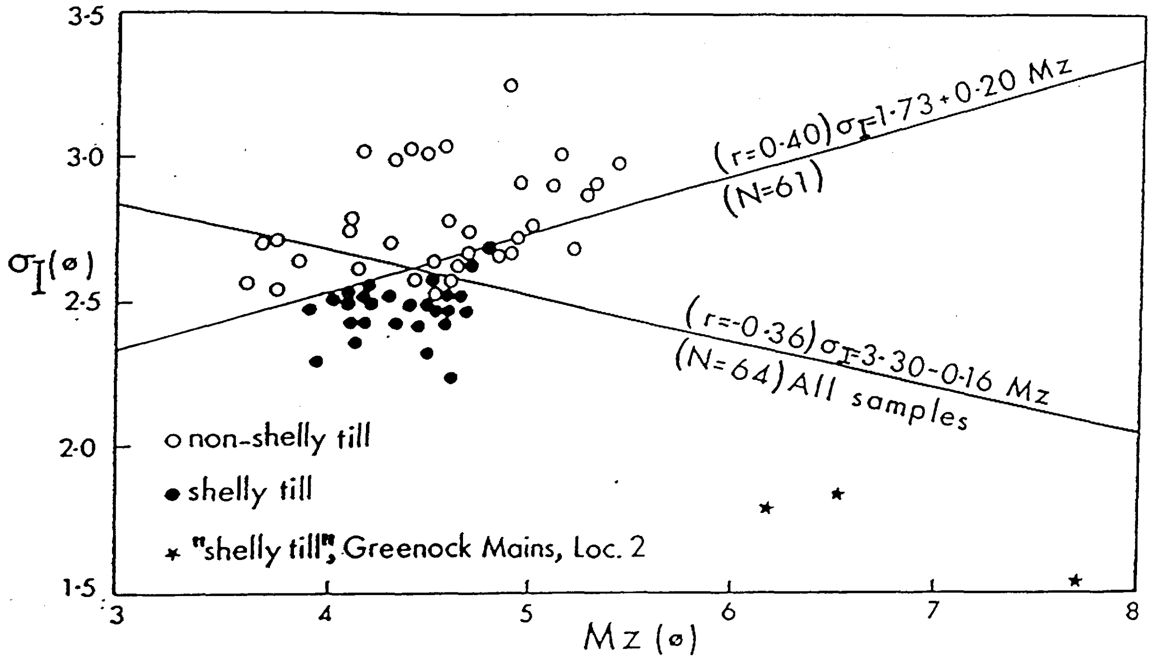


Figure 10.47 Samples from Northern Ayrshire: scatter plot of mean size (Mz) versus sorting (σ_I).

N = 61: all till samples from Northern Ayrshire, except the 3 samples of Lower "shelly till" at Greenock Mains, Location 2.

N = 64: all till samples from Northern Ayrshire, including the 3 samples of Lower "shelly till" at Greenock Mains, Location 2.

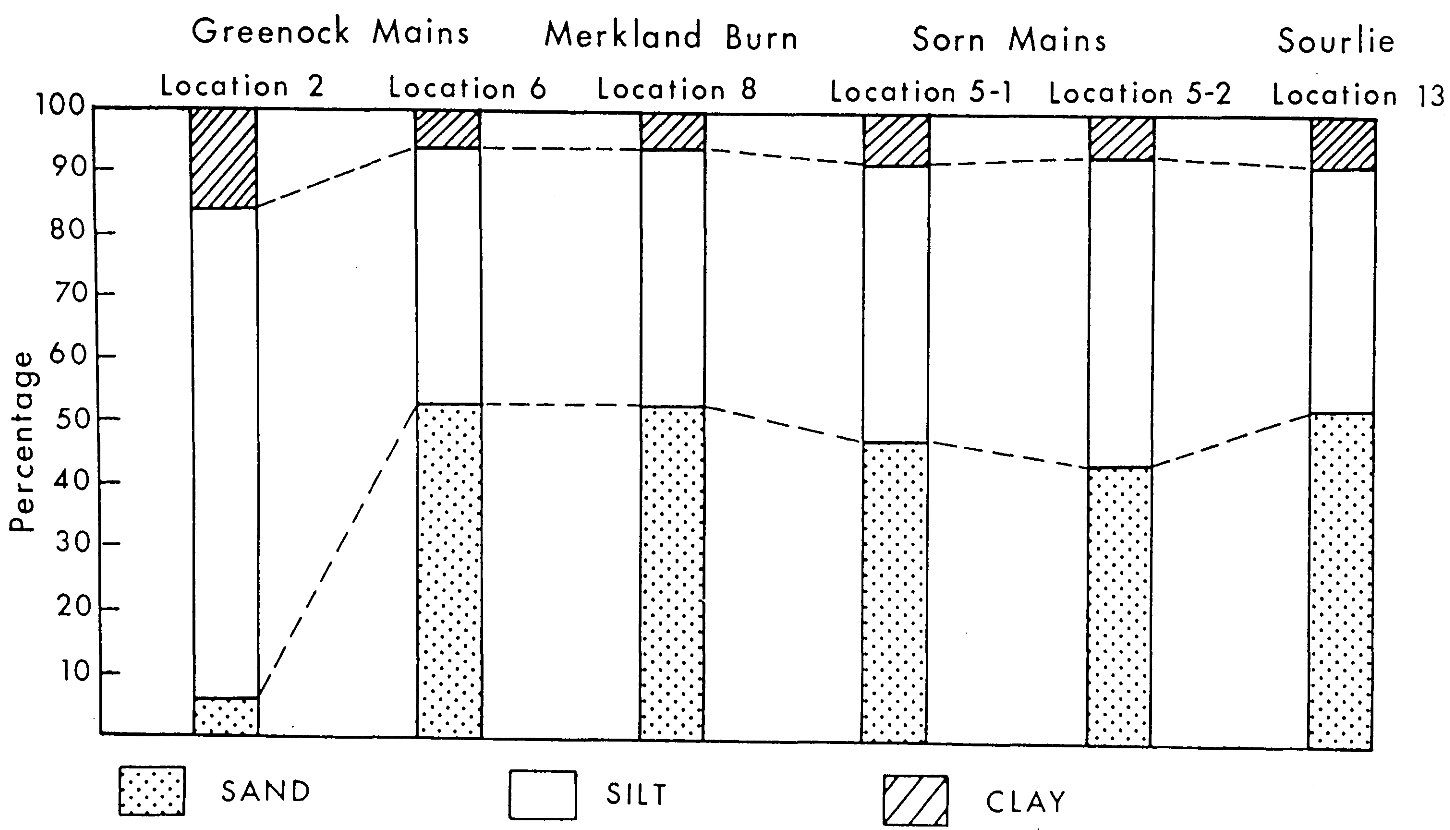


Figure 10.48 Average percentages of sand, silt and clay in the shelly till at five Locations and in the "shelly till" at Greenock Mains, Location 2.

Table 10.1 Till samples from Northern Ayrshire. Percentage by weight in each grade size. Grade sizes in phi units.

Till unit and Location	Sample number	sand					silt				clay
		-1 – 0ϕ	0 – 1ϕ	1 – 2ϕ	2 – 3ϕ	3 – 4ϕ	4 – 5ϕ	5 – 6ϕ	6 – 7ϕ	7 – 8ϕ	>8ϕ
Lower "shelly till", Greenock Mains, Location 2	2 – 1	0.30	0.62	1.62	2.46	2.49	7.78	21.08	24.64	23.31	15.70
	2 – 2	0.00	0.02	0.04	0.15	1.21	9.58	25.82	20.85	24.85	17.48
	2 – 3	0.38	0.61	1.71	3.05	3.59	11.19	27.66	17.22	20.38	14.21
Upper till, Greenock Mains, Location 2	2 – 4	3.77	5.08	11.84	19.63	15.42	9.73	9.40	7.57	9.75	7.81
	2 – 5	2.88	5.40	11.53	16.55	12.62	9.42	7.90	7.54	13.00	13.15
	2 – 6	3.79	6.45	12.20	17.08	9.80	7.35	8.07	7.72	12.36	15.48
	2 – 7	4.77	8.27	17.65	24.12	14.32	5.28	5.68	4.32	9.27	6.32
	2 – 8	3.29	6.81	16.40	25.21	15.61	4.93	7.51	5.82	9.05	5.37
	2 – 9	2.80	4.61	12.99	22.37	15.77	7.50	5.88	5.99	11.30	10.79
	2 –10	3.32	5.76	14.20	21.71	13.12	11.48	2.58	7.05	12.72	8.06
Lower shelly till, Greenock Mains, Location 6	6 – 1	2.61	4.57	11.97	21.45	17.70	7.42	12.20	8.83	8.47	4.78
	6 – 2	2.98	5.05	12.68	20.73	13.93	7.10	12.21	8.97	10.03	6.32
	6 – 3	3.18	5.19	12.79	20.88	14.78	10.41	9.78	7.80	9.36	5.83
	6 – 4	2.66	4.86	11.97	20.36	15.82	9.47	11.33	8.84	9.26	5.43
	6 – 5	2.55	4.95	12.95	20.15	14.30	6.58	11.84	9.82	11.53	5.33
	6 – 6	3.30	4.94	10.54	16.15	12.85	13.49	11.52	10.19	11.34	5.68
	6 – 7	3.56	5.02	10.85	17.62	12.93	14.62	11.60	9.11	10.10	4.59
	6 – 8	1.78	3.70	8.82	17.61	14.03	16.09	13.28	9.12	10.31	5.26

Table 10.1 (continued)

Till unit and Location	Sample number	sand					silt				clay
		-1 - 0ϕ	0 - 1ϕ	1 - 2ϕ	2 - 3ϕ	3 - 4ϕ	4 - 5ϕ	5 - 6ϕ	6 - 7ϕ	7 - 8ϕ	>8ϕ
Shelly till, Merkland Burn, Location 8	8 - 1	2.85	4.07	10.96	17.28	12.61	16.90	10.78	8.60	10.27	5.68
	8 - 2	3.60	4.64	11.84	20.25	14.63	8.85	11.14	8.72	10.45	5.87
	8 - 3	3.25	5.23	11.91	19.75	14.47	9.13	11.09	8.71	11.07	5.39
	8 - 4	3.02	5.03	11.29	17.65	13.27	19.08	10.01	7.43	7.96	5.26
	8 - 6	3.54	5.49	12.96	21.61	16.20	7.21	10.92	7.51	9.23	5.33
Lower red till, Merkland Burn, Location 8	8 - 7	3.47	5.54	16.00	24.94	14.60	5.86	7.32	6.38	9.15	6.74
	8 - 8	4.00	6.56	16.88	26.96	15.06	5.24	6.05	4.75	6.87	7.63
	8 - 9	4.29	6.05	13.99	19.42	12.60	7.69	9.06	7.72	11.05	8.13
Upper red till, Merkland Burn, Location 8	8 -10	3.54	6.71	19.02	25.90	12.92	5.18	5.86	4.66	6.60	9.61

Table 10.1 (continued)

Till unit and Location	Sample number	sand -1 – 0ϕ	0 – 1ϕ	1 – 2ϕ	2 – 3ϕ	3 – 4ϕ	silt 4 – 5ϕ	5 – 6ϕ	6 – 7ϕ	7 – 8ϕ	clay >8ϕ
Shelly till, Sorn Mains, Location 5-1	5-1 – 1	2.18	3.88	10.60	18.80	16.70	4.28	6.41	14.36	15.21	7.58
	5-1 – 2	2.25	3.84	9.41	16.94	15.66	10.36	12.40	9.50	12.65	7.01
	5-1 – 3	2.00	3.51	8.96	16.20	14.90	11.19	12.73	10.12	13.17	7.22
	5-1 – 4	1.88	3.38	8.91	16.40	15.29	10.66	11.95	9.20	12.86	9.53
	5-1 – 5	1.95	3.38	9.03	16.73	14.26	11.99	12.83	10.88	12.53	6.42
	5-1 – 6	1.94	3.51	9.01	16.11	14.32	9.84	10.19	10.30	13.12	11.66
Shelly till, Sorn Mains, Location 5-2	5-2 – 1	2.88	3.67	8.87	14.78	10.82	17.92	12.11	7.91	13.47	7.57
	5-2 – 2	2.22	3.71	9.92	17.01	13.30	10.82	12.27	9.56	14.42	6.77
	5-2 – 3	3.89	4.71	10.74	15.47	10.16	10.91	13.14	9.82	14.23	6.93
	5-2 – 4	2.51	3.94	9.80	16.90	13.70	11.14	13.55	10.27	12.74	5.45
	5-2 – 5	1.95	2.98	7.87	14.61	12.15	22.57	11.50	9.80	11.58	4.99
Grey till, Sorn Mains, Location 5-3	5-3 – 1	3.23	4.46	9.38	14.98	11.83	10.20	14.01	11.05	13.66	7.20
Red till, Sorn Mains, Location 5-3	5-3 – 2	2.06	4.05	9.14	16.91	15.41	9.94	12.02	10.06	12.96	7.45

Table 10.1 (continued)

Till unit and Location	Sample number	sand					silt				clay
		-1 - 0ϕ	0 - 1ϕ	1 - 2ϕ	2 - 3ϕ	3 - 4ϕ	4 - 5ϕ	5 - 6ϕ	6 - 7ϕ	7 - 8ϕ	>8ϕ
Upper Grey till, Sourlie, Location 3	3 - 1	4.92	4.85	7.03	10.73	11.20	5.27	10.96	11.10	19.31	14.63
	3 - 2	3.39	4.39	7.63	13.48	12.86	8.35	12.02	8.35	17.91	11.62
	3 - 3	2.87	3.56	8.21	14.71	13.07	10.54	8.90	9.40	16.44	12.30
	3 - 4	3.91	4.88	8.14	15.47	13.68	9.32	9.11	9.09	15.94	10.46
	3 - 5	4.32	4.67	9.03	15.06	12.71	4.10	9.79	11.34	16.46	12.52
Lower Grey till, Sourlie, Location 3	3 - 6	2.86	3.75	10.72	20.21	12.30	9.44	7.54	8.49	14.88	9.81
	3 - 7	2.92	3.54	9.95	17.99	9.70	11.62	8.78	9.89	14.90	10.71
	3 - 8	3.67	3.54	7.77	14.10	10.58	9.14	10.50	8.91	18.52	13.27
Shelly till, Sourlie, Location 13	13 - 1	2.37	3.76	11.58	20.05	14.96	9.72	8.50	9.38	10.98	8.70
	13 - 2	2.63	3.64	11.74	20.79	15.47	9.58	8.82	8.46	10.27	8.60
	13 - 3	3.10	3.98	11.91	20.22	15.14	7.91	10.57	8.22	11.02	7.93
Upper Grey till, Sourlie, Location 13	13 - 4	4.86	4.94	7.23	11.20	10.13	7.67	8.54	9.93	18.38	17.12
	13 - 5	4.38	4.53	6.37	10.33	9.02	5.82	12.39	10.62	20.32	16.22
	13 - 6	4.15	4.82	6.98	11.16	10.61	4.75	9.45	12.25	17.78	18.05

Table 10.1 (continued)

Till unit and Location	Sample number	sand					silt				clay
		-1 - 0ϕ	0 - 1ϕ	1 - 2ϕ	2 - 3ϕ	3 - 4ϕ	4 - 5ϕ	5 - 6ϕ	6 - 7ϕ	7 - 8ϕ	>8ϕ
Red till, Tayburn, Location 5B	5B - 1	6.40	7.15	10.56	13.27	9.27	8.84	11.75	9.32	12.46	10.98
	5B - 2	6.76	7.07	10.73	13.38	9.22	7.33	11.16	10.38	13.33	10.64
	5B - 3	7.06	7.48	10.80	13.83	9.71	8.21	11.03	10.11	11.77	10.00
	5B - 4	6.85	7.63	12.09	13.98	9.46	7.00	11.91	8.63	12.07	10.38
Grey till, Tayburn, Location 5B	5B - 5	4.62	5.40	7.83	11.11	9.19	8.51	11.19	11.13	17.64	13.38
	5B - 6	3.49	4.62	7.01	10.67	8.15	18.44	12.50	10.07	14.07	10.98
	5B - 7	4.35	5.18	7.59	11.14	8.64	11.05	13.82	9.36	15.71	13.16
	5B - 8	3.28	4.06	6.67	11.22	8.84	8.25	14.19	11.70	17.39	14.40
Red till, Tayburn, Location 7B	7B - 1	7.74	7.46	7.56	8.17	6.71	6.61	11.67	11.75	16.01	16.32
Grey till, Tayburn, Location 7B	7B - 1	3.76	4.38	7.12	11.32	8.77	6.76	12.73	11.23	16.42	17.51

Table 10.2 Till samples from Northern Ayrshire. The seven phi percentiles derived from grain-size analysis.

Till unit and Location	Sample number	∅ 5	∅ 16	∅ 25	∅ 50	∅ 75	∅ 84	∅ 95
Lower "shelly till", Greenock Mains, Location 2	2 - 1	3.00	5.00	5.50	6.50	7.50	8.00	9.40
	2 - 2	5.10	6.20	6.60	7.70	8.70	9.10	10.30
	2 - 3	2.80	4.60	5.10	6.10	7.30	7.80	9.20
Upper till, Greenock Mains, Location 2	2 - 4	0.40	1.70	2.20	3.60	6.00	7.10	8.60
	2 - 5	0.60	1.80	2.40	4.20	7.10	7.70	9.10
	2 - 6	0.30	1.50	2.10	4.10	7.30	8.00	9.50
	2 - 7	0.10	1.20	1.70	2.80	5.00	7.00	8.30
	2 - 8	0.40	1.40	1.90	3.00	5.50	6.80	8.20
	2 - 9	0.60	1.80	2.30	3.50	6.50	7.50	8.90
	2 -10	0.40	1.50	2.10	3.40	6.20	7.30	8.80
Lower shelly till, Greenock Mains, Location 6	6 - 1	0.60	1.80	2.30	3.50	5.70	6.50	7.90
	6 - 2	0.50	1.60	2.20	3.60	6.00	7.00	8.30
	6 - 3	0.40	1.60	2.30	3.60	5.80	6.90	8.20
	6 - 4	0.60	1.80	2.30	3.70	5.90	6.90	8.10
	6 - 5	0.50	1.70	2.30	3.70	6.20	7.10	8.10
	6 - 6	0.40	1.90	2.50	4.20	6.30	7.10	8.10
	6 - 7	0.40	1.70	2.40	4.00	5.90	6.80	7.90
	6 - 8	0.90	2.10	2.70	3.40	6.00	7.00	8.00
Shelly till, Merkland Burn, Location 8	8 - 1	0.60	1.90	2.50	4.10	6.00	7.00	8.10
	8 - 2	0.40	1.70	2.30	3.70	6.00	7.10	8.20
	8 - 3	0.40	1.60	2.20	3.60	6.00	7.00	8.10
	8 - 4	0.50	1.80	2.30	4.00	5.60	6.60	8.10
	8 - 6	0.30	1.60	2.10	3.40	5.70	6.70	8.10
Lower red till, Merkland Burn, Location 8	8 - 7	0.30	1.50	2.00	3.00	5.60	7.00	8.40
	8 - 8	0.20	1.40	1.90	2.90	5.00	6.50	8.60
	8 - 9	0.10	1.50	2.00	3.50	6.20	7.20	8.70
Upper red till, Merkland Burn, Location 8	8 -10	0.30	1.40	1.80	2.80	5.30	7.00	8.90

Table 10.2 (continued)

Till unit and Location	Sample number	ø 5	ø 16	ø 25	ø 50	ø 75	ø 84	ø 95
Shelly till, Sorn Mains, Location 5-1	5-1 - 1	0.80	1.90	2.50	3.90	6.80	7.40	8.60
	5-1 - 2	0.70	2.00	2.60	4.20	6.40	7.20	8.40
	5-1 - 3	0.90	2.10	2.70	4.60	6.60	7.30	8.50
	5-1 - 4	1.00	2.10	2.70	4.40	6.70	7.40	8.80
	5-1 - 5	0.90	2.10	2.70	4.40	6.40	7.20	8.40
	5-1 - 6	0.80	2.10	2.60	4.60	7.00	7.70	9.20
Shelly till, Sorn Mains, Location 5-2	5-2 - 1	0.70	2.00	2.70	4.50	6.50	7.30	8.50
	5-2 - 2	0.90	2.00	2.50	4.40	6.60	7.30	8.40
	5-2 - 3	0.40	1.70	2.30	4.50	6.70	7.30	8.40
	5-2 - 4	0.80	2.00	2.50	4.20	6.30	7.10	8.20
	5-2 - 5	1.10	2.30	2.90	4.50	6.10	7.00	8.00
Grey till, Sorn Mains, Location 5-3	5-3 - 1	0.50	1.90	2.50	4.60	6.60	7.30	8.40
Red till, Sorn Mains, Location 5-3	5-3 - 2	0.80	2.10	2.60	4.30	6.50	7.20	8.60
Upper Grey till, Sourlie, Location 3	3 - 1	0.10	1.90	2.80	5.50	7.40	7.90	9.30
	3 - 2	0.50	2.10	2.70	5.00	7.20	7.70	9.10
	3 - 3	0.70	2.20	2.80	4.70	7.20	7.70	9.20
	3 - 4	0.30	2.00	2.60	4.40	7.10	7.60	9.00
	3 - 5	0.30	1.90	2.50	4.40	7.10	7.50	8.90
Lower Grey till, Sourlie, Location 3	3 - 6	0.70	1.90	2.40	4.10	7.00	7.50	8.80
	3 - 7	0.75	1.95	2.50	4.50	7.10	7.60	9.00
	3 - 8	0.50	2.10	2.70	5.10	7.30	7.80	9.20
Shelly till, Sourlie, Location 13	13 - 1	0.80	1.95	2.50	3.80	6.50	7.10	8.80
	13 - 2	0.70	1.85	2.40	3.70	6.40	7.00	8.70
	13 - 3	0.50	1.80	2.15	3.70	6.20	7.00	8.50
Upper Grey till, Sourlie, Location 13	13 - 4	0.10	1.90	2.80	5.40	7.60	8.10	9.60
	13 - 5	0.20	2.10	3.00	5.80	7.50	7.90	9.50
	13 - 6	0.30	2.00	2.90	5.90	7.70	8.20	9.70

Table 10.2 (continued)

Till unit and Location	Sample number	ø 5	ø 16	ø 25	ø 50	ø 75	ø 84	ø 95
Red till, Tayburn, Location 5B	5B - 1	-0.40	1.30	2.10	4.40	6.90	7.60	9.00
	5B - 2	-0.50	1.20	2.00	4.40	6.80	7.50	8.90
	5B - 3	-0.60	1.20	2.00	4.30	6.50	7.40	8.90
	5B - 4	-0.60	1.10	1.90	3.90	6.50	7.40	8.80
Grey till, Tayburn, Location 5B	5B - 5	0.10	1.80	2.60	5.20	7.30	7.80	9.30
	5B - 6	0.40	2.10	2.90	4.90	7.00	7.50	9.00
	5B - 7	0.20	1.90	2.80	5.10	7.20	7.80	9.30
	5B - 8	0.50	2.10	3.00	5.60	7.40	7.90	9.40
Red till, Tayburn, Location 7B	7B - 1	-0.50	1.10	2.30	5.50	7.40	8.00	9.40
Grey till, Tayburn, Location 7B	7B - 2	0.40	2.10	2.90	5.70	7.50	8.10	9.50

Table 10.3 Till samples from Northern Ayrshire. Sand-silt-clay percentages and grain-size parameters of matrix.

Till unit and Location	Sample number	% sand	% silt	% clay	grain-size parameters Mz	σ_I	Sk_I	K_G
Lower "shelly till", Greenock Mains, Location 2	2 - 1	7.49	76.81	15.70	6.50	1.82	0.03	1.31
	2 - 2	1.42	81.10	17.48	7.67	1.51	0.25	1.01
	2 - 3	9.34	76.45	14.21	6.17	1.77	0.02	1.19
Upper till, Greenock Mains, Location 2	2 - 4	55.74	36.46	7.81	4.13	2.59	0.26	0.88
	2 - 5	48.98	37.86	13.16	4.56	2.76	0.17	0.14
	2 - 6	49.02	35.50	15.48	4.53	3.02	0.19	0.72
	2 - 7	69.13	24.55	6.32	3.67	2.69	0.39	1.02
	2 - 8	67.32	26.31	5.37	3.73	2.53	0.37	0.89
	2 - 9	58.24	30.67	10.79	4.27	2.68	0.39	0.81
	2 -10	58.11	33.83	8.06	4.06	2.72	0.26	0.84
Lower shelly till, Greenock Mains, Location 6	6 - 1	58.30	36.92	4.78	3.93	2.28	0.24	0.88
	6 - 2	55.37	38.31	6.32	4.07	2.53	0.22	0.84
	6 - 3	56.82	37.35	5.83	4.03	2.50	0.21	0.91
	6 - 4	55.67	38.90	5.43	4.13	2.41	0.21	0.85
	6 - 5	54.90	39.77	5.33	4.17	2.50	0.20	0.88
	6 - 6	47.48	46.54	5.68	4.40	2.47	0.06	0.80
	6 - 7	49.98	45.43	4.59	4.16	2.41	0.07	0.83
	6 - 8	45.94	48.80	5.26	4.47	2.30	0.07	0.88
Shelly till, Merkland Burn, Location 8	8 - 1	47.77	46.55	5.68	4.33	2.41	0.10	0.88
	8 - 2	54.96	39.17	5.87	4.17	2.53	0.21	0.86
	8 - 3	54.61	40.00	5.39	4.07	2.52	0.21	0.83
	8 - 4	50.26	44.48	5.26	4.13	2.35	0.08	0.94
	8 - 6	59.80	34.87	5.33	3.90	2.46	0.18	0.89
Lower red till, Merkland Burn, Location 8	8 - 7	64.55	28.71	6.74	3.83	2.63	0.39	0.94
	8 - 8	69.46	22.91	7.63	3.60	2.55	0.38	1.11
	8 - 9	56.35	35.52	8.13	4.07	2.73	0.25	0.84
Upper red till, Merkland Burn, Location 8	8 -10	68.09	22.30	9.61	3.73	2.70	0.46	1.01

Table 10.3 (continued)

Till unit and Location	Sample number	% sand	% silt	% clay	grain-size parameters Mz	σ_I	Sk_I	K_G
Shelly till, Sorn Mains, Location 5-1	5-1 - 1	52.16	40.26	7.58	4.40	2.56	0.24	0.74
	5-1 - 2	48.10	44.89	7.01	4.47	2.47	0.12	0.83
	5-1 - 3	45.57	47.21	7.22	4.67	2.45	0.03	0.79
	5-1 - 4	45.80	44.67	9.53	4.63	2.51	0.13	0.80
	5-1 - 5	45.35	48.23	6.42	4.57	2.41	0.08	0.83
	5-1 - 6	44.89	43.45	11.66	4.80	2.67	0.10	0.78
Shelly till, Sorn Mains, Location 5-2	5-2 - 1	41.02	51.41	7.57	4.06	2.51	0.04	0.84
	5-2 - 2	46.16	47.07	6.77	4.57	2.46	0.08	0.75
	5-2 - 3	44.97	48.10	6.93	4.50	2.61	-0.01	0.74
	5-2 - 4	46.85	47.70	5.45	4.43	2.40	0.11	0.80
	5-2 - 5	39.56	55.45	4.99	4.60	2.22	0.04	0.88
Grey till, Sorn Mains, Location 5-3	5-3 - 1	43.88	48.92	7.20	4.60	2.55	-0.02	0.79
Red till, Sorn Mains, Location 5-3	5-3 - 2	47.57	45.18	7.25	4.53	2.46	0.12	0.82
Upper Grey till, Sourlie, Location 3	3 - 1	38.73	46.64	14.63	5.10	2.89	-0.19	0.82
	3 - 2	41.75	46.63	11.62	4.93	2.70	-0.04	0.78
	3 - 3	42.42	45.28	12.30	4.87	2.66	0.07	0.79
	3 - 4	46.08	43.46	10.46	4.67	2.72	0.10	0.79
	3 - 5	45.79	41.69	12.52	4.60	2.60	0.08	0.77
Lower Grey till, Sourlie, Location 3	3 - 6	49.84	40.35	9.81	4.50	2.63	0.19	0.72
	3 - 7	44.10	45.19	10.71	4.68	2.66	0.09	0.74
	3 - 8	39.66	47.07	13.27	5.00	2.74	0.06	0.78
Shelly till, Sourlie, Location 13	13 - 1	52.72	38.58	8.70	4.28	2.50	0.26	0.82
	13 - 2	54.27	37.13	8.60	4.18	2.49	0.27	0.82
	13 - 3	54.35	37.72	7.93	4.16	2.51	0.23	0.81
Upper Grey till, Sourlie, Location 13	13 - 4	38.36	44.52	17.12	5.13	2.99	-0.12	0.81
	13 - 5	34.63	49.15	16.22	5.27	2.86	-0.24	0.85
	13 - 6	37.72	44.23	18.05	5.43	2.97	-0.22	0.80

Table 10.3 (continued)

Till unit and Location	Sample number	% sand	% silt	% clay	grain-size parameters Mz	σ_I	Sk_I	K_G
Red till, Tayburn, Location 5B	5B - 1	46.65	42.37	10.98	4.43	3.00	-0.01	0.80
	5B - 2	47.16	42.20	10.64	4.37	3.00	-0.03	0.80
	5B - 3	48.88	41.12	10.00	4.30	2.98	-0.02	0.86
	5B - 4	50.01	39.61	10.38	4.13	3.00	0.08	0.84
Grey till, Tayburn, Location 5B	5B - 5	38.15	48.47	13.38	4.93	2.89	-0.12	0.80
	5B - 6	33.94	55.08	10.98	4.83	2.65	-0.04	0.86
	5B - 7	36.90	49.94	13.16	4.93	2.70	-0.09	0.85
	5B - 8	34.07	51.53	14.40	5.20	2.67	-0.19	0.83
Red till, Tayburn, Location 7B	7B - 1	37.64	46.04	16.32	4.87	3.23	-0.24	0.80
Grey till, Tayburn, Location 7B	7B - 2	35.35	47.14	17.51	5.30	2.88	-0.18	0.81
Marine clay, Afton Lodge, Location 12	12 - 1	5.63	80.07	14.30	-	-	-	-
	12 - 2	8.23	77.89	13.88	-	-	-	-
	12 - 3	10.39	75.56	14.05	-	-	-	-

Table 10.4 Till samples from Northern Ayrshire. Average percentage by weight in each grade size. Grade sizes in phi units.

Till unit and Location	sand					silt				clay
	-1 - 0ϕ	0 - 1ϕ	1 - 2ϕ	2 - 3ϕ	3 - 4ϕ	4 - 5ϕ	5 - 6ϕ	6 - 7ϕ	7 - 8ϕ	>8ϕ
Lower "shelly till", Greenock Mains, Location 2	0.23	0.42	1.12	1.89	2.43	9.52	24.85	20.90	22.85	15.80
Upper till, Greenock Mains, Location 2	3.52	6.05	13.83	20.95	13.81	7.96	6.72	6.57	11.06	9.57
Lower shelly till, Greenock Mains, Location 6	2.83	4.79	11.57	19.37	14.54	10.65	11.72	9.09	10.05	5.40
Shelly till, Merkland Burn, Location 8	3.25	4.89	11.79	19.31	14.24	12.23	10.79	8.19	9.80	5.51
Lower red till, Merkland Burn, Location 8	3.92	6.05	15.62	23.77	14.09	6.26	7.48	6.28	9.02	7.50
Upper red till, Merkland Burn, Location 8	3.54	6.71	19.02	25.90	12.92	5.18	5.86	4.66	6.60	9.61

Table 10.4 (continued)

Till unit and Location	sand					silt				clay
	-1 - 0ϕ	0 - 1ϕ	1 - 2ϕ	2 - 3ϕ	3 - 4ϕ	4 - 5ϕ	5 - 6ϕ	6 - 7ϕ	7 - 8ϕ	>8ϕ
Shelly till, Sorn Mains, Location 5-1	2.03	3.58	9.32	16.86	15.19	9.72	11.09	10.73	13.26	8.24
Shelly till, Sorn Mains, Location 5-2	2.69	3.80	9.44	15.75	12.03	14.67	12.51	9.47	13.29	6.34
Grey till, Sorn Mains, Location 5-3	3.23	4.46	9.38	14.98	11.83	10.20	14.01	11.05	13.66	7.20
Red till, Sorn Mains, Location 5-3	2.06	4.05	9.14	16.91	15.41	9.94	12.02	10.06	12.96	7.45
Upper Grey till, Sourlie, Looation 3	3.88	4.47	8.01	13.89	12.70	7.52	10.16	9.86	17.21	12.31
Lower Grey till, Sourlie, Location 3	3.15	3.61	9.48	17.43	10.86	10.07	8.94	9.10	16.10	11.26

Table 10.4 (continued)

Till unit and Location			sand					silt		clay
	-1 - 0ϕ	0 - 1ϕ	1 - 2ϕ	2 - 3ϕ	3 - 4ϕ	4 - 5ϕ	5 - 6ϕ	6 - 7ϕ	7 - 8ϕ	>8ϕ
Shelly till, Sourlie, Location 13	2.70	3.79	11.74	20.35	15.19	9.07	9.30	8.69	10.76	8.41
Upper Grey till, Sourlie, Location 13	4.46	4.76	6.86	10.90	9.92	6.08	10.13	10.93	18.98	17.13
Red till, Tayburn, Location 5B	6.77	7.33	11.05	13.62	9.42	7.85	11.46	9.61	12.41	10.50
Grey till, Tayburn, Location 5B	3.94	4.82	7.28	11.04	8.71	11.56	12.91	10.57	16.02	16.32
Red till, Tayburn, Location 7B	7.74	7.46	7.56	8.17	6.71	6.61	11.67	11.75	16.01	16.32
Grey till, Tayburn, Location 7B	3.76	4.38	7.12	11.32	8.77	6.76	12.73	11.23	16.42	17.51

Table 10.5 Till samples from Northern Ayrshire. Values of range, mean ($\overline{X}$) and standard deviation (S) of sand, silt and clay percentages of the various types of till at the different locations. N gives the number of samples.

Till unit and Location		sand	silt	clay
Lower "shelly till", Greenock Mains, Location 2	Range	1.42 - 9.34	76.45 - 81.10	14.21 - 17.48
	$\overline{X}$	6.08	78.12	15.79
	S	3.38	2.11	1.33
	N	3	3	3
Upper till, Greenock Mains, Location 2	Range	48.98 - 69.13	24.55 - 37.86	5.37 - 15.48
	$\overline{X}$	58.08	32.17	9.57
	S	7.34	4.76	3.44
	N	7	7	7
Lower shelly till, Greenock Mains, Location 6	Range	45.94 - 58.30	36.92 - 48.80	4.59 - 6.32
	$\overline{X}$	53.06	41.50	5.40
	S	4.31	4.36	0.52
	N	8	8	8
Shelly till, Merkland Burn, Location 8	Range	47.77 - 59.80	34.87 - 46.55	5.26 - 5.87
	$\overline{X}$	53.41	41.01	5.51
	S	4.25	4.12	0.23
	N	5	5	5
Lower red till, Merkland Burn, Location 8	Range	56.35 - 69.46	22.91 - 35.52	6.74 - 8.13
	$\overline{X}$	63.45	29.05	7.50
	S	5.41	5.15	0.57
	N	3	3	3
Upper red till, Merkland Burn, Location 8	N = 1	68.09	22.30	9.61
All red till at Merkland Burn, Location 8	Range	56.35 - 69.46	22.30 - 35.52	6.46 - 9.61
	$\overline{X}$	64.61	27.36	8.03
	S	5.88	6.16	1.20
	N	4	4	4

Table 10.5 (continued)

Till unit and Location		sand	silt	clay
Shelly till, Sorn Mains, Location 5-1	Range	44.89 - 52.16	40.26 - 48.23	6.42 - 11.66
	$\bar{X}$	46.98	44.79	8.24
	S	2.53	2.58	1.81
	N	6	6	6
Shelly till, Sorn Mains, Location 5-2	Range	39.56 - 46.85	47.07 - 55.45	4.99 - 7.57
	$\bar{X}$	43.71	49.95	6.34
	S	2.89	3.13	0.97
	N	5	5	5
All shelly till at Sorn Mains	Range	39.56 - 52.16	40.26 - 55.45	4.99 - 11.26
	$\bar{X}$	45.49	47.13	7.38
	S	3.31	4.02	1.84
	N	11	11	11
Grey till, Sorn Mains, Location 5-3	N = 1	43.88	48.92	7.20
Red till, Sorn Mains, Location 5-3	N = 1	47.57	45.18	7.25
Upper Grey till, Sourlie, Location 3	Range	46.08 - 48.73	41.69 - 46.64	10.46 - 14.63
	$\bar{X}$	42.95	44.74	12.31
	S	2.73	1.92	1.37
	N	5	5	5
Lower Grey till, Sourlie, Location 3	Range	39.66 - 49.84	40.35 - 47.07	9.81 - 13.27
	$\bar{X}$	44.53	44.20	11.26
	S	4.17	2.83	1.47
	N	3	3	3
Shelly till, Sourlie, Location 13	Range	52.72 - 54.35	37.13 - 38.58	7.93 - 8.70
	$\bar{X}$	53.78	37.81	8.41
	S	0.75	0.60	0.34
	N	3	3	3

Table 10.5 (continued)

Till unit and Location		sand	silt	clay
Upper Grey till, Sourlie, Location 13	Range	34.63 - 38-36	44.23 - 49.15	16.22 - 18.05
	$\bar{X}$	36.90	45.97	17.13
	S	1.63	2.25	0.75
	N	3	3	3
All Upper Grey till at Sourlie	Range	34.63 - 48.73	41.69 - 49.15	10.46 - 18.05
	$\bar{X}$	40.69	45.20	14.11
	S	4.04	2.28	2.79
	N	8	8	8
Red till, Tayburn, Location 5B	Range	46.65 - 50.01	39.61 - 42.37	10.00 - 10.98
	$\bar{X}$	48.18	31.33	10.50
	S	1.34	1.10	0.36
	N	4	4	4
Grey till, Tayburn, Location 5B	Range	33.94 - 38.15	48.47 - 55.08	10.98 - 14.40
	$\bar{X}$	35.77	51.26	12.98
	S	1.82	2.46	1.25
	N	4	4	4
Red till, Tayburn, Location 7B	N = 1	37.64	46.04	16.32
Grey till, Tayburn, Location 7B	N = 1	35.35	47.14	17.51
All red till at Tayburn	Range	37.64 - 50.01	39.61 - 46.04	10.00 - 16.32
	$\bar{X}$	46.07	42.27	11.66
	S	4.89	2.38	2.63
	N	5	5	5
All grey till at Tayburn	Range	33.94 - 38.15	47.14 - 55.08	10.98 - 17.51
	$\bar{X}$	35.68	50.43	13.89
	S	1.82	3.07	2.37
	N	5	5	5

Table 10.5 (continued)

Till unit and Location		sand	silt	clay
All shelly till except "shelly till" at Greenock Mains, Location 2	Range	39.56 - 59.80	34.87 - 55.45	4.59 - 11.66
	$\bar{X}$	50.13	43.29	6.56
	S	5.36	5.20	1.65
	N	27	27	27
Marine clay, Afton Lodge, Location 12	Range	5.63 - 10.39	75.56 - 80.07	13.88 - 14.30
	$\bar{X}$	8.08	77.84	14.08
	S	2.38	2.26	0.21
	N	3	3	3

Table 10.6 Till samples from Northern Ayrshire. Values of range (R), mean ($\overline{X}$) and standard deviation (S) of grain-size parameters of the various types of till at the different locations. N gives the number of samples.

Till unit and Location		Mz	σ_I	Sk_I	K_G
Lower "shelly till", Greenock Mains, Location 2	R	6.17 - 7.67	1.51 - 1.82	0.02 - 0.25	1.01 - 1.31
	$\overline{X}$	0.78	1.70	0.10	1.17
	S	0.79	0.17	0.13	0.15
	N	3	3	3	3
Upper till, Greenock Mains, Location 2	R	3.67 - 4.56	2.53 - 3.02	0.17 - 0.39	0.72 - 1.02
	$\overline{X}$	4.14	2.71	0.29	0.84
	S	0.35	0.16	0.09	0.10
	N	7	7	7	7
Lower shelly till, Greenock Mains, Location 6	R	3.93 - 4.47	2.28 - 2.53	0.06 - 0.24	0.80 - 0.91
	$\overline{X}$	4.17	2.43	0.16	0.86
	S	0.18	0.09	0.08	0.03
	N	8	8	8	8
Shelly till, Merkland Burn, Location 8	R	3.90 - 4.33	2.35 - 2.53	0.08 - 0.21	0.83 - 0.94
	$\overline{X}$	4.12	2.45	0.16	0.88
	S	0.16	0.08	0.06	0.04
	N	5	5	5	5
Lower red till, Merkland Burn, Location 8	R	3.60 - 4.07	2.55 - 2.73	0.25 - 0.39	0.84 - 1.11
	$\overline{X}$	3.83	2.64	0.34	0.96
	S	0.24	0.09	0.08	0.14
	N	3	3	3	3
Upper red till, Merkland Burn, Location 8	N = 1	3.73	2.70	0.46	1.01
All red till at Merkland Burn, Location 8	R	3.60 - 4.07	2.55 - 2.73	0.25 - 0.46	0.84 - 1.11
	$\overline{X}$	3.81	2.65	0.37	0.98
	S	0.20	0.08	0.09	0.11
	N	4	4	4	4

Table 10.6 (continued)

Till unit and Location		Mz	σ_I	Sk_I	K_G
Shelly till, Sorn Mains, Location 5-1	R	4.40 - 4.80	2.41 - 2.67	0.03 - 0.24	0.74 - 0.83
	$\bar{X}$	4.59	2.51	0.12	0.80
	S	0.14	0.09	0.07	0.03
	N	6	6	6	6
Shelly till, Sorn Mains, Location 5-2	R	4.43 - 4.60	2.22 - 2.61	-0.01 - 0.11	0.74 - 0.88
	$\bar{X}$	4.54	2.44	0.05	0.80
	S	0.07	0.15	0.05	0.06
	N	5	5	5	5
All shelly till at Sorn Mains	R	4.40 - 4.80	2.22 - 2.67	-0.01 - 0.24	0.74 - 0.88
	$\bar{X}$	4.57	2.48	0.09	0.80
	S	0.11	0.12	0.07	0.04
	N	11	11	11	11
Grey till, Sorn Mains, Location 5-3	N = 1	4.60	2.55	-0.02	0.79
Red till, Sorn Mains, Location 5-3	N = 1	4.53	2.46	0.12	0.82
Upper Grey till, Sourlie, Location 3	R	4.60 - 5.10	2.60 - 2.89	-0.19 - 0.10	0.77 - 0.82
	$\bar{X}$	4.83	2.71	0.01	0.79
	S	0.20	0.11	0.12	0.02
	N	5	5	5	5
Lower Grey till, Sourlie, Location 3	R	4.50 - 5.00	2.63 - 2.74	0.06 - 0.19	0.72 - 0.78
	$\bar{X}$	4.73	2.68	0.11	0.75
	S	0.25	0.06	0.07	0.03
	N	3	3	3	3
Shelly till, Sourlie, Location 13	R	4.16 - 4.28	2.49 - 2.51	0.23 - 0.27	0.81 - 0.82
	$\bar{X}$	4.21	2.50	0.25	0.82
	S	0.06	0.01	0.02	0.01
	N	3	3	3	3

Table 10.6 (continued)

Till unit and Location		Mz	σ_I	Sk_I	K_G
Upper Grey till, Sourlie, Location 13	R	5.13 - 5.43	2.86 - 2.99	-0.24 - -0.12	0.80 - 0.85
	$\overline{X}$	5.28	2.94	-0.19	0.82
	S	0.15	0.07	0.06	0.03
	N	3	3	3	3
All Upper Grey till at Sourlie	R	4.60 - 5.43	2.60 - 2.99	-0.24 - 0.01	0.77 - 0.85
	$\overline{X}$	5.00	2.80	-0.07	0.80
	S	0.29	0.15	0.14	0.02
	N	8	8	8	8
Red till, Tayburn, Location 5B	R	4.13 - 4.43	2.98 - 3.00	-0.03 - 0.08	0.80 - 0.86
	$\overline{X}$	4.31	3.00	0.01	0.83
	S	0.13	0.01	0.05	0.03
	N	4	4	4	4
Grey till, Tayburn, Location 5B	R	4.83 - 5.20	2.65 - 2.89	-0.19 - -0.04	0.80 - 0.86
	$\overline{X}$	4.97	2.73	-0.11	0.84
	S	0.16	0.11	0.06	0.03
	N	4	4	4	4
Red till, Tayburn, Location 7B	N = 1	4.87	3.23	-0.24	0.80
Grey till, Tayburn, Location 7B	N = 1	5.30	2.88	-0.18	0.81
All red till at Tayburn	R	4.13 - 4.87	2.98 - 3.23	-0.24 - 0.08	0.80 - 0.86
	$\overline{X}$	4.42	3.04	-0.04	0.82
	S	0.28	0.11	0.12	0.03
	N	5	5	5	5
All grey till at Tayburn	R	4.83 - 5.20	2.65 - 2.89	-0.19 - -0.04	0.77 - 0.85
	$\overline{X}$	5.04	2.76	-0.12	0.83
	S	0.20	0.12	0.06	0.03
	N	5	5	5	5

Table 10.6 (continued)

Till unit and Location		Mz	σ_I	Sk_I	K_G
All shelly till except "shelly till" at Greenock Mains, Location 2	R	3.90 - 4.80	2.22 - 2.67	-0.01 - 0.27	0.74 - 0.94
	$\bar{X}$	4.32	2.46	0.14	0.83
	S	0.24	0.10	0.08	0.05
	N	27	27	27	27

CHAPTER 11

CLAY MINERALOGY OF TILLS OF NORTHERN AYRSHIRE

11.1 Introduction and previous research

During the last three decades there has been an increase in the laboratory treatment of tills. More attention has been given to the composition of the clay fraction (<2 µm) as revealed by X-ray analysis (e.g. recently: Snäll *et al*. 1979; Melkerud 1984; Snäll 1986). Most authors, however, have studied mineral alteration during weathering rather than the characteristics of unleached tills.

Research on Antarctic soils (Blakemore & Swindale 1958) and on soils developed on Scottish drift deposits (Wilson *et al*. 1984) gives useful clay mineral data, and work relevant to the present study has also been carried out on the mineralogy of modern sediments in Europe and North America (Packham *et al*. 1961; Potter *et al*. 1975). Previous work on the clay mineralogy of tills in Britain has been presented by Perrin (1957), Glentworth *et al*. (1964), Beaumont (1971) and Madgett & Catt (1978), but none has been documented from Northern Aryshire.

Work specifically on the clay mineralogy of Ayrshire soils is limited (Mitchell & Mitchell 1956), but more extensive work has been presented on the clay mineralogy of the soils and bedrocks of Scotland as a whole (Walker 1947, 1948, 1950; Wilson, 1967, 1973, 1976; Wilson & Bain 1970; Bain 1977a, 1977b; Bain & Russell 1981; Wilson *et al*. 1981, 1984).

The general objectives of this chapter are to determine and record the clay mineral content of the sampled Quaternary deposits of

Northern Ayrshire and to observe and account for the distribution of the clay minerals. More specific objectives are to examine the clay mineralogy of the deposits in relation to Aims 8 to 12 of the research project (Chapter 4.1.2). For this reason, following presentation of the data and of the methods used in their interpretation (section 11.2 of the text below), discussion of the results is arranged on a thematic basis; little attempt is made to discuss individual sites.

11.2 Data and interpretation

Using XRD, it is possible to identify and semi-quantitatively assess the amounts of clay minerals present in the samples that were examined. The identified clay minerals include illite, kaolinite, montmorillonite, chlorite and less frequently vermiculite (Table 11.1). The term montmorillonite as used here includes all clay material that expands to 17 Å with ethylene glycol. Mixed-layer vermiculite-montmorillonite and illite-montmorillonite are included with montmorillonite.

The clay minerals are identified and their proportions assessed as described in Chapter 6.4.

14 Å peak

In all samples, a peak due to montmorillonite and/or chlorite and vermiculite occurs at about 14 Å. The position, intensity and sharpness of this peak is quite variable and reacts differently to ethylene glycol and heat treatment. In some samples the peak is sharp and has only moderate intensity, while in others it is broad and more intense. The more intense and broad the peak is in the air-dried "untreated" sample, the more the peak is affected by glycolation and the more the peak is lost after heating to 450°C. In most samples the glycolation treatment results in the appearance of separate peaks at 17 Å and 14 Å, showing the presence of expanding and non-expanding phases respectively. Heating at 450°C completely shifts the 17Å peak to 10Å and intensifies that peak at 10 Å. The 14 Å peak is usually unaffected by heating to 450°C. These results suggest the presence of montmorillonite (expanding and thermally unstable) and chlorite (non-expanding and thermally stable). In some samples, the 14 Å peak collapsed completely after heating at 450°C and shifted to the 10 Å peak, indicating the presence of vermiculite (non-expanding and thermally unstable).

Most samples contain both montmorillonite and chlorite, some contain montmorillonite only and, in rare samples, combinations of montmorillonite, chlorite and vermiculite or of chlorite and vermiculite are present.

10 Å peak

A 10 Å peak is present in every sample, indicating the presence of illite. The intensity and sharpness of this peak is quite variable. In some samples, the 10 Å peak is symmetrical and unaffected by ethylene glycol or by heat treatment, while in others the 10 Å peak of the air-dried sample is asymmetrical on the "high" side of the peak. The loss of this asymmetry after glycolation and heating to 450°C indicates that some of the illite is hydrated and mixed-layer illite-montmorillonite is developing.

7 Å peak

A sharp, intense 7 Å peak is recorded in all samples, indicating the presence of kaolinite. The problem of the identification of kaolinite in the presence of chlorite arises here in the case of samples containing the two minerals. HCl-treated samples were made in order to examine whether the 7 Å peak is attributable to kaolinite, or to chlorite, or to both minerals. It is not difficult to demonstrate the presence of kaolinite when chlorite is present. In the samples containing both kaolinite and chlorite, following heating to 450°C, the intensity of the 14 Å peak remains after heating, showing the presence of chlorite. Any diffraction effect noted at the 7 Å and 3.5 Å peaks can be attributed to kaolinite only, since the higher orders of chlorite are lost upon heating to 450°C (Johns et al. 1954).

10-14 Å peak

A broad diffraction peak in the region of 10 to 14 Å is recorded occasionally in some samples, indicating the presence of mixed-layer minerals. The changes of X-ray patterns after ethylene glycol treatment and heating at 450°C show that a swelling component (montmorillonite) is present in the interstratified minerals. After glycolation, the mixed-layer has a diffuse peak at about 17 Å. This peak collapses completely, to 10 Å reflection, after heating to 450°C.

11.3 Clay mineralogy of the shelly till of Northern Ayrshire

11.3.1 Clay mineralogy of the shelly till at individual Locations and Northern Ayrshire as a whole.

At Greenock Mains, Location 6, eight samples of shelly till were examined (Table 11.1). Kaolinite and illite are the dominant minerals (averages 47.1% and 31.3% respectively), with minor amounts of chlorite and montmorillonite (7.6% and 8.3%) and occasional vermiculite (5.8%).

At Merkland Burn, Location 8, five samples of shelly till indicated that the till matrix is dominated by kaolinite (35.4%) and illite (29.9%), with a subordinate amount of chlorite (21.7%) and minor amount of montmorillonite (13.0%).

The shelly till at Sorn Mains shows an almost identical clay mineralogy at Locations 5-1 and 5-2. The main clay minerals present are kaolinite and illite (36.0% and 34.3%), with subordinate amounts of chlorite (18.0%) and minor amounts of montmorillonite (10.1%).

At Sourlie, Location 13, the shelly till is dominated by kaolinite and illite (39.9% and 29.0%), with subordinate amounts of chlorite and montmorillonite (19.2% and 11.2%). The clay mineralogy of the shelly till at Sourlie therefore closely resembles that of the shelly till at other sites where samples were collected, although Sourlie is located c. 30km to the north-west of the other sites.

Quantitatively, it can be stated that kaolinite is the dominant clay mineral in the shelly till samples, the quantity present probably varying from c. 30% to 54%. Illite is the mineral of second importance in terms of percentage (c. 25% to 39%), all of it being of trioctahedral types ($I_{(002)}/I_{(002)}>5$), and it shows different degrees of hydration. Chlorite content varies between c. 8% and 34%, and montmorillonite content between 4.7% and 18.5%. Vermiculite occurs only occasionally, in two samples at Greenock Mains, Location 6, and one at Sorn Mains, Location 5-1 (Table 11.1). The diffuse nature and the asymmetry of a number of the 10 Å peaks suggest the presence of at least small quantities of mixed-layer clay minerals.

In summary, the shelly till examined from five different Locations (four Sites) in Northern Ayrshire (Figs. 11.1 and 11.2) shows a uniform clay mineral composition.

11.3.2 The two tills at Tayburn and at Sorn Mains, Location 5-3, in comparison with the shelly till of N Ayrshire as a whole

The (upper) grey till at the two Tayburn Locations, 5B and 7B (Fig. 11.3), is characterised by the presence of considerable amounts of kaolinite (average 51.9%), with subordinate amounts of illite (18.2%) and minor amounts of chlorite (6.3%). Vermiculite and montmorillonite occur occasionally, the latter mainly as mixed-layer with illite.

In striking contrast, the clay fraction of the (lower) red till at Tayburn (Fig. 11.4) is dominated by the presence of montmorillonite (67.9%) to a degree not seen in the other Northern Ayrshire tills. Kaolinite and illite occur in subordinate amounts (19.7% and 12.6%).

Clearly, on the evidence of clay mineralogy, only the (upper) grey till, of the two tills at Tayburn, could be the possible equivalent of the shelly till of other parts of Northern Ayrshire.

The clay mineral contents of the (upper) grey till and (lower) red till at Sorn Mains, Location 5-3 (Fig.11.5), are remarkably similar depite the contrast in colour between the tills. Kaolinite is dominant (67.6% and 64.1% respectively), with subordinate amounts of illite (27.0% and 25.6%) and minor amounts of montmorillonite (5.4% and 10.3%). No chlorite was detected. On this evidence, neither the grey till nor the red till of Location 5-3 is likely to be the equivalent of the shelly till at Locations 5-1 and 5-2 of the same Site (Sorn Mains) or of N Ayrshire as a whole.

11.4 Comparison of the Upper and Lower grey tills at Sourlie

The Upper grey till at Sourlie (Fig. 11.6) is characterised by the presence of considerable quantities of kaolinite and illite (averages 39.4% and 26.9%), with subordinate amounts of chlorite and montmorillonite (18.2% and 15.5%).

The clay fraction of the Lower grey till (Fig. 11.6) is mostly kaolinite (average 56.4%), with subordinate amounts of illite (25.2%) and minor amounts of chlorite and montmorillonite (13.9% and 4.6%).

There appear to be only minor differences in the clay mineralogy of the Upper and Lower grey tills at Sourlie; kaolinite occurs in greater proportion in the Lower, and montmorillonite in greater proportion in the Upper till.

11.5 Changes through vertical profiles

Changes through vertical profiles in the tills of Northern Ayrshire are more complex than those in the tills of the NW Glasgow area, mainly because the clay mineral assemblage of the N Ayrshire tills includes montmorillonite and mixed-layer illite-montmorillonite and vermiculite-montmorillonite in addition to the clay minerals present in the tills of both areas. Briefly, the processes thought to be involved in weathering of the N Ayrshire tills, comparable to those noted in northern Vermont by Cannon (1964) and in Illinois by Willman et al. (1966), are as follows.

The alteration of illite and chlorite by weathering eventually produces expandable clay mineral types (montmorillonite). Chlorite alters to vermiculite and, with more intense weathering, the vermiculite expands to intermediate mixed-layer minerals (vermiculite-montmorillonite). With sufficient intensity of weathering, swelling montmorillonite occurs. Alteration of illite proceeds through a mixed-layer stage (illite-montmorillonite) to montmorillonite. Illite may alter to non-expandable vermiculite. Weathering of vermiculite derived from illite will produce mixed-layer material vermiculite-montmorillonite and, with sufficient alteration, this material also weathers to what is called montmorillonite.

In the Upper till at Greenock Mains, Location 2 (Fig. 11.7), alteration of illite was detected to depths as great as 3m below the top. Weathering of the clay minerals commenced with a decrease in the amount of illite and the replacement of illite by expandable clay minerals (montmorillonite and mixed-layer). The intensity of the 14 Å peak was found to have increased relative to that of the 10 Å peak upwards through the profile.

In the shelly till at Greenock Mains, Location 6 (Fig. 11.8), weathering starts as deep as 5m below the top of the till. The lowermost two samples (6-8 and 6-7) contain chlorite and vermiculite. Upwards through the profile, samples 6-6 to 6-3 show decrease of chlorite and the formation of mixed-layers of illite-montmorillonite and vermiculite-montmorillonite. Higher in the profile, chlorite completely disappears and only montmorillonite is present in the 14 Å reflection. The 10 Å peak becomes much more asymmetrical upwards, indicating that more expandable material is present in the mixed-layers of illite-montmorillonite.

Weathering trends are present in the shelly till at Sorn Mains, Location 5-1 (Fig. 11.9). The 14 Å reflection is found to have increased upwards relative to that of the 10 Å peak, and chlorite disappears in the uppermost sample and is replaced by vermiculite, presumably an indication of vermiculitization.

In the Upper grey till at Sourlie, Location 3 (Fig. 11.10), the tendency of montmorillonite to increase upwards through the profile at the expense of illite and chlorite is not clear. However, a slight increase in the asymmetry of the 10 Å peak is obvious, indicating that illite is hydrated and mixed-layer illite-montmorillonite has developed towards the top of the profile.

The tendency for montmorillonite and mixed-layer illite-montmorillonite to increase at the expense of illite and chlorite is obvious upwards through the Lower grey till profile at Sourlie, Location 3 (Fig. 11.11) and through the shelly till profile at Sourlie, Location 13 (Fig. 11.12). A slight increase in the asymmetry of the 10 Å peak upwards is also recorded in both profiles.

The weathering trends are very clear in the (upper) grey till at Tayburn, Location 5B (Table 11.2 and Fig. 11.3). The disappearance of chlorite and the degradation of illite, together with vermiculitization and interlayering of illite and montmorillonite, increase progressively up the profile.

11.6 Weathering of the clay minerals

The effects of weathering on clay minerals are thought to be confined to vermiculitization of illite and chlorite. However, montmorillonite and mixed-layer minerals may be inherited to a small extent. Their increasing abundance upwards in some of the profiles studied in N Ayrshire strongly suggests that they have resulted from the decomposition of illite, chlorite and, occasionally, vermiculite. The occurrence of montmorillonite or swelling clay minerals in soil profiles developed on tills has been reported by several authors, e.g. Brady et al. (1963), Wiklander & Aleksandrovic (1969) and Provan et al. (1969), and these minerals have been interpreted as pedogenically formed secondary minerals. The weathering processes involved have transformed primary rock-forming minerals and micas relatively rapidly to montmorillonite as depicted below (Droste 1956; Gjems 1960, 1963, 1967 and 1970; Smeck et al. 1968; Wilding et al. 1971):

1) Mica --> illite --> vermiculite --> montmorillonite.
2) Ferromagnesian minerals --> chlorite --> vermiculite --> montmorillonite

11.7 The Lower "shelly till" of Greenock Mains, Location 2, in relation to other Quaternary deposits

The clay fraction of the "shelly till" at Greenock Mains, Location 2 (Fig.11.13), is dominated by illite (average 45.6%) and kaolinite

(27.5%). Chlorite and montmorillonite occur in subordinate amounts (14.7% and 12.1%). In terms of clay mineral assemblages, this shell-bearing deposit therefore resembles the average shelly till of Northern Ayrshire (Table 11.1), although the proportions, especially of kaolinite and illite, differ between the two deposits.

For purposes of comparison, the marine clays from Afton Lodge were analysed (Fig. 11.13). The X-ray diffraction traces for these clays are almost identical to those of the shell-bearing deposit at Greenock Mains, Location 2. In terms of clay mineralogy, in the Afton Lodge samples, illite (40.1%) is dominant, followed by kaolinite (34.3%), with subordinate chlorite (15.8%) and minor amounts of montmorillonite (9.7%).

11.8 The non-shelly tills at Greenock Mains and Merkland Burn

The non-shelly tills at Greenock Mains, Location 2, and Merkland Burn, Location 8, show a fair degree of resemblance in their clay mineral content (Table 11.1). Kaolinite (average of 7 samples, 58.0%) is dominant in the Upper till at Greenock Mains, illite (33.2%) being subordinate and montmorillonite (8.7%) of minor occurrence. No chlorite was detected. In the Upper red till at Merkland Burn, unfortunately represented by only one analysed sample, kaolinite again is dominant (49.4%), illite (30.7%) being subordinate, montmorillonite (19.9%) less plentiful and chlorite absent. In the Lower red till at Merkland Burn (3 samples), illite (48.1%) is more plentiful than kaolinite (39.8%), while montmorillonite (11.7%) is much less plentiful and chlorite is absent. These results suggest that the Upper till at Greenock Mains and the Upper red till at Merkland Burn may be correlatable, and that the source of these two tills may have been similar to that of the Lower red till at Merkland Burn (which is separated from the Upper red till at that Location by c. 6.5m of shelly till).

11.9 Conclusions

The results of clay mineralogical analysis presented above suggest the following:

1) The clay mineralogy of the shelly till at five Locations (four Sites) - Greenock Mains, Location 6; Merkland Burn, Location 8; Sorn Mains, Locations 5-1 and 5-2; Sourlie, Location 13 - is extremely similar, showing only minor variations in the proportions of kaolinite and illite (which are dominant), and chlorite and montmorillonite.
2) The (lower) red till at Tayburn differs markedly from all the other tills in its very high content of montmorillonite.
3) It is possible that the (upper) grey till at Tayburn is the equivalent of the shelly till at other sites in N Ayrshire, but it is most unlikely that the red till at Tayburn, and both the grey till and red till at Sorn Mains, Location 5-3, are equivalent to the shelly till.
4) Several of the till profiles show weathering of clay minerals progressively upwards through the profile. Illite and chlorite and, occasionally, vermiculite show alteration to montmorillonite and mixed-layer clay minerals.
5) The clay mineral assemblages of the Lower "shelly till" at Greenock Mains, Location 2, and of the marine clays at Afton Lodge are closely similar.
6) The clay mineralogy of the Upper till at Greenock Mains, Location 2, is closely similar to that of the Upper red till at Merkland Burn, Location 8, and there are only minor differences between the clay mineralogy of each of these till units and that of the Lower red till at Merkland Burn, Location 8.

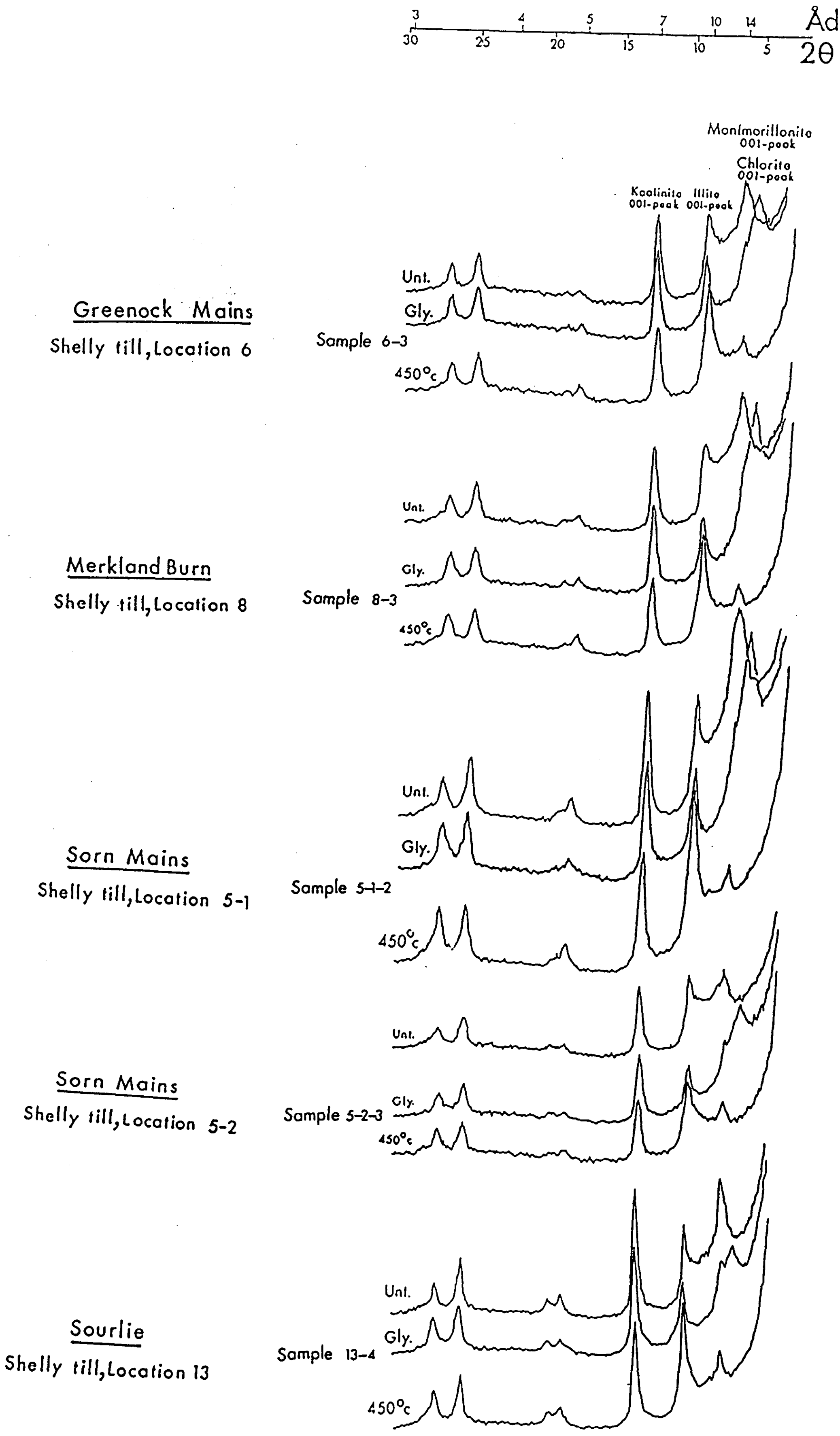


Figure 11.1 Selected X-ray diffractograms for oriented samples of the clay fraction (<2 µm) of the shelly till from locations in Northern Ayrshire.

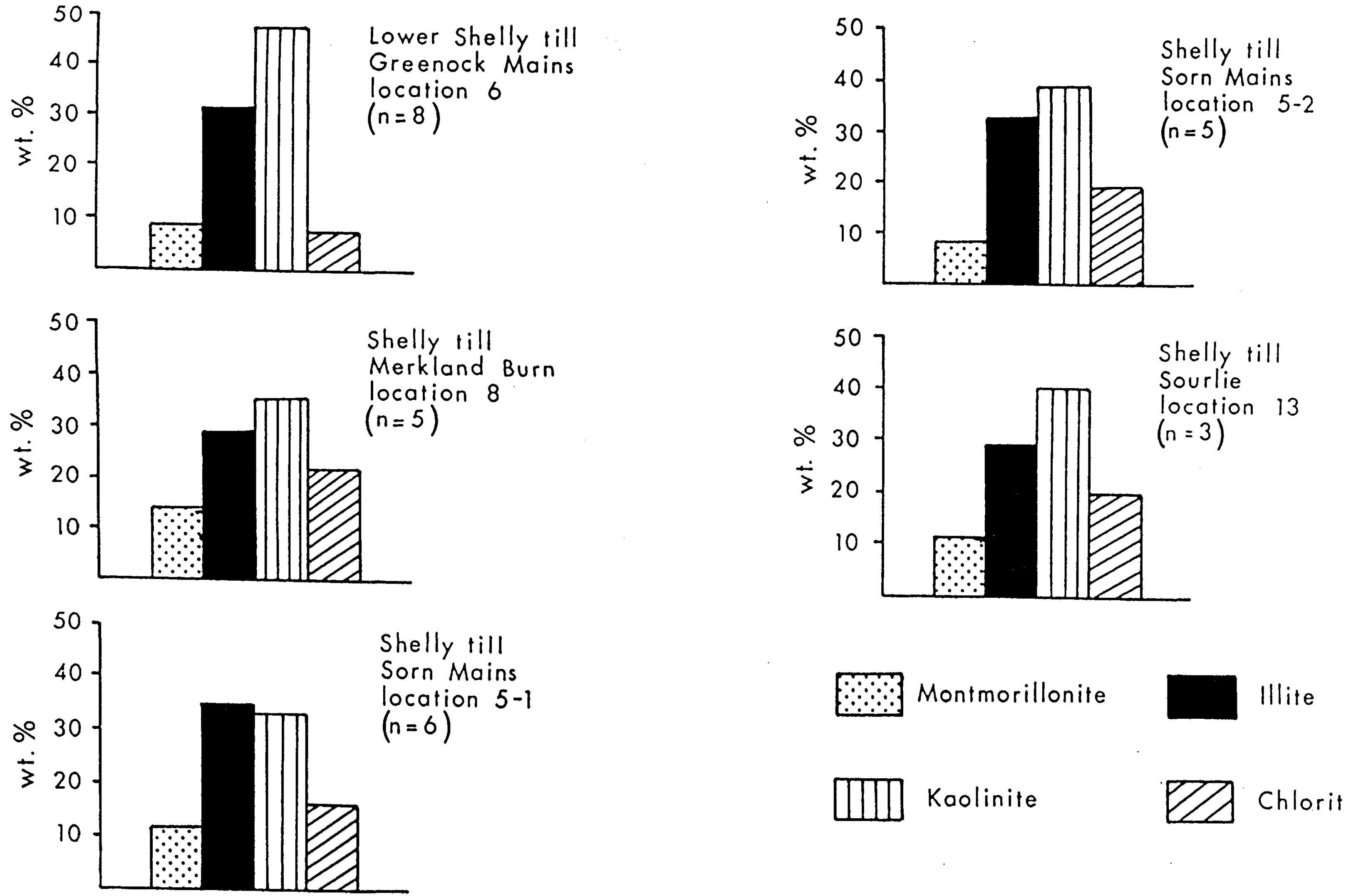


Figure 11.2 Average distribution of clay minerals in the clay fraction (<2 µm) of the shelly till from locations in Northern Ayrshire.

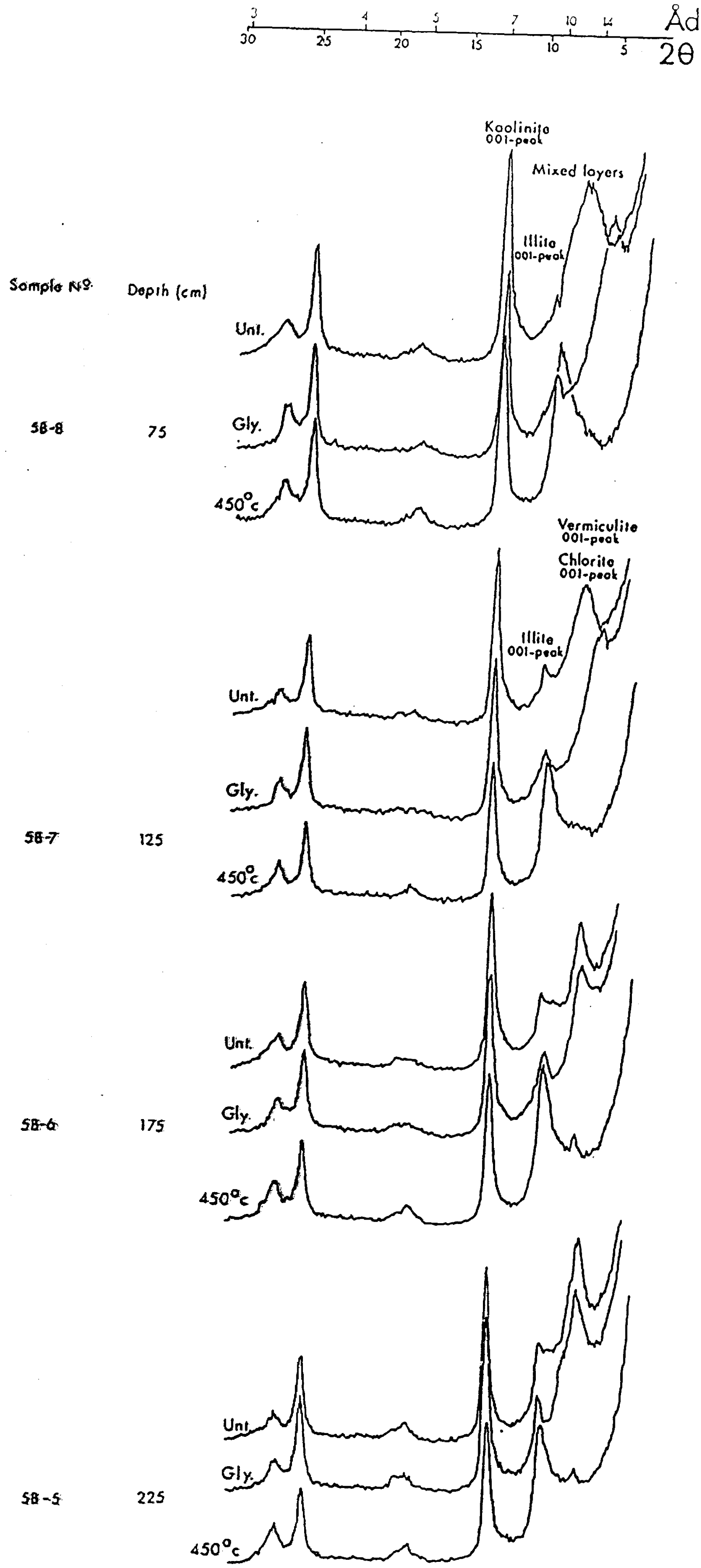


Figure 11.3 XRD diffractograms for oriented samples of the clay fraction (<2 µm) separated from the grey till at Tayburn, Location 5B, at various depth levels below ground surface.

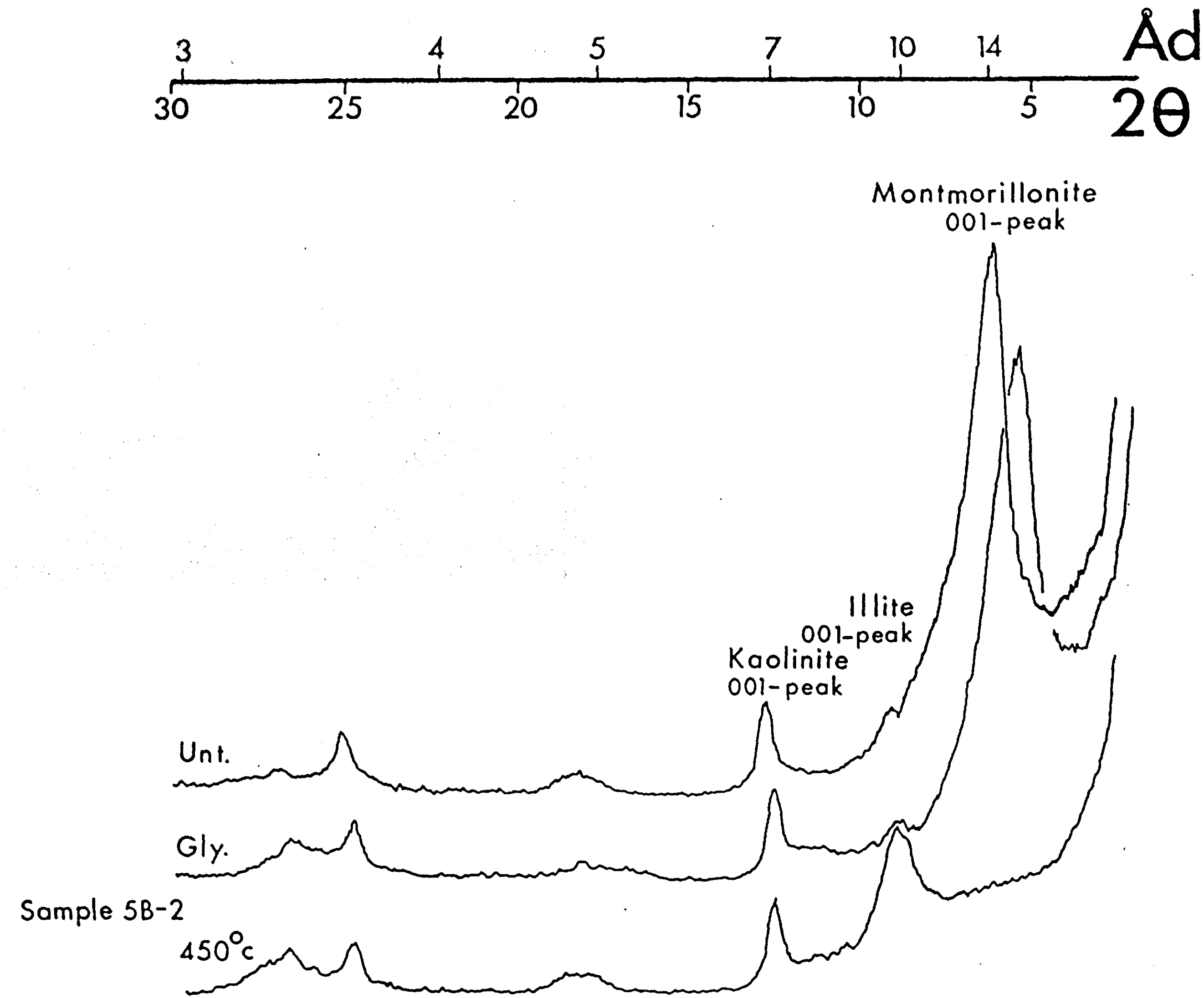
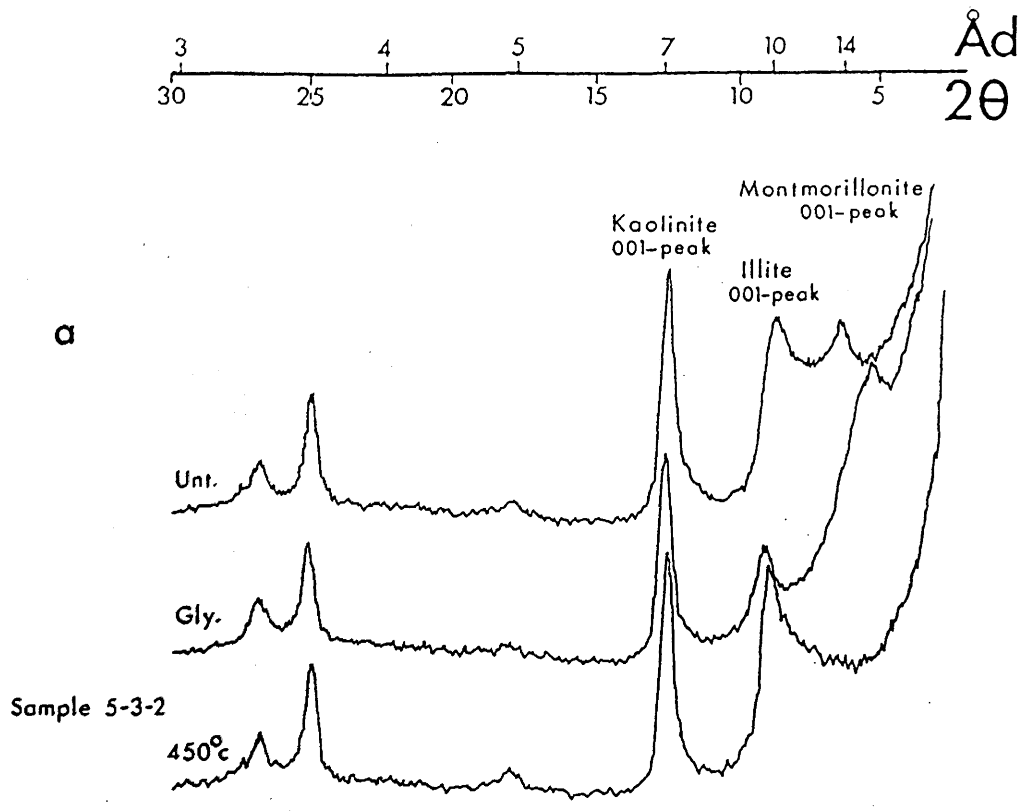


Figure 11.4 X-ray diffractograms for an oriented sample of the clay fraction (<2 µm) from the red till at Tayburn, Location 5B.



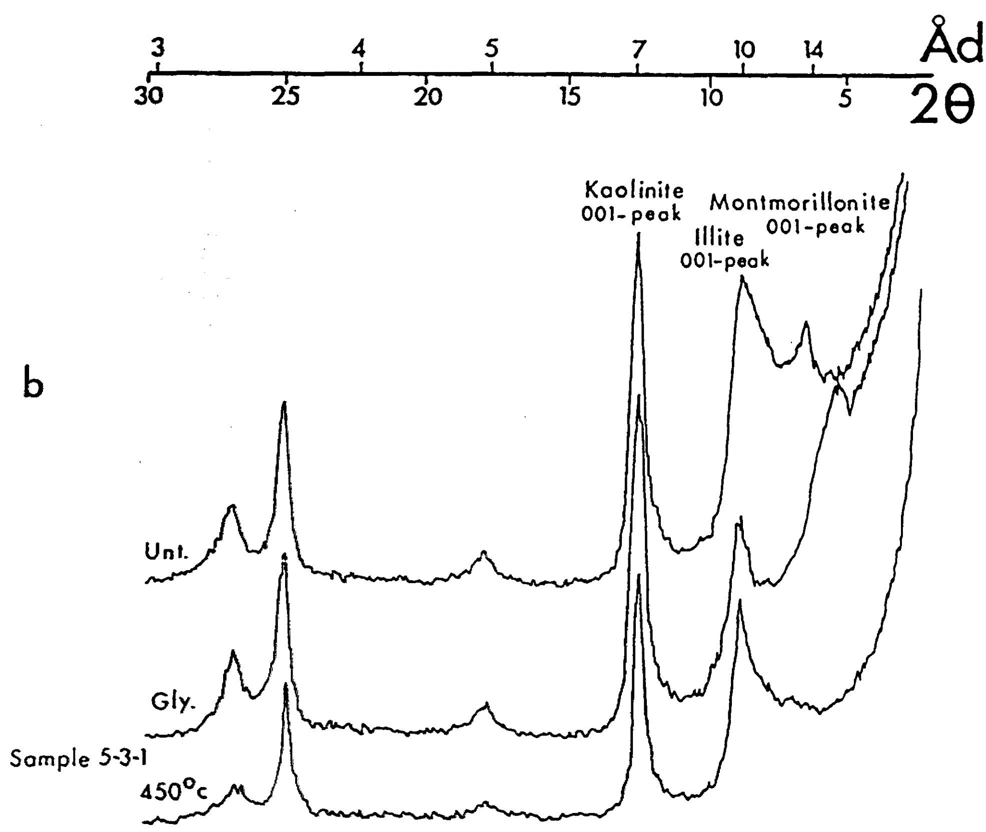


Figure 11.5 XRD diffractograms for oriented samples of the clay fraction (<2 μm):

a grey till at Sorn Mains, Location 5-3

b red till at Sorn Mains, Location 5-3

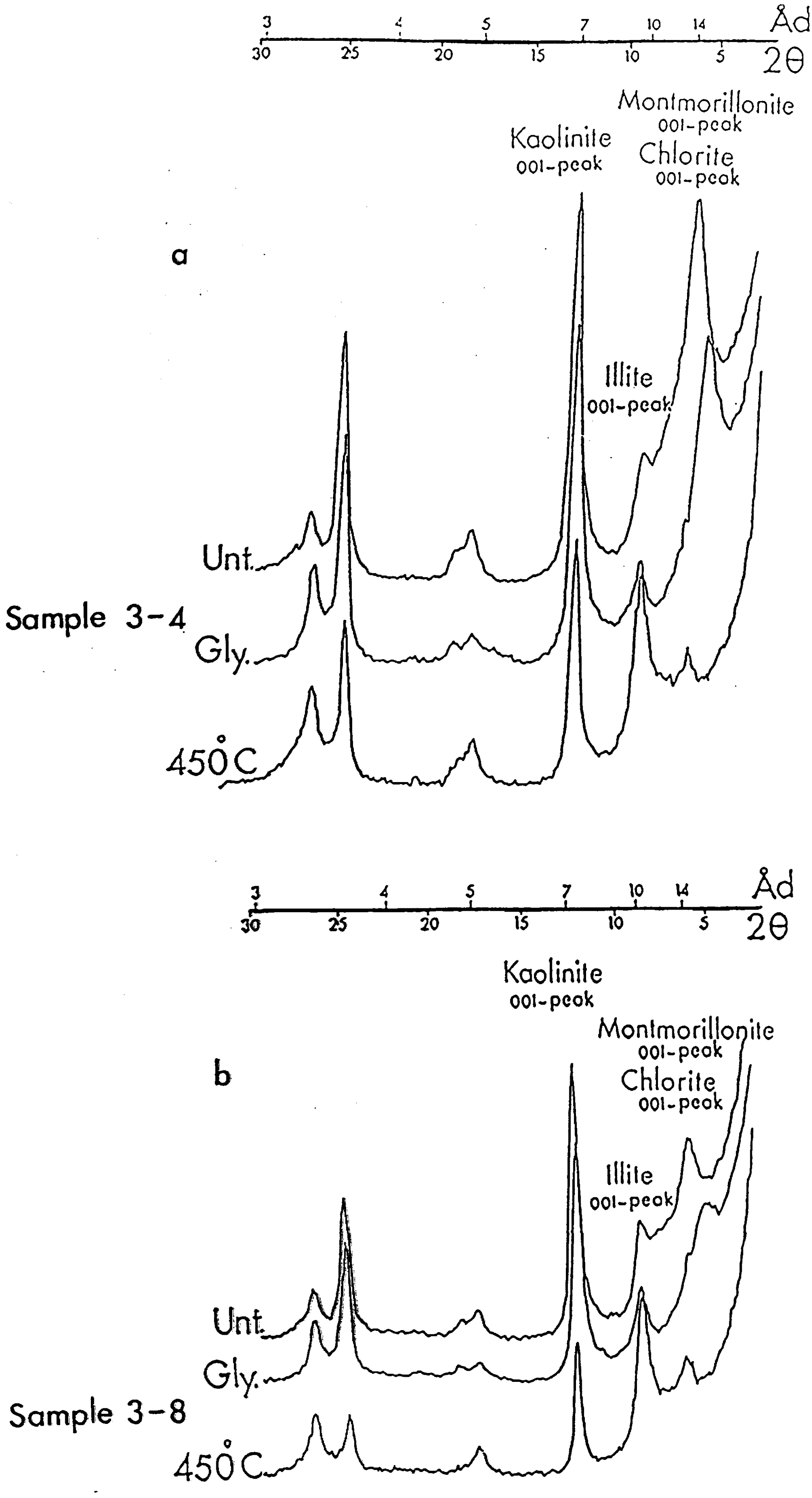


Figure 11.6 XRD diffractograms for oriented samples of the clay fraction (<2 µm):

a Upper grey till at Sourlie, Location 3

b Lower grey till at Sourlie, Location 3

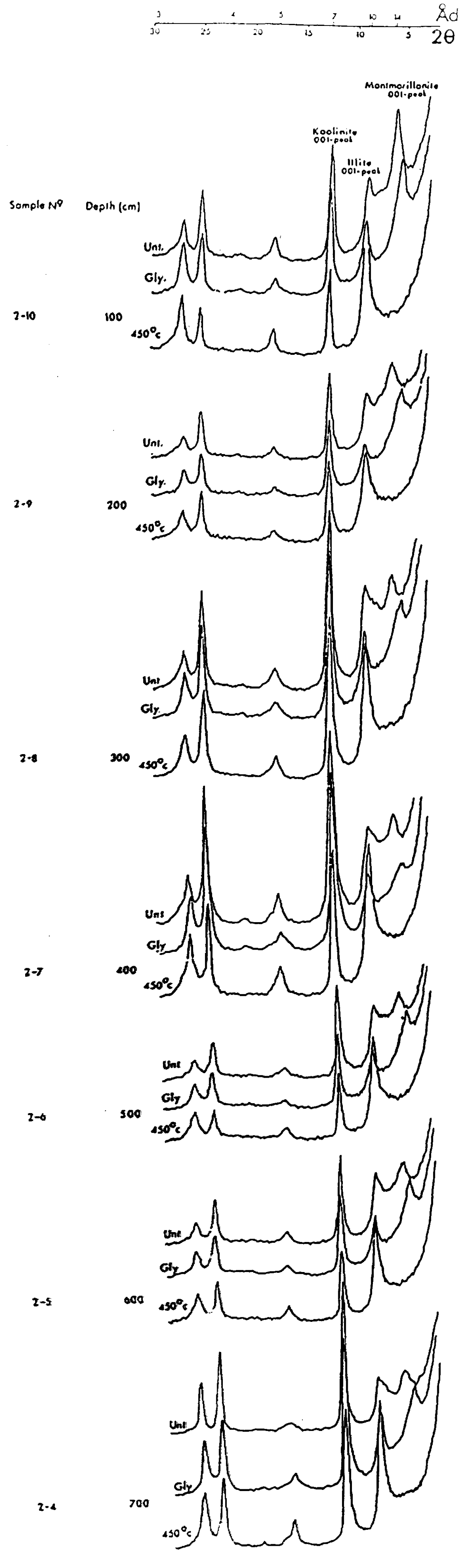


Figure 11.7 XRD diffractograms for oriented samples of the clay fraction (<2 µm) separated from the Upper till at Greenock Mains, Location 2, at various depth levels below ground surface.

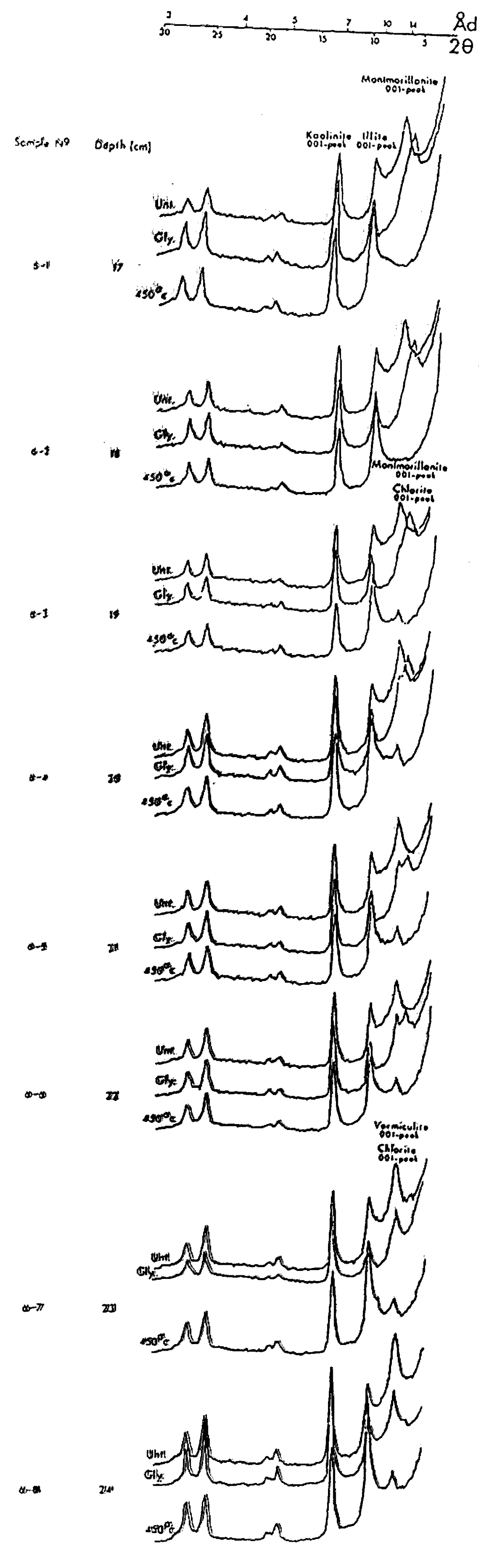


Figure 11.8 XRD diffractograms for oriented samples of the clay fraction (<2 μm) separated from the shelly till at Greenock Mains, Location 6, at various depth levels below ground surface.

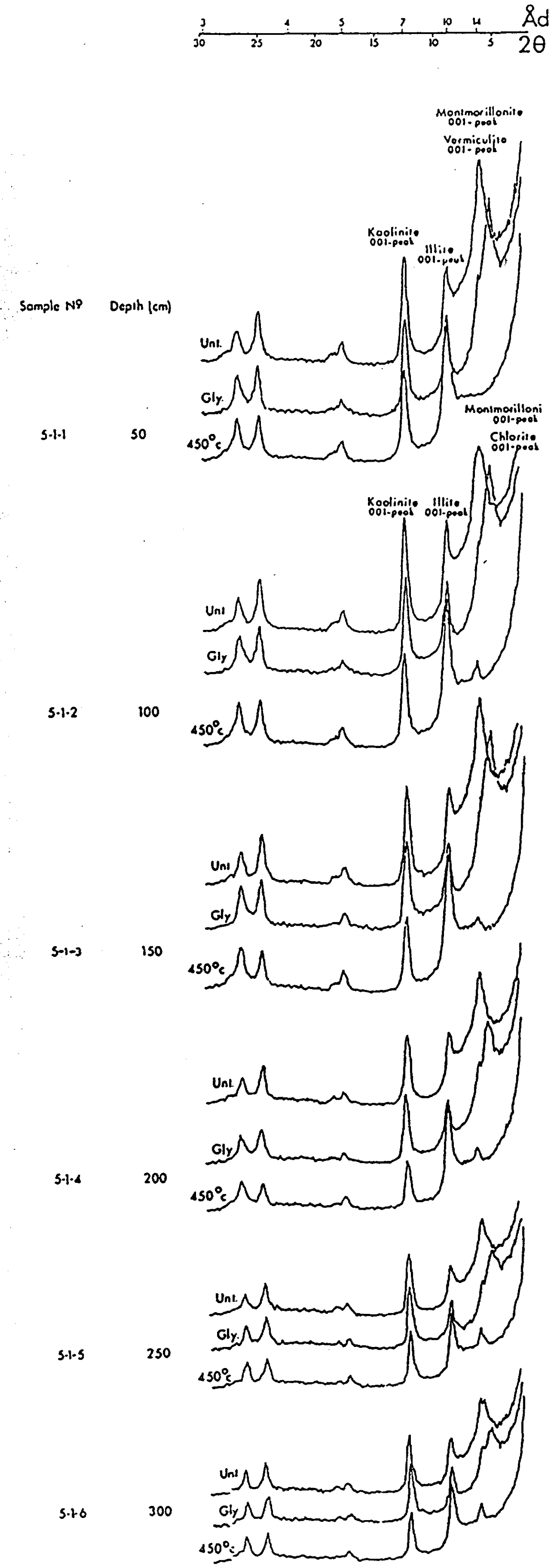


Figure 11.9 XRD diffractograms for oriented samples of the clay fraction (<2 µm) separated from the shelly till at Sorn Mains, Location 5-1, at various depth levels below ground surface.

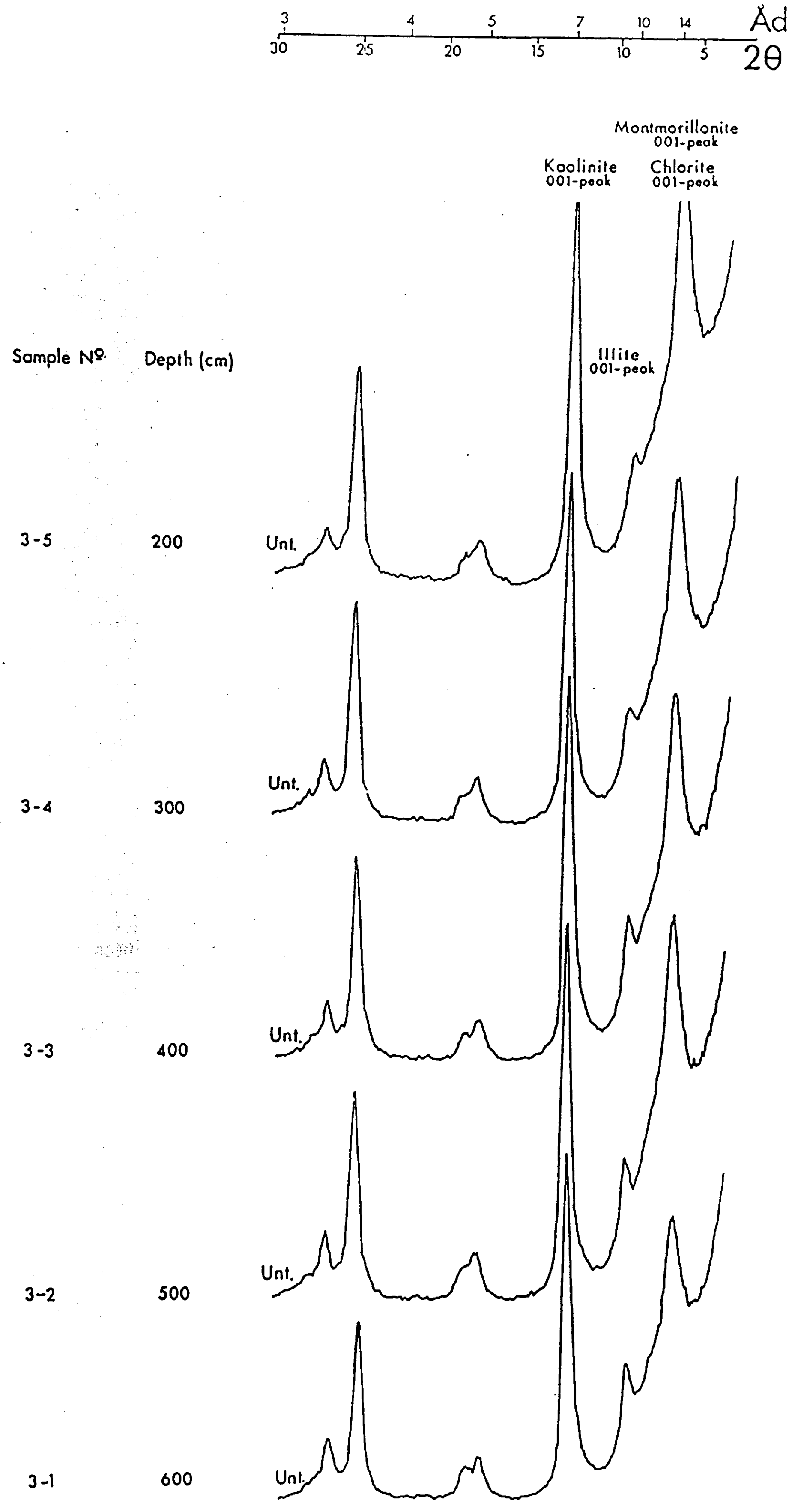


Figure 11.10 XRD diffractograms for oriented samples of the clay fraction (<2 µm) separated from the Upper grey till at Sourlie, Location 3, at various depth levels below ground surface.

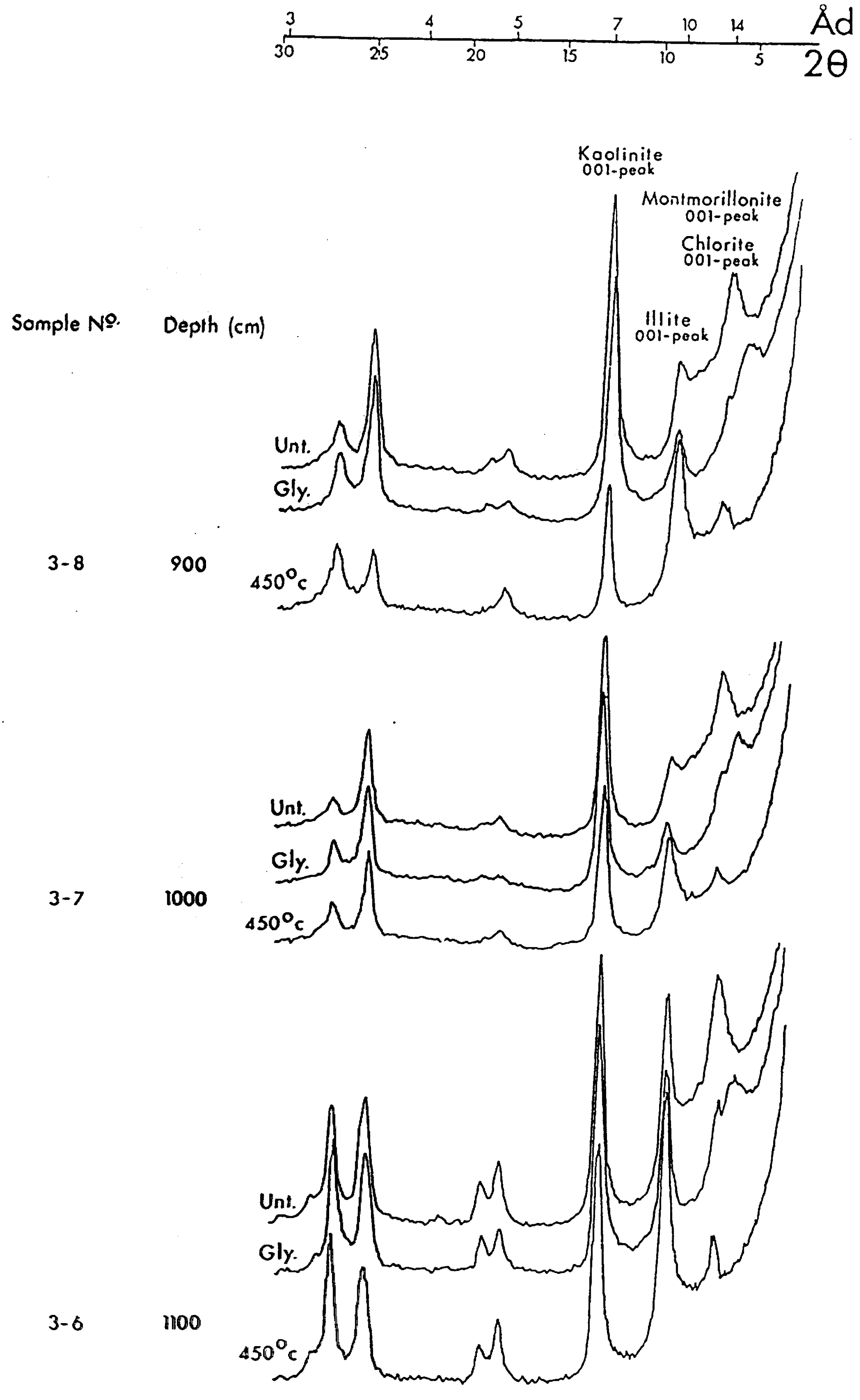


Figure 11.11 **XRD diffractograms for oriented samples of the clay fraction (<2 µm)** separated from the Lower grey till at Sourlie, Location 3, at various depth levels below ground surface.

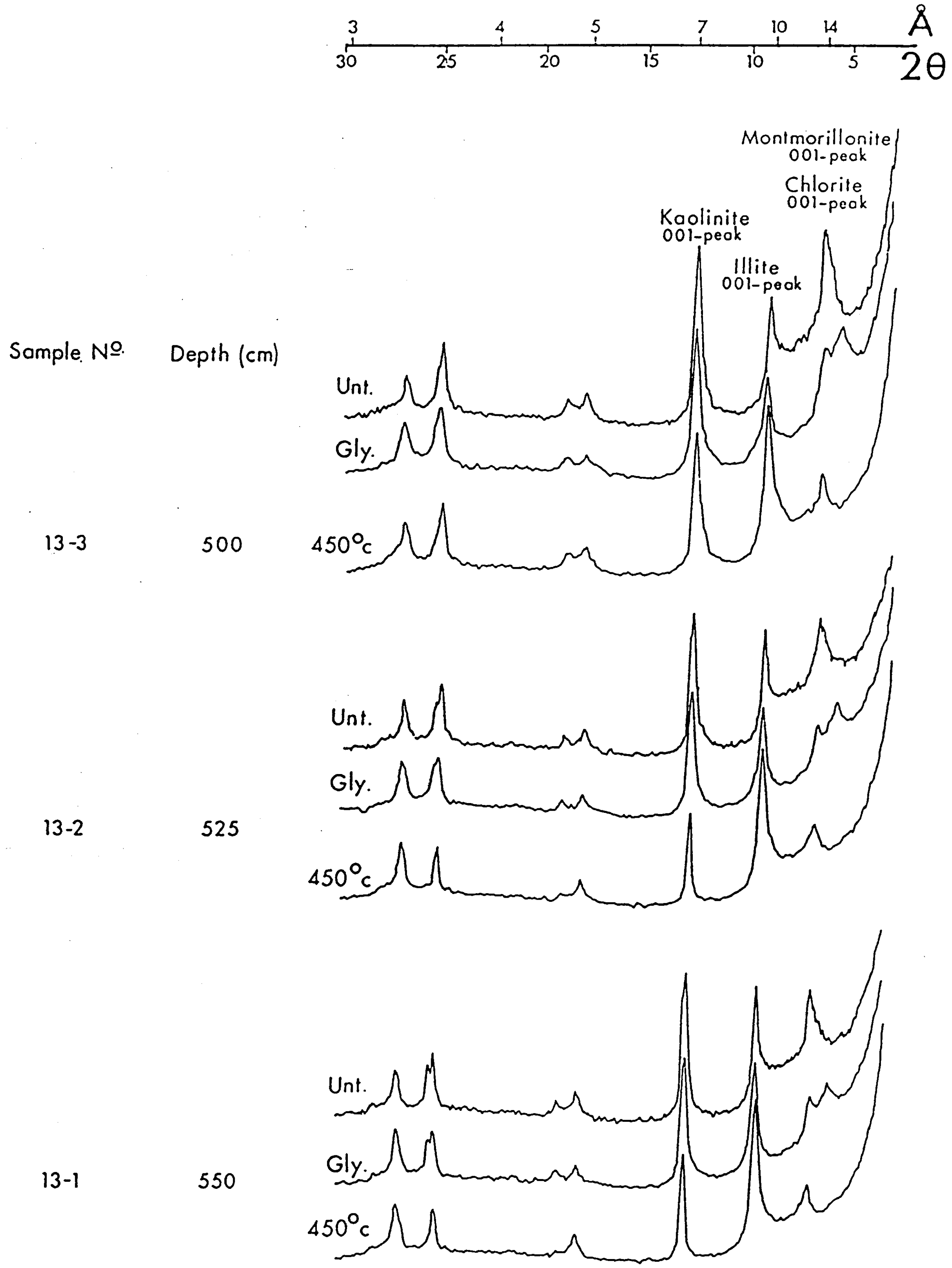


Figure 11.12 XRD diffractograms for oriented samples of the clay fraction (<2 μm) separated from the shelly till at Sourlie, Location 13, at various depth levels below ground surface.

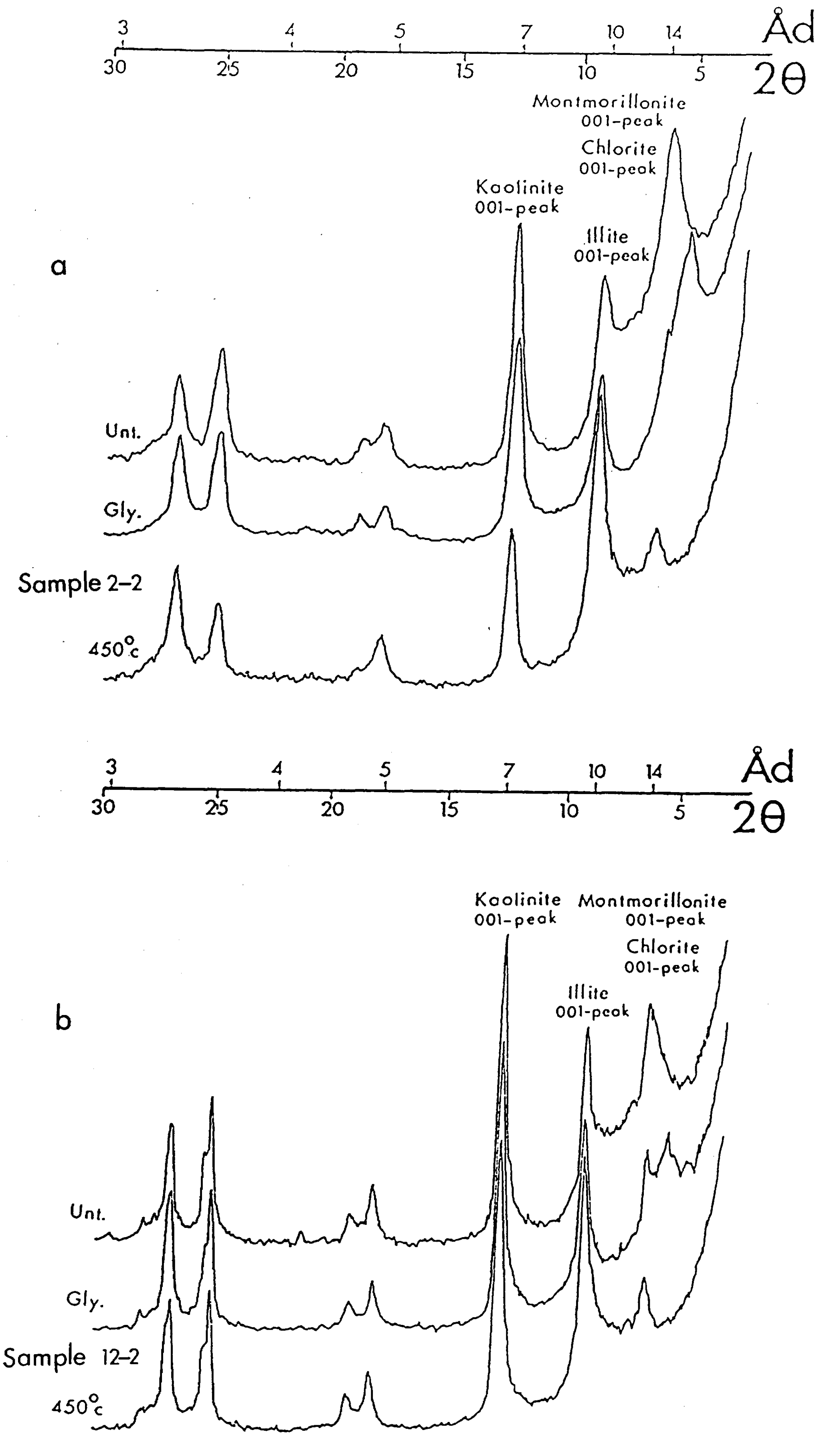


Figure 11.13 XRD diffractograms for oriented samples of the clay fraction (<2 μm):

a "shelly till" at Greenock Mains, Location 2

b marine clays at Afton Lodge

Table 11.1 Percentage clay mineral composition of samples collected in Northern Ayrshire, with values of mean ($\bar{X}$) and standard deviation (S). In each case N gives the number of samples.

Till unit and Location	Sample number	% Montmorillonite	% Illite	% Kaolinite	% Chlorite	% Vermiculite
Lower "shelly till", Greenock Mains, Location 2	2 - 1	12.3	44.1	27.8	15.8	-
	2 - 2	13.2	45.7	26.0	15.1	-
	2 - 3	10.8	47.3	28.8	13.1	-
(N = 3)	$\bar{X}$	12.1	45.6	27.5	14.7	-
	S	1.21	1.60	1.42	1.40	-
Upper till, Greenock Mains, Location 2	2 - 4	5.6	30.8	63.6	-	-
	2 - 5	3.9	38.4	57.7	-	-
(N = 7)	2 - 6	3.8	26.0	70.2	-	-
	2 - 7	9.9	37.9	52.2	-	-
	2 - 8	10.9	40.4	48.7	-	-
	2 - 9	11.4	31.7	56.9	-	-
	2 -10	16.0	27.2	56.8	-	-
	$\bar{X}$	8.7	33.2	58.0	-	-
	S	4.51	5.72	7.07	-	-
Lower shelly till, Greenock Mains, Location 6	6 - 1	19.7	30.9	49.4	-	-
	6 - 2	15.6	31.5	52.9	-	-
	6 - 3	9.0	33.3	49.3	8.4	-
(N = 8)	6 - 4	10.4	32.5	46.9	10.2	-
	6 - 5	4.7	29.1	54.0	12.2	-
	6 - 6	7.2	32.9	48.4	11.5	-
	6 - 7	-	28.2	35.9	10.3	25.6
	6 - 8	-	31.7	39.7	7.9	20.6
	$\bar{X}$	8.3	31.3	47.1	7.6	5.8
	S	6.96	1.8	6.24	4.88	10.77

Table 11.1 (continued)

Till unit and Location	Sample number	% Montmorillonite	% Illite	% Kaolinite	% Chlorite	% Vermiculite
Shelly till, Merkland Burn, Location 8 (N = 5)	8 - 1	12.4	31.8	38.2	17.6	-
	8 - 2	18.5	32.0	30.4	19.1	-
	8 - 3	14.2	29.1	37.2	19.5	-
	8 - 4	9.0	25.1	31.8	34.1	-
	8 - 6	10.7	31.4	39.6	18.3	-
	$\bar{X}$	13.0	29.9	35.4	21.7	-
	S	3.65	2.91	4.08	6.96	-
Lower red till, Merkland Burn, Location 8 (N = 3)	8 - 7	14.0	44.1	41.9	-	-
	8 - 8	15.2	46.1	38.7	-	-
	8 - 9	6.0	54.2	38.8	-	-
	$\bar{X}$	11.7	48.1	39.8	-	-
	S	5.00	5.35	1.82	-	-
Upper red till, Merkland Burn, Location 8	8 -10	19.9	30.7	49.4	-	-
All red till at Merkland Burn, Location 8 (N = 4)	$\bar{X}$	13.8	43.8	42.2	-	-
	S	5.77	9.75	5.02	-	-
Shelly till, Sorn Mains, Location 5-1 (N = 6)	5-1-1	11.4	38.7	32.8	-	17.1
	5-1-2	14.8	36.2	30.9	18.1	-
	5-1-3	13.8	36.4	32.7	17.1	-
	5-1-4	14.4	34.3	35.3	16.0	-
	5-1-5	9.4	30.2	35.4	25.0	-
	5-1-6	8.7	34.9	33.3	23.1	-
	$\bar{X}$	12.1	35.1	33.4	16.6	2.9
	S	2.64	2.85	1.72	8.84	6.98
Shelly till, Sorn Mains, Location 5-2 (N = 5)	5-2-1	5.6	34.7	44.4	15.3	-
	5-2-2	8.5	31.7	39.9	19.9	-
	5-2-3	8.1	28.6	40.2	23.1	-

Table 11.1 (continued)

Till unit and Location	Sample number	% Montmorillonite	% Illite	% Kaolinite	% Chlorite	% Vermiculite
Shelly till, Sorn Mains, Location 5-2 (continued)	5-2-4	8.6	37.2	35.7	18.5	-
	5-2-5	7.6	34.4	35.9	22.1	-
	$\overline{X}$	7.7	33.3	39.2	19.8	-
(N = 5)	S	1.23	2.28	3.59	3.09	-
All shelly till at Sorn Mains	$\overline{X}$	10.1	34.3	36.0	18.0	-
(N = 11)	S	3.06	3.04	3.98	6.77	-
Grey till, Sorn Mains, Location 5-3	5-3-1	5.4	27.0	67.6	-	-
Red till, Sorn Mains, Location	5-3-2	10.3	25.6	64.1	-	-
Upper Grey till, Sourlie, Location 3	3 - 1	21.4	23.0	40.7	13.9	-
	3 - 2	18.3	30.0	30.9	20.8	-
(N = 5)	3 - 3	12.5	31.5	33.6	22.4	-
	3 - 4	16.2	23.5	47.5	12.8	-
	3 - 5	19.5	20.8	50.6	9.1	-
	$\overline{X}$	17.6	25.8	40.7	15.8	-
	S	3.41	4.70	8.52	5.61	-
Lower Grey till, Sourlie, Location 3	3 - 6	3.5	34.5	48.3	13.7	-
	3 - 7	6.3	21.8	56.8	15.1	-
(N = 3)	3 - 8	3.9	19.2	64.0	13.9	-
	$\overline{X}$	4.6	25.2	56.4	13.9	-
	S	1.51	8.19	7.86	1.11	-
Shelly till, Sourlie, Location 13	13 - 1	8.0	33.7	38.0	20.3	-
	13 - 2	9.7	28.3	40.6	21.4	-
(N = 3)	13 - 3	15.8	24.9	41.2	18.1	-
	$\overline{X}$	11.2	29.0	39.9	19.9	-
	S	4.10	4.44	1.70	1.68	-

Table 11.1 (continued)

Till unit and Location	Sample number	% Montmor-illonite	% Illite	% Kaolinite	% Chlorite	% Vermi-culite
Upper Grey till, Sourlie, Location 13 (N = 3)	13 - 4	6.5	32.3	38.7	22.5	-
	13 - 5	11.8	33.7	31.3	23.1	-
	13 - 6	17.4	20.2	41.7	20.7	-
	$\bar{X}$	11.9	28.7	37.2	22.1	-
	S	5.45	7.42	5.35	1.25	-
All Upper Grey till at Sourlie (N = 8)	$\bar{X}$	15.5	26.9	39.4	18.2	-
	S	4.88	5.54	7.27	5.39	-
Red till, Tayburn, Location 5B (N = 4)	5B - 1	72.2	10.1	17.7	-	-
	5B - 2	75.8	16.1	8.1	-	-
	5B - 3	67.1	12.2	20.7	-	-
	5B - 4	61.0	12.4	26.6	-	-
	$\bar{X}$	69.0	12.7	18.3	-	-
	S	6.43	2.49	7.72	-	-
Grey till, Tayburn, Location 5B (N = 4)	5B - 5	-	19.0	41.1	12.9	27.0
	5B - 6	-	23.7	42.9	9.8	23.6
	5B - 7	23.3	14.4	62.3	-	-
	5B - 8	29.4	9.5	61.1	-	-
	$\bar{X}$	13.2	16.6	51.9	5.7	9.5
	S	15.42	6.09	11.41	6.67	12.03
Red till, Tayburn, Location 7B	7B - 1	63.2	12.3	25.5	-	-
Grey till, Tayburn, Location 7B	7B - 2	14.8	24.3	52.3	8.6	-
All red till at Tayburn (N = 5)	$\bar{X}$	67.9	12.6	19.7	-	-
	S	6.15	2.17	7.43	-	-

Table 11.1 (continued)

Till unit and Location	Sample number	% Montmor-illonite	% Illite	% Kaolinite	% Chlorite	% Vermi-culite
All grey till at Tayburn	$\bar{X}$	10.5	18.2	51.9	6.3	13.1
(N = 5)	S	14.59	5.63	9.88	5.93	12.74
All shelly till of Northern Ayrshire	$\bar{X}$	10.2	32.0	39.6	15.8	-
(N = 27)	S	4.76	3.40	6.72	7.96	-
Marine clays at Afton Lodge	12 - 1	9.7	41.9	32.3	16.1	-
(N = 3)	12 - 2	11.5	38.5	34.6	15.4	-
	12 - 3	8.0	40.0	36.0	16.0	-
	$\bar{X}$	9.7	40.1	34.3	15.8	
	S	1.75	1.70	2.64	0.38	

Table 11.2 Clay mineralogy of the (upper) grey till profile at Tayburn, Location 5B, showing weathering. Sample 5B - 8 is the uppermost sample, 5B - 5 the lowermost.

Sample number	10 Å peak	14 Å peak
5B - 8 and 5B - 7	more mixed-layer illite-montmorillonite than in lower samples; some unaltered illite	mixed-layer vermiculite-montmorillonite; no vermiculite; no chlorite
5B - 6 and 5B - 5	illite slightly hydrated; some mixed-layer illite-montmorillonite	vermiculite and chlorite

CHAPTER 12

GEOCHEMICAL ANALYSIS OF TILLS OF NORTHERN AYRSHIRE

12.1 Introduction

Chemical analysis of the tills of Northern Ayrshire was undertaken in order to chemically characterise each of the sampled till units. For the purposes of assessment of the significance of the chemical data it was thought to be useful to divide the sampled tills into two groups, those that are shelly (i.e. in the field they visibly contain small quantities of shell fragments; > 2mm) and those that are non-shelly (i.e. in the field they appear to be devoid of shells). However, it must be said that, in making this division, the shelly tills constitute a much more uniform unit than the non-shelly tills. The latter consist of a number of till units many of which are sited tens of km apart; where two units are superimposed at one site they in fact were selected for study in relation to the major aims of the project (Chapter 4.1.2) because of their apparent differences rather than their similarities.

The shelly till group (27 samples) consists of those tills identified in the field as containing shell fragments and, in Chapter 10 above, as having their primary grain-size mode in the fine sand grade. This group therefore comprises the shelly till at five Locations: Greenock Mains, Location 6; Merkland Burn, Location 8; Sorn Mains, Locations 5-1 and 5-2; and Sourlie, Location 13. The non-shelly till group (34 samples) is much more diverse. It comprises all the sampled tills of Northern Ayrshire other than: a) those included above as shelly tills, and b) the Lower "shelly till" sampled at Greenock Mains, Location 2. The identity of the last-mentioned deposit is in doubt (Chapter 10.5). Its nature is examined more fully below (Chapter 12.6) on the basis of its geochemistry.

The results of the major and trace element analyses on the matrix (< 2mm) of the tills are given in Tables 12.1 and 12.2, with summary statistics in Tables 12.3 to 12.9, and general discussion of the chemistry of the tills is given in sections 12.2 to 12.5 in the text below.

A more specific aim of this part of the project, discussed in section 12.6 of the text below, is to determine whether, on geochemical evidence, the Lower "shelly till" at Greenock Mains, Location 2, differs significantly from the shelly till collected at other Northern Ayrshire sites but resembles other Quaternary deposits in Northern Ayrshire.

12.2 Grain-size control on major and trace elements

Grain-size control on major element distribution within both the shelly and non-shelly tills of Northern Ayrshire is pronounced. Negative correlations of TiO_2, Al_2O_3, Fe_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5, CO_2 and H_2O (Table 12.4) with sand-sized material suggest that these oxides are associated with the finer fractions (silt and clay). Conversely, SiO_2 is positively correlated with the sand sized material and negatively correlated with both silt- and clay-sized material (Table 12.4), implying that the sand-sized fraction is relatively enriched in SiO_2 and, consequently, in quartz. Previous studies on till lithology (Vagners 1969; Dreimanis & Vagners 1969; 1971a; 1971b) have demonstrated the predominance of less-resistant minerals in the finer size fractions. This may account for most major element associations within the Northern Ayrshire tills. The results here agree with data presented by Haldorsen (1983), who attributed the enrichment of quartz and SiO_2 in the sand fraction of till to preferential comminution of feldspar and mica to form silt and clay fractions.

Grain-size control on trace element concentration in both shelly and non-shelly tills is illustrated in Table 12.5. All the trace elements except Ba show negative correlation with the sand-sized material, indicating that all trace elements have a tendency to be concentrated preferentially in the silt- and clay-sized fraction. The negative correlation of Ba with the silt and clay fractions (Table 12.5) suggests that this element has been derived from a mineral that is not readily comminuted to particles smaller than sand size (< 0.063mm).

12.3 Major elements

Table 12.6 gives the calculated correlation coefficients between the major constituents of the Northern Ayrshire tills. The following is a discussion of the distribution of these constituents.

12.3.1 Distribution of silica

As might be expected, Table 12.3 shows that the shelly till has a small range of SiO_2 values (70-77%), whereas the non-shelly tills have a wide range (59-81%). On average, the shelly till is slightly richer in SiO_2 and poorer in Al_2O_3 than the non-shelly tills, suggesting there is a higher quartz and lower clay content in the shelly till than in most of the non-shelly tills. The relationship between SiO_2 and clay content (Fig. 12.1a) supports this view. Table 12.6 shows that there is a negative correlation between SiO_2 and Al_2O_3, TiO_2, Fe_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O and P_2O_5 (Figs. 12.1b to 12.6a). This inevitably arises from a combination of the constant summation effect of the percentages, the predominance of SiO_2

and probably also since SiO_2 is mainly present as quartz.

12.3.2 Distribution of aluminium and iron

Table 12.6 shows that there is a positive correlation between Al_2O_3 and Fe_2O_3, FeO, MgO and K_2O (see also Figs. 12.6b to 12.8a). There are also positive correlations of Fe_2O_3 with MgO and K_2O and of FeO with MgO and K_2O (Table 12.6). These relationships indicate that Al and iron in the sampled Northern Ayrshire tills are mainly present in clay minerals.

12.3.3 Distribution of calcium and magnesium

There is a good positive correlation of CaO with CO_2 (Table 12.6 and Fig.12.8b). This means that Ca is found mainly as $CaCO_3$ in the sampled Northern Ayrshire tills. The negative correlations of SiO_2 with CaO and CO_2 (Table 12.6) support this view. However, minor amounts of Ca may be present in detrital apatite, as inferred from the positive correlation of CaO with P_2O_5 (Table 12.6 and Fig.12.9a).

MgO, on the other hand, shows a positive correlation with Al_2O_3 and with Fe_2O_3, and a negative correlation with CO_2 (Table 12.6). This indicates that Mg occurs as a main constituent of clay minerals. In fact, Mg is mainly encountered in chlorite, vermiculite and illite, clay minerals that have been found in Northern Ayrshire tills. Certainly the negative correlation of MgO with CO_2 (Table 12.6) demonstrates a lack of dolomite or magnesite.

Comparison of the CaO and CO_2 contents of the shelly till (1.86% and 1.84% respectively) and non-shelly tills (2.10% and 2.74% respectively) produces an interesting problem. Clearly, the shelly till matrix, on average, has a lower carbonate, in particular a lower calcite, content than the average non-shelly till matrix, whereas field observation indicates that, when the fractions of the tills > 2mm are considered, the shelly till alone contains fragments of shells. Several explanations may be valid. Two of these may be:

1) The non-shelly tills may be visibly devoid of shells but contain fine-grained shell fragments too small to be observed in the field. If this is the case, comminuted shell material may account for the high carbonate content in these tills compared with that in the shelly till.
2) The non-shelly tills may be completely devoid of shells but contain finely ground Carboniferous limestone detritus.

The latter explanation implies a greater content of local bedrock in the non-shelly tills than the shelly till. This might be expected as the shelly till, according to Holden (1977), is derived at least partly from marine clays and would therefore contain a smaller proportion of bedrock constituents.

12.3.4 Distribution of Na_2O and K_2O

Both Na_2O and K_2O contents of the non-shelly till samples show a wide spread of values, while the shelly till samples show a small range of values (Table 12.3). The negative correlation of Na_2O with al-alk ($r = 0.73$; Fig. 12.9b) and the poor positive correlation of Na_2O with Al_2O_3 (Fig. 12.10a; Table 12.6) indicate that Na is found mainly in Na-feldspar that may occur in the till matrix.

K_2O, on the other hand, shows a positive correlation with Al_2O_3 (Fig. 12.8a; Table 12.6), and the plot of Niggli k against al-alk ($r = 0.73$; Fig. 12.10b) supports the view that K_2O is in the clay minerals of the Northern Ayrshire till matrices rather than in the K-feldspars. In fact, potassium is mainly encountered in illite, a clay mineral that has been found in Northern Ayrshire tills.

12.3.5 Distribution of P_2O_5, TiO_2 and MnO

The positive relationship of P_2O_5 with CaO and its good positive correlations with Al_2O_3 and K_2O (Table 12.6) suggest that P_2O_5 may be ascribed to both apatite and clay minerals in the Northern Ayrshire tills.

The negative correlation of TiO_2 with al-alk ($r = -0.08$; Fig. 12.11a) and the strong positive relationship of TiO_2 with Fe_2O_3 (Table 12.6) indicate that TiO_2 may be present in accessory minor minerals, like ilmenite.

The positive correlation of MnO with al-alk ($r = 0.12$; Fig. 12.11b) indicates that MnO favours an association with clay minerals.

12.4 Trace elements

The distribution of trace elements Ga, Pb, Rb, Th, U, Y and Zn (Table 12.7) does not differ significantly between the shelly till and the non-shelly tills. However, on average, Ba, Ce, Co, Cr, Cu, Ni, Sr and Zr contents are higher in the non-shelly tills than in the shelly till. The higher Sr content in the non-shelly tills correlates well with the higher CaO content in the non-shelly tills than in the shelly tills (Table 12.3).

12.5 Trace elements trends in relation to clay minerals

Numerous plots of trace elements against al-alk (Figs. 12.12a to 12.19b) have been made to show which elements were added to the sediments in clay minerals and mica. Plots involving al-alk fall into three categories:

1) Plots that show a good positive correlation of the trace element concerned with al-alk, i.e. the plots for Ce, Cu, Ga, La, Pb, Rb, Th, U, Y and Zn (Figs. 12.12a to 12.16b). These plots suggest

that those elements are associated with clay minerals.

2) Plots that fail to show any significant correlation (either very poor positive or very poor negative) of the trace element concerned with al-alk, i.e. the plots for Co, Cr, Ni and Zr (Figs. 12.17a to 12.18b). These plots suggest that those elements are not solely contained in clay minerals or mica.

3) Plots showing a negative correlation of the trace elements concerned with al-alk, i.e. the plots for Ba and Sr (Figs. 12.19a and 12.19b). These plots suggest that those trace elements are not associated with clay minerals. Sr correlates positively with CaO (r = 0.45, Fig. 12.20a), suggesting control by calcite and apatite, since Sr^{+2} commonly substitutes for Ca^{+2} (Krauskopf 1967). This could also account for the negative correlation between Sr and al-alk. Ba fails to show any significant correlation with either K_2O or CaO (Figs. 12.20b and 12.21). This may be due to the presence of Ba as $BaSO_4$ (barytes), possibly derived from barytes veins in the underlying bedrock.

To further highlight the relationships between samples and variables, a correlation matrix between major and trace elements was calculated (Table 12.8). Significant positive correlations were recognised between Al_2O_3, Ga, FeO, MgO and K_2O, possibly indicative of a strong clay mineral component within all the sampled Northern Ayrshire tills, and between CaO, Sr and P_2O_5, representing typical chemical relationships developed in calcite and apatite. A Ni-Co-Cr correlation was also detected. This probably derives from finely ground basic igneous material, presumably basalt.

12.6 The Lower "shelly till" of Greenock Mains, Location 2, in relation to other deposits

It was shown in Chapters 10 and 11 that the Lower "shelly till" at Greenock Mains, Location 2, differs in grain size and clay mineral content from the shelly till that is present at five other Locations (four Sites) in Northern Ayrshire. It is important, therefore, to compare the geochemical data obtained for this shell-bearing deposit at Location 2 with the data for the shelly till of Northern Ayrshire as a whole.

The shelly till has a higher SiO_2 and a lower Al_2O_3, Fe_2O_3, FeO, MgO, CaO, Na_2O and K_2O content than the shell-bearing deposit at Location 2 (Table 12.9). This is to be expected in view of the higher quartz and lower clay mineral contents of the shelly till compared with those of the Lower "shelly till" at Location 2. For the same reason, all trace element values obtained for the shell-bearing deposit at Location 2 show larger means than those for the shelly till of Northern Ayrshire as a whole (Table 12.7). The statistics show consistent dissimilarity between the two deposits.

It is interesting to compare the average major elements composition of the shell-bearing deposit at Location 2 with the corresponding data for the shell-bearing clays at Afton Lodge (NS 4157 2587), clays that are generally regarded as marine in origin (Sutherland 1981, 294; 1984, 180). When this is done (Table 12.9), it is found that the shell-bearing deposits at Greenock Mains, Location 2, and Afton Lodge are remarkably similar in composition. Since this result agrees well with the findings of grain-size and clay mineralogical analysis, the possibility arises of the shell-bearing clays at Greenock Mains, Location 2, being marine in origin. They certainly do not appear to be part of the shelly till deposit of Ayrshire, contrary to the claim of Holden (1977, 36).

12.7 Conclusions

1) The concentrations of the major and trace elements in both the

shelly and non-shelly till groups are influenced by the grain-size of the studied samples. SiO_2 is preferentially concentrated in the sand fraction (2.00 - 0.063mm), but Al_2O_3, Fe_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O, and P_2O_5 and all trace elements except Ba occur preferentially in the silt and clay fractions (< 0.063mm).

2) In both till groups, there is a significant component of quartz, believed to be derived from sandstone bedrock.

3) The inverse relationships of Al_2O_3, TiO_2, Fe_2O_3, FeO, MnO, MgO and K_2O with SiO_2 may be due to decreasing amount of clays with increasing SiO_2 content.

4) The shelly till samples from five Locations (four different Sites) are distinctly similar in their major element composition. This may indicate that they had similar sources.

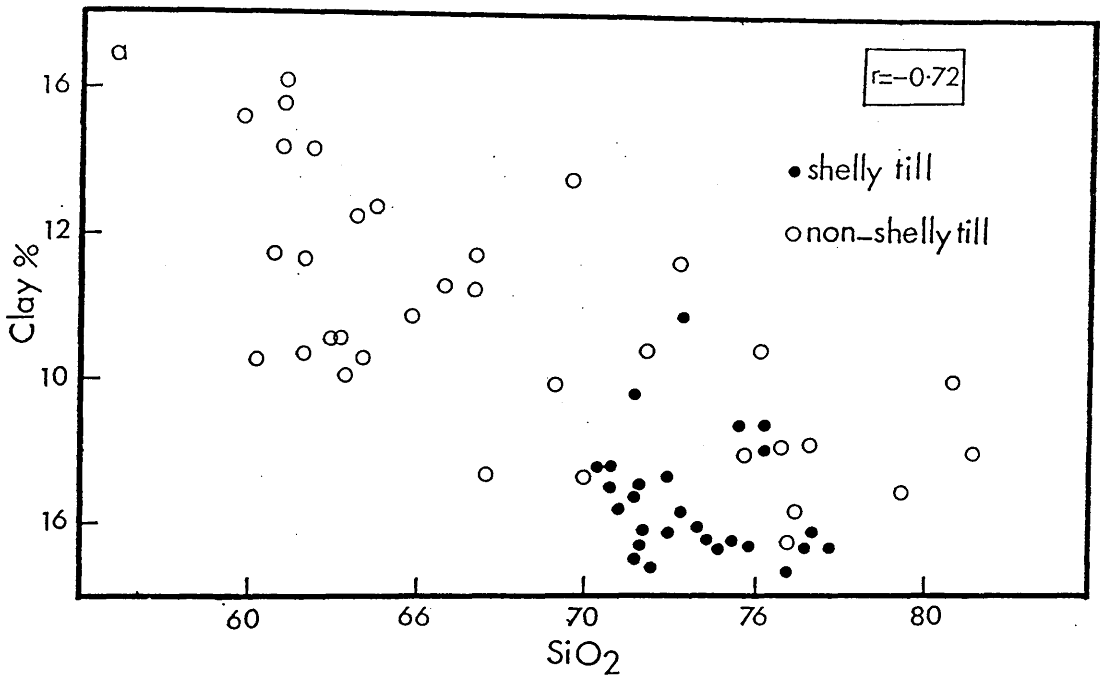
5) Surprisingly, compared with the shelly till, the non-shelly tills have higher average percentage contents of CaO and CO_2, which reflect a higher carbonate content in the matrices of the non-shelly tills than in the shelly till. A greater proportion of Carboniferous limestone detritus in the non-shelly till matrices than in the shelly till matrix may account for this unexpected 'anomaly'.

6) The average trace element contents of the shelly and non-shelly till groups show close similarity, except in the cases of Ba, Ce, Co, Cr, Cu, Ni, Sr and Zr, where the content is higher in the non-shelly tills.

7) In both groups of till, the trace elements Ce, Cu, Ga, La, Pb, Th, U, Y and Zn are assumed to be derived from the clay fraction, as suggested by the good positive correlations of these elements with al-alk and also with the silt and clay fractions. Co, Cr, Ni, Zr and Ba are randomly distributed through the till matrix. Sr is

concentrated mainly in the Ca-minerals, as inferred from its negative correlation with al-alk and its positive correlation with CaO.

8) There is a distinct dissimilarity in both major and trace element contents between the Lower "shelly till" sampled at Greenock Mains, Location 2, and the shelly till sampled at five other Locations spread over a wide area of Northern Ayrshire. In contrast, there is a close similarity between the major element compositions of the shell-bearing deposit at Greenock Mains, Location 2, and Quaternary marine clays exposed at Afton Lodge. The shell-bearing deposit at Location 2 therefore is not part of the shelly till which is widespread in Northern Ayrshire. It may be a deposit that was marine in origin.



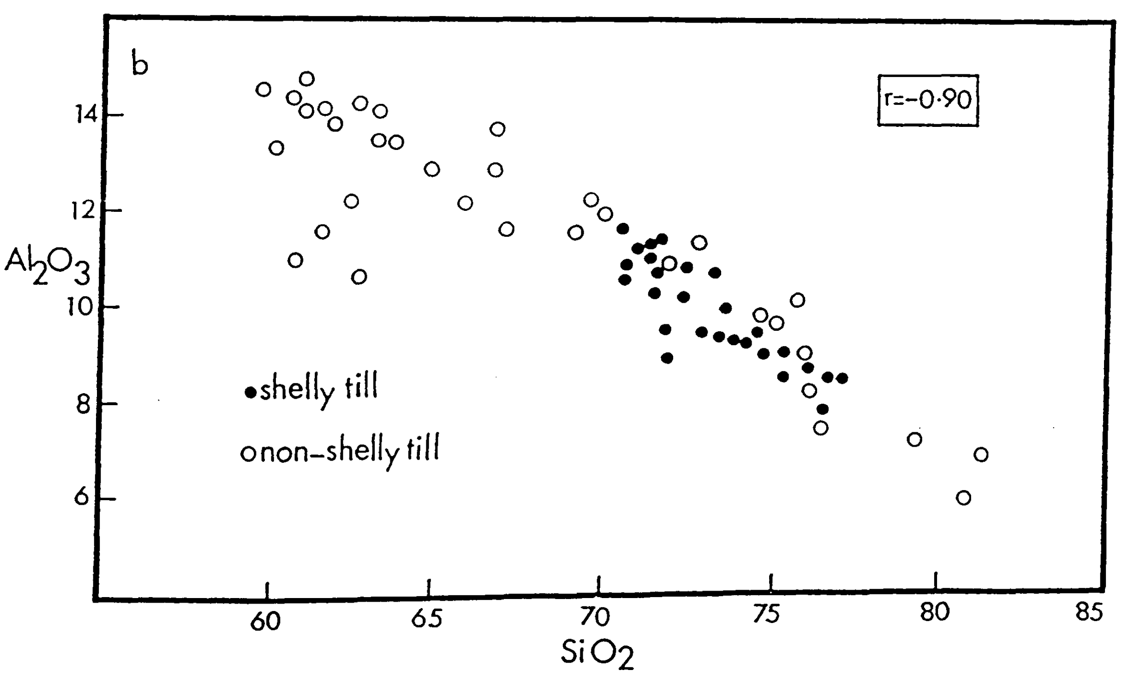


Figure 12.1 Plots of (a) clay % against SiO_2, and (b) Al_2O_3 against SiO_2

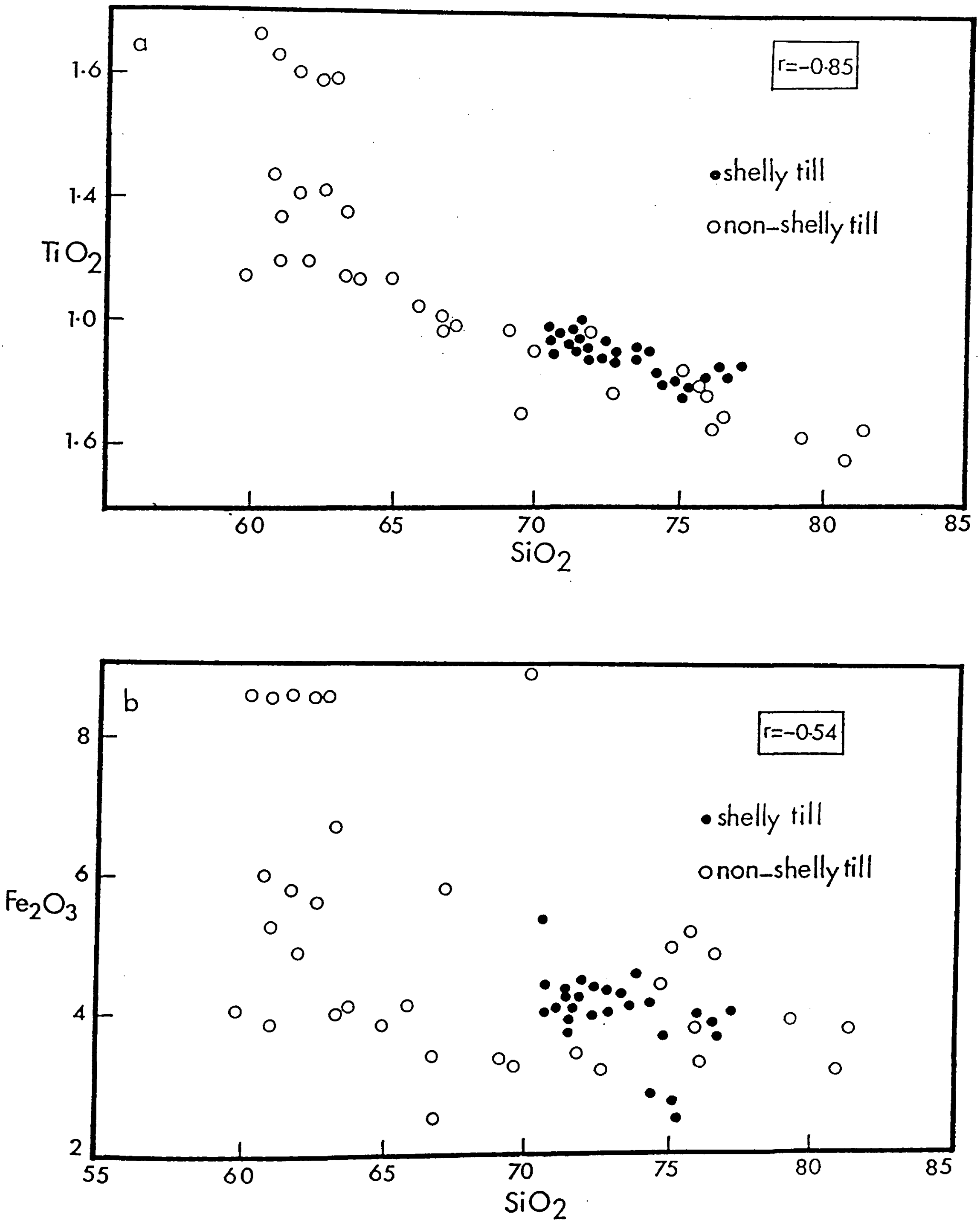


Figure 12.2 Plots of (a) TiO_2 against SiO_2, and (b) Fe_2O_3 against SiO_2

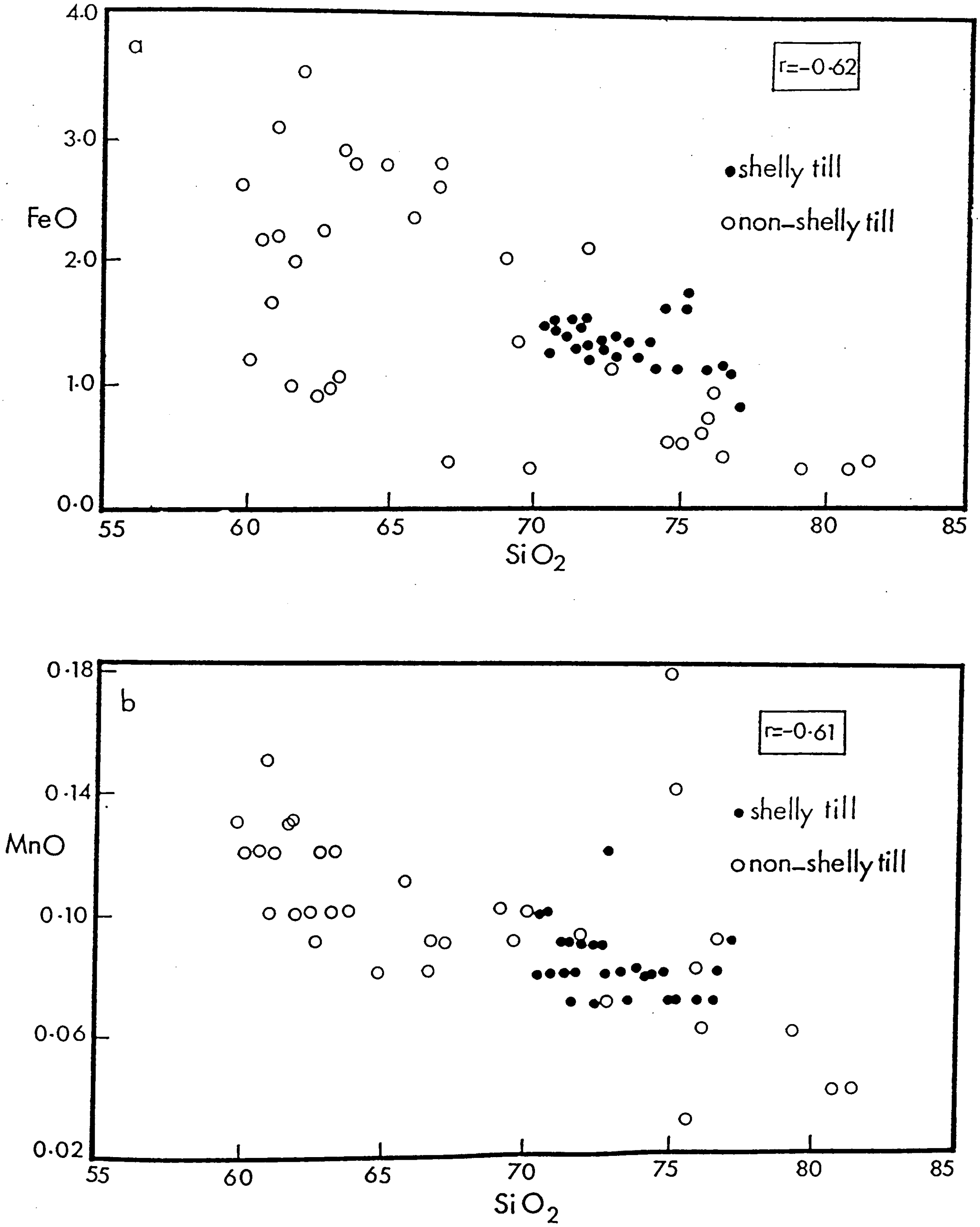


Figure 12.3 Plots of (a) FeO against SiO_2, and (b) MnO against SiO_2

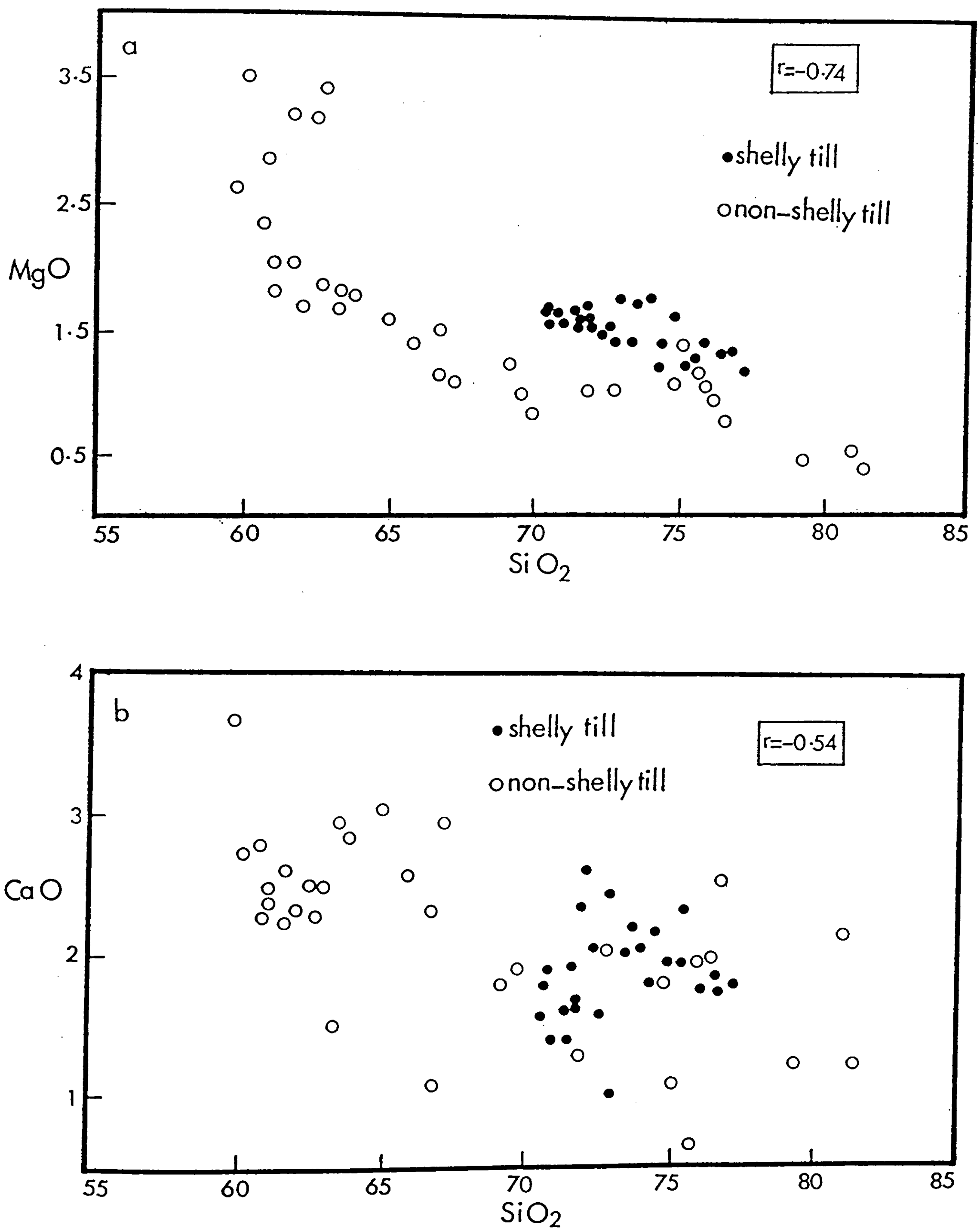
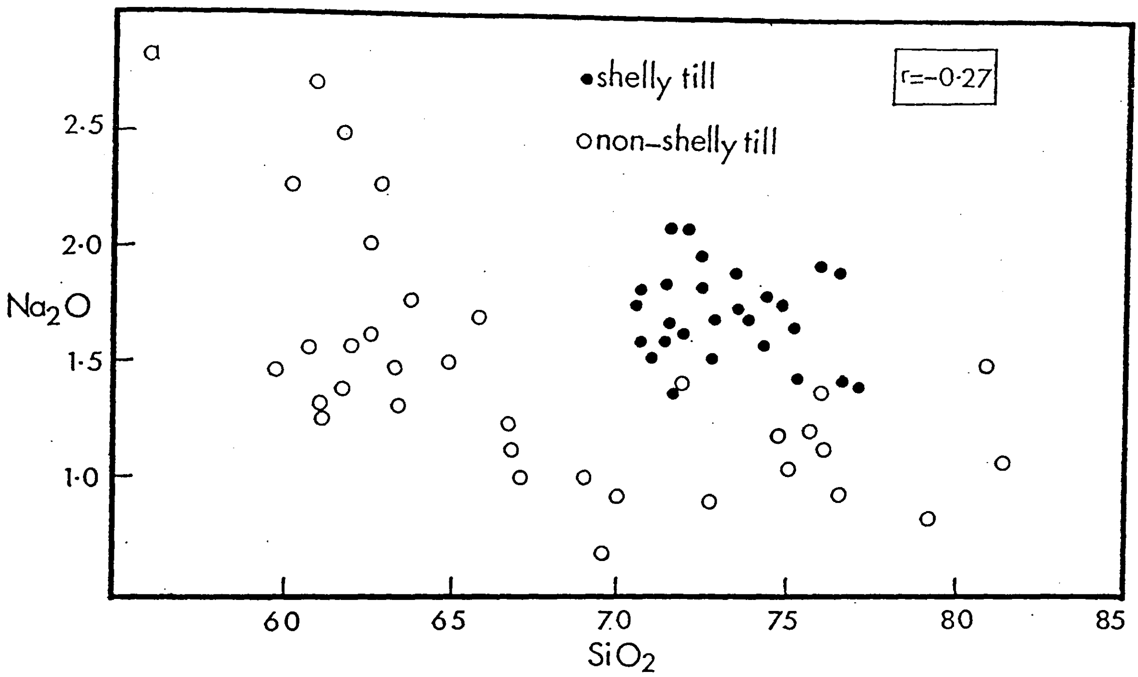


Figure 12.4 Plots of (a) MgO against SiO_2, and (b) CaO against SiO_2



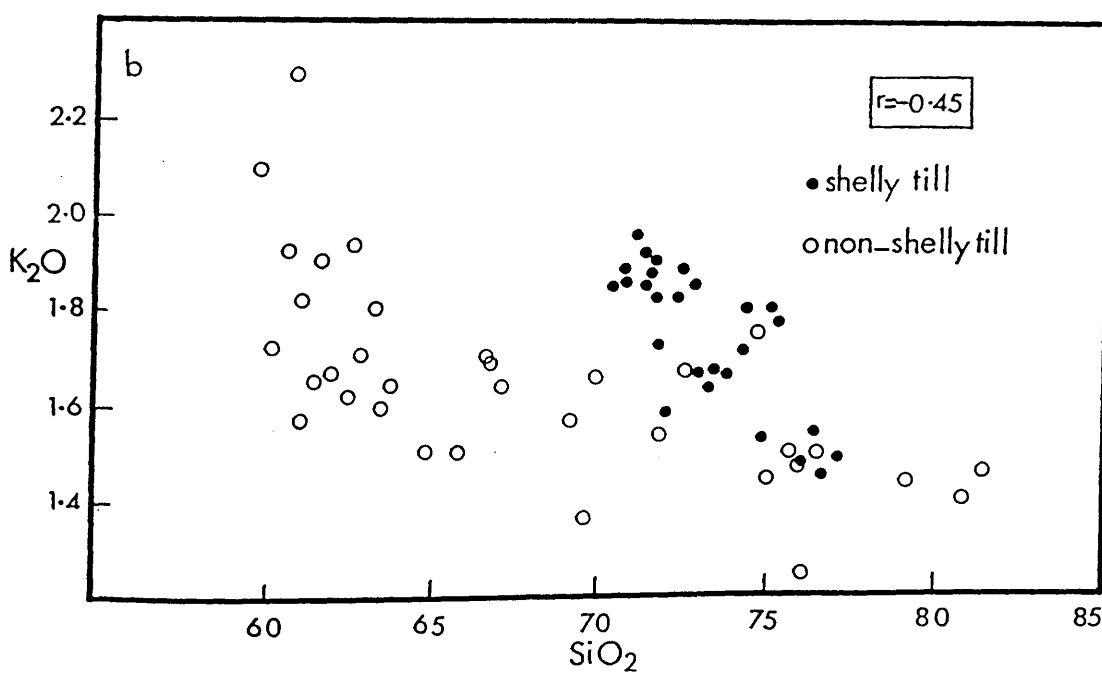


Figure 12.5 Plots of (a) Na_2O against SiO_2, and (b) K_2O against SiO_2

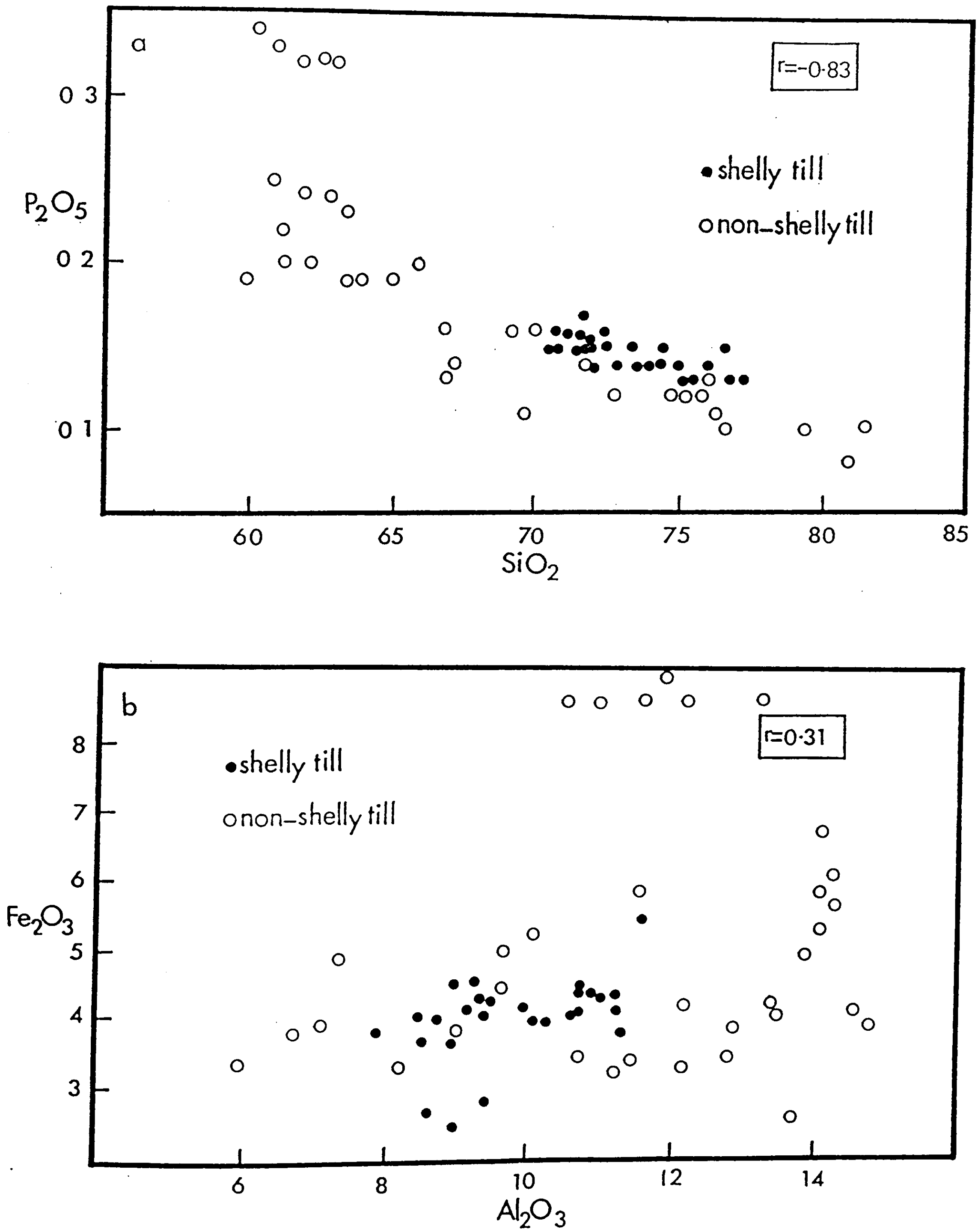


Figure 12.6 Plots of (a) P_2O_5 against SiO_2, and (b) Fe_2O_3 against Al_2O_3

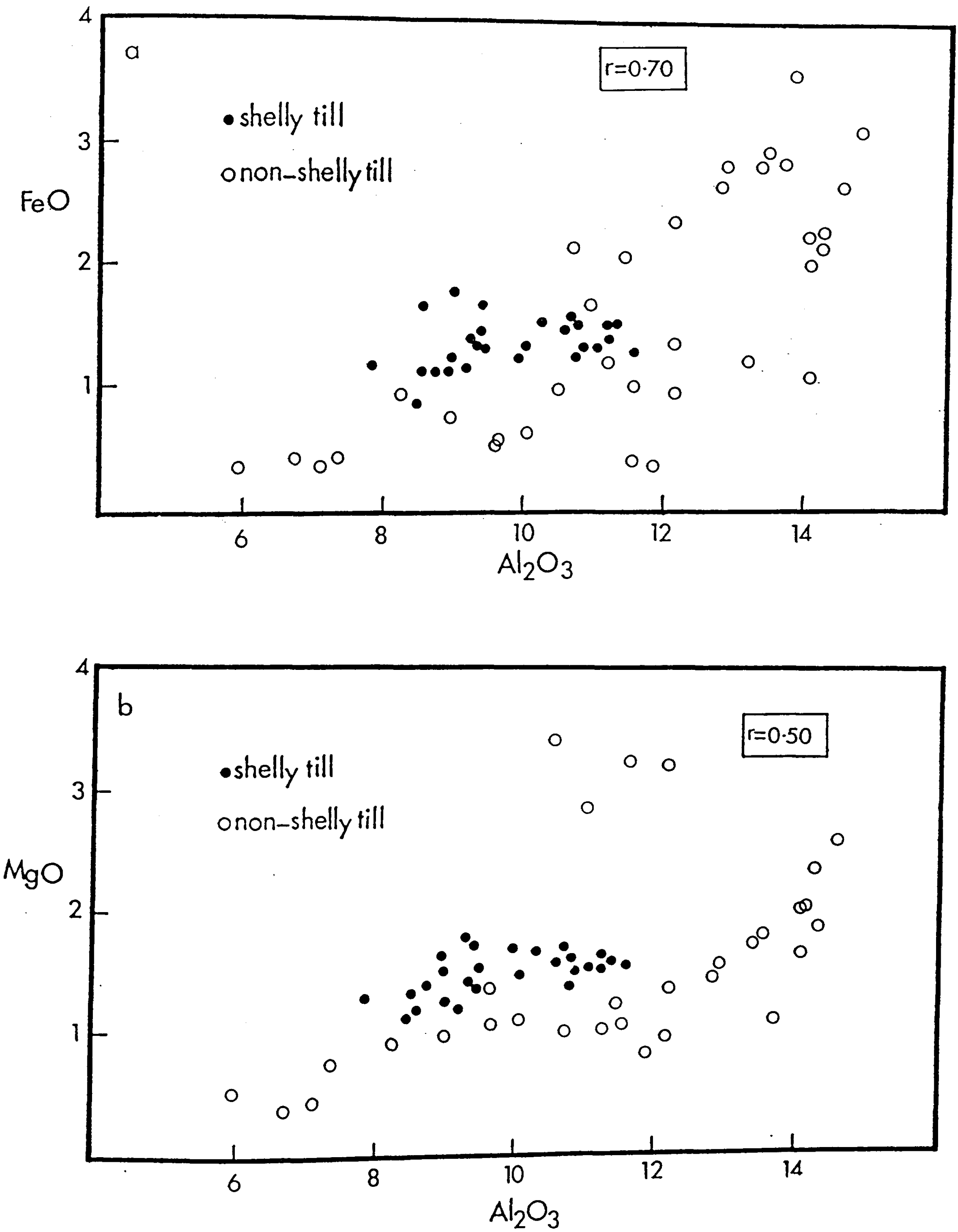
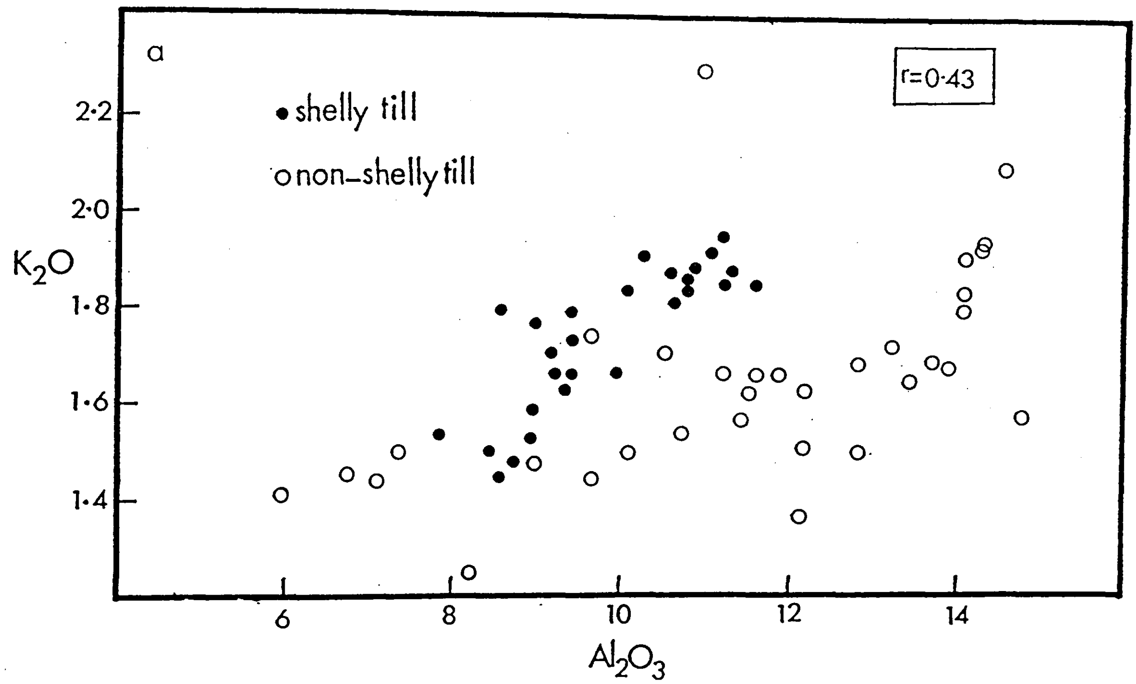


Figure 12.7 Plots of (a) FeO against Al_2O_3, and (b) MgO against Al_2O_3



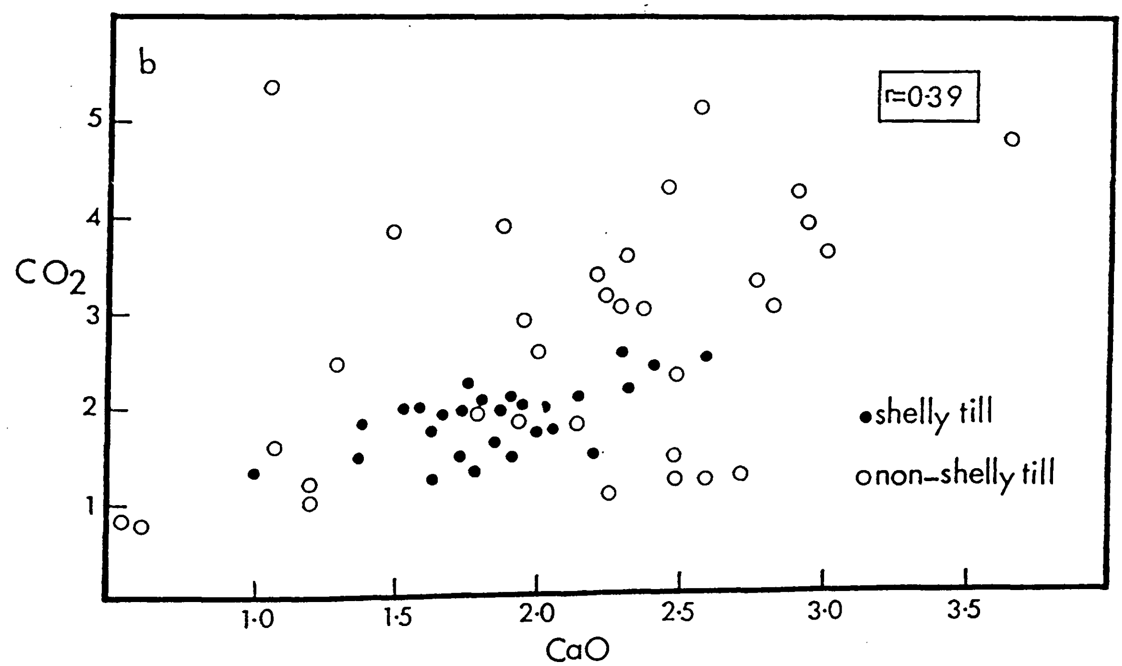
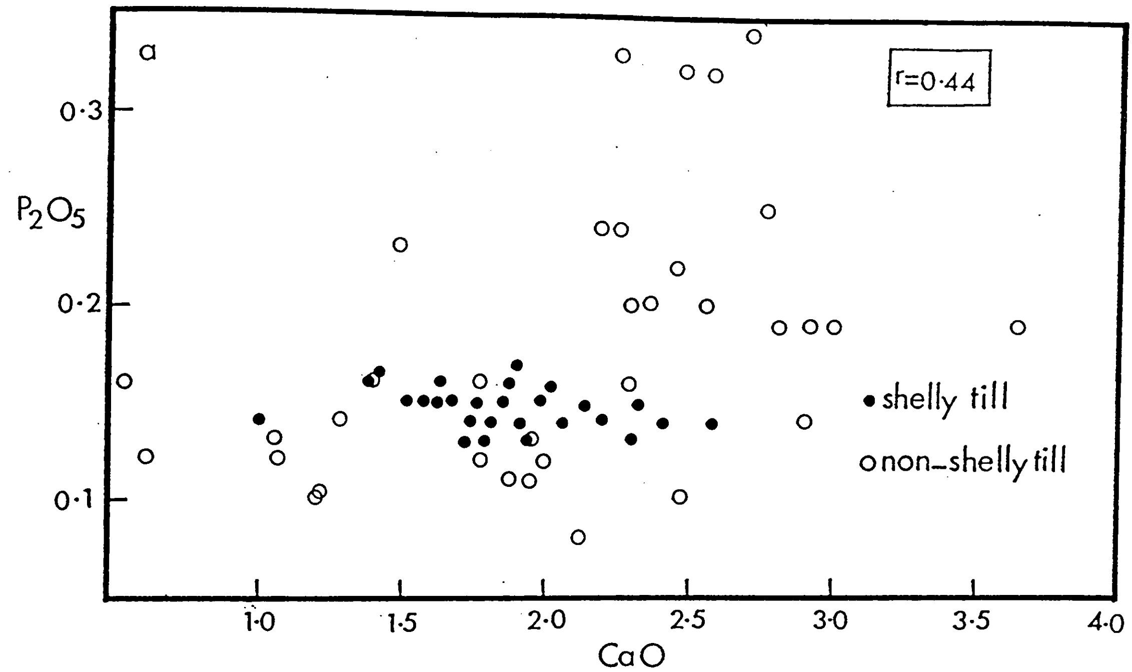


Figure 12.8 Plots of (a) K_2O against Al_2O_3, and (b) CO_2 against CaO



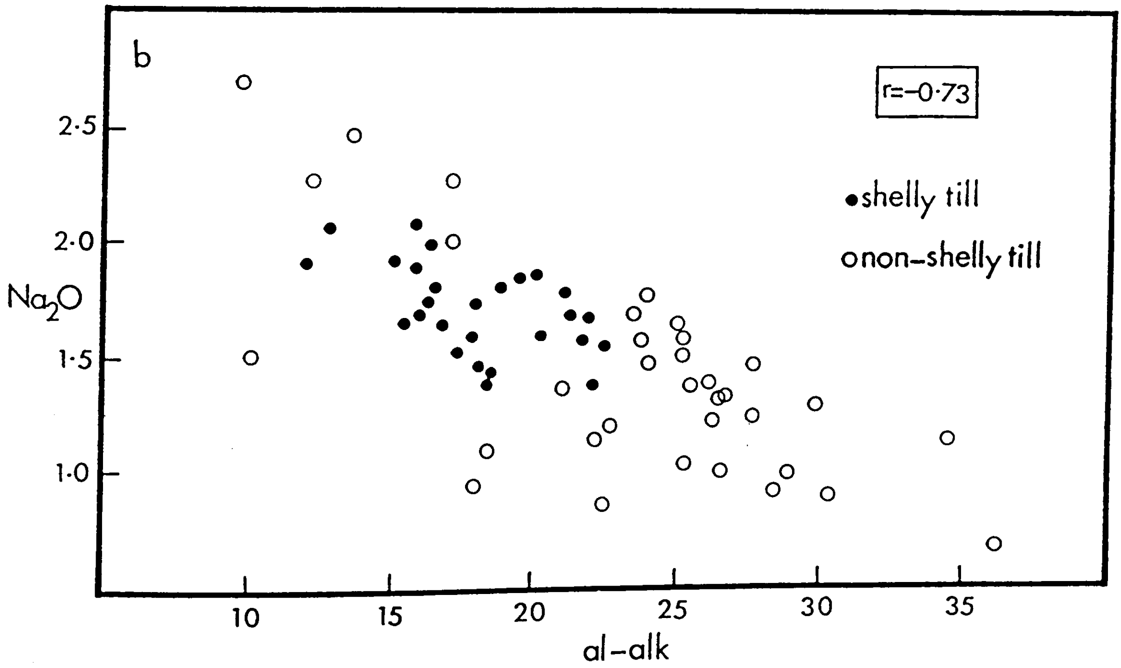


Figure 12.9 Plots of (a) P_2O_5 against CaO, and (b) Na_2O against al-alk

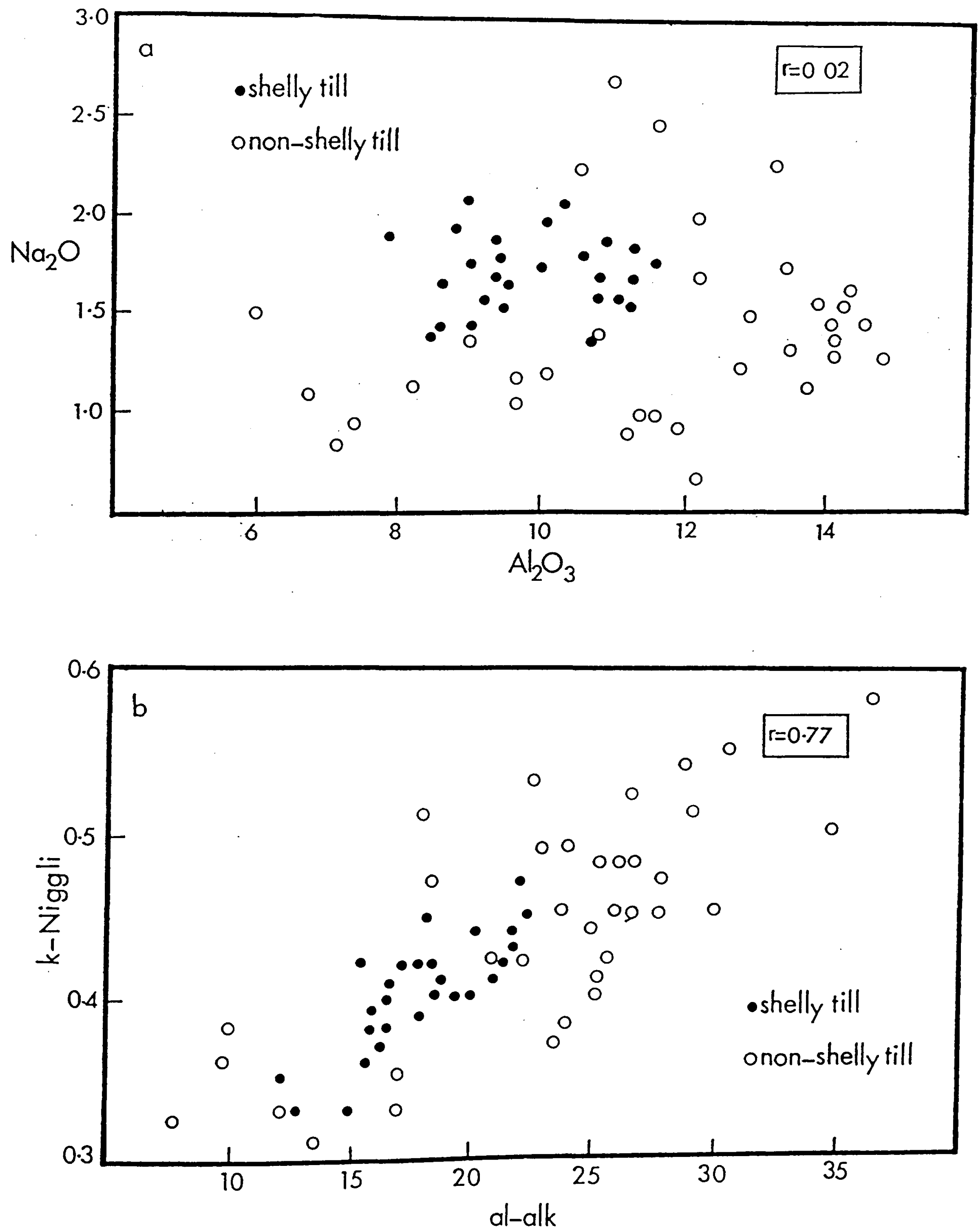
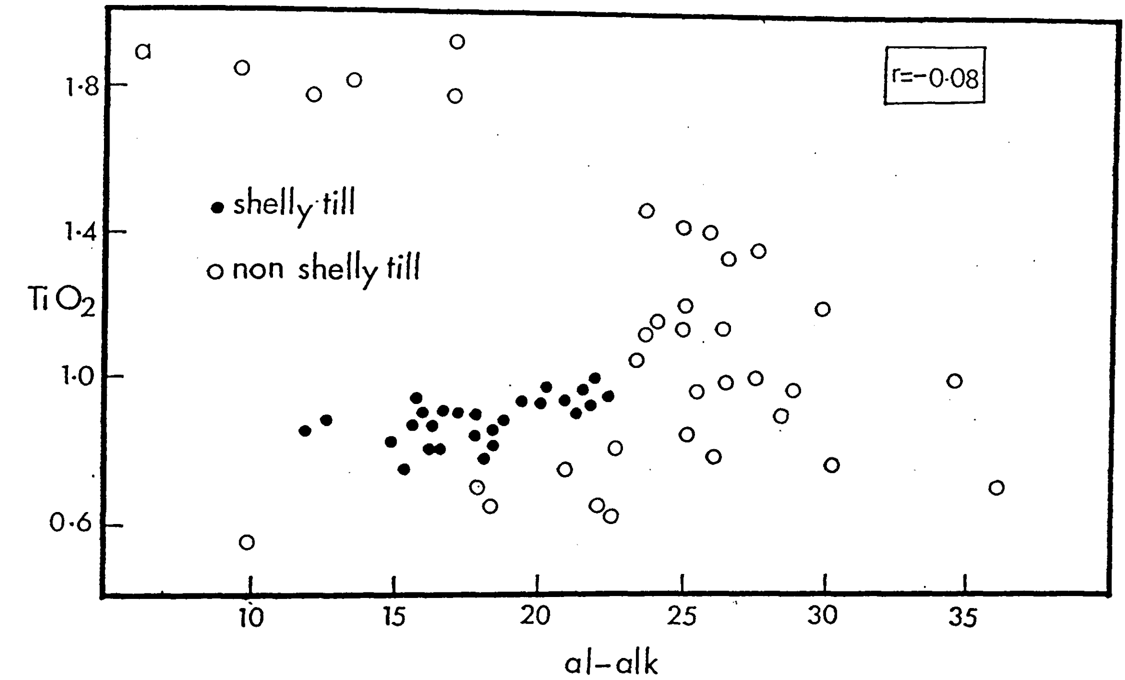


Figure 12.10 Plots of (a) Na_2O against Al_2O_3, and (b) k-Niggli against al-alk



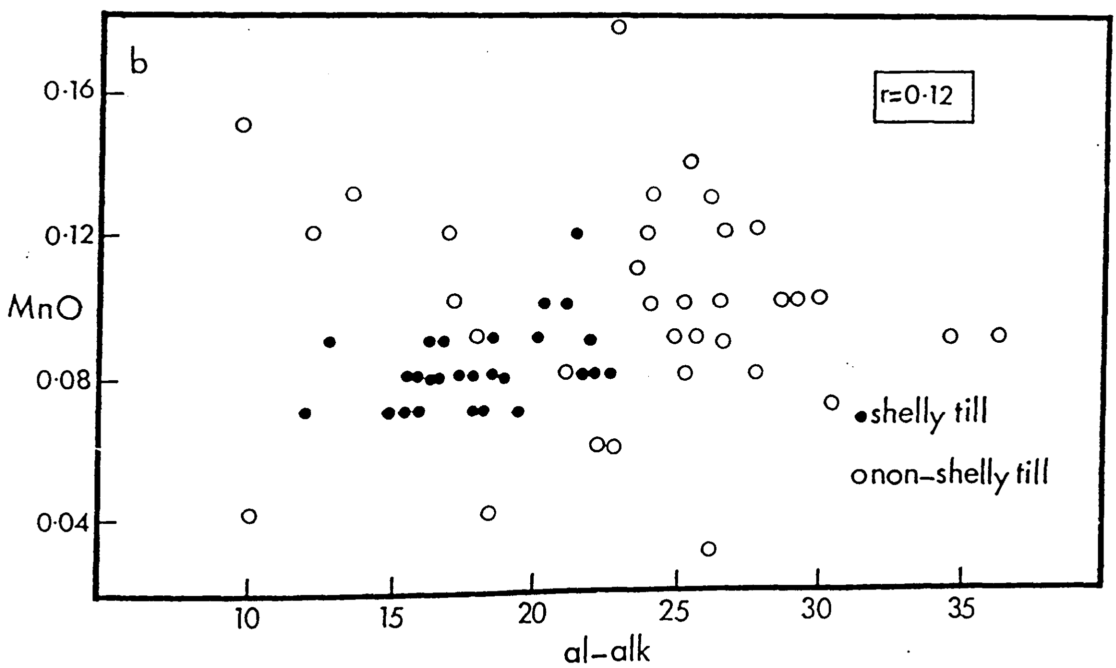


Figure 12.11 Plots of (a) TiO_2 against al-alk, and (b) MnO against al-alk

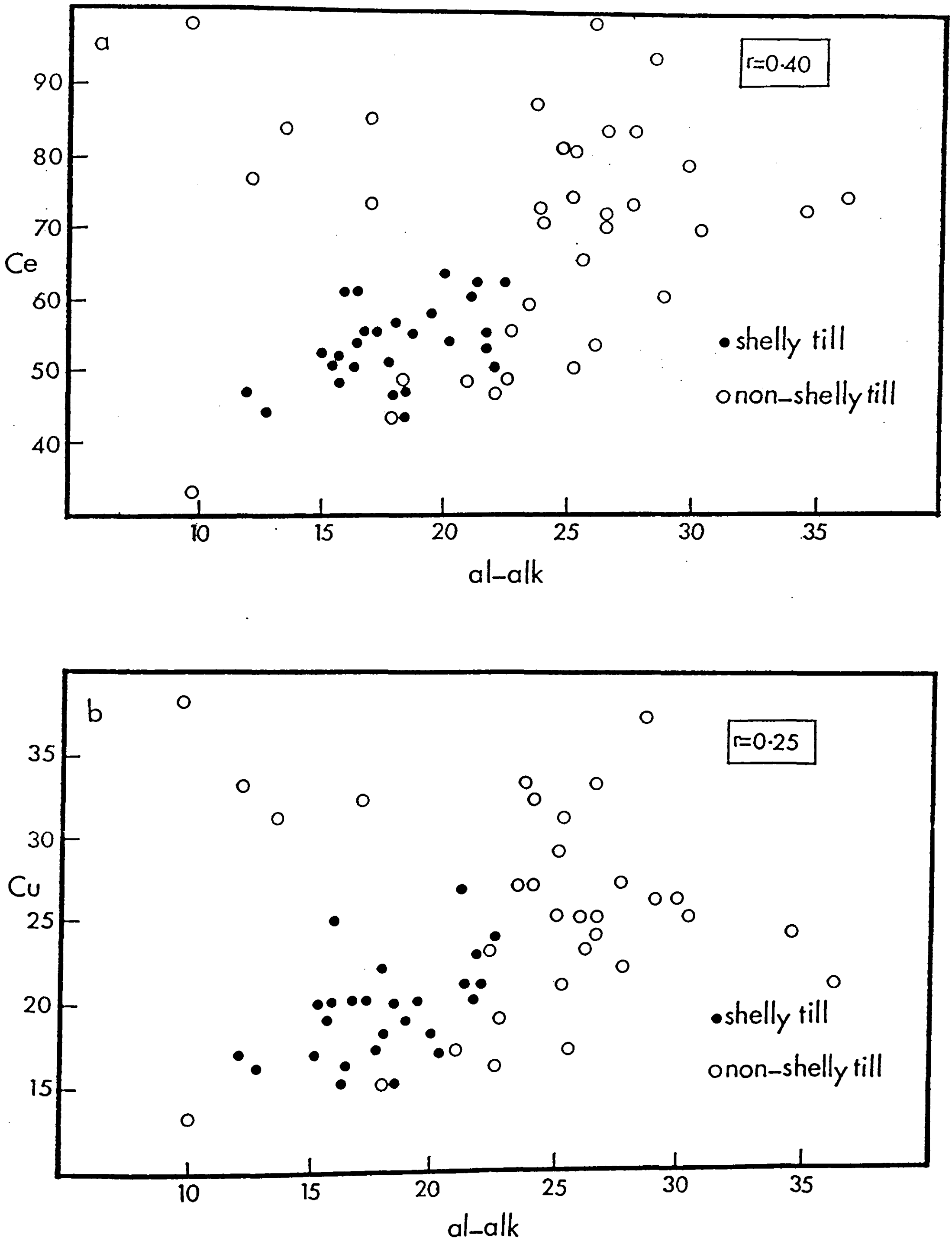


Figure 12.12 Plots of (a) Ce against al-alk, and (b) Cu against al-alk

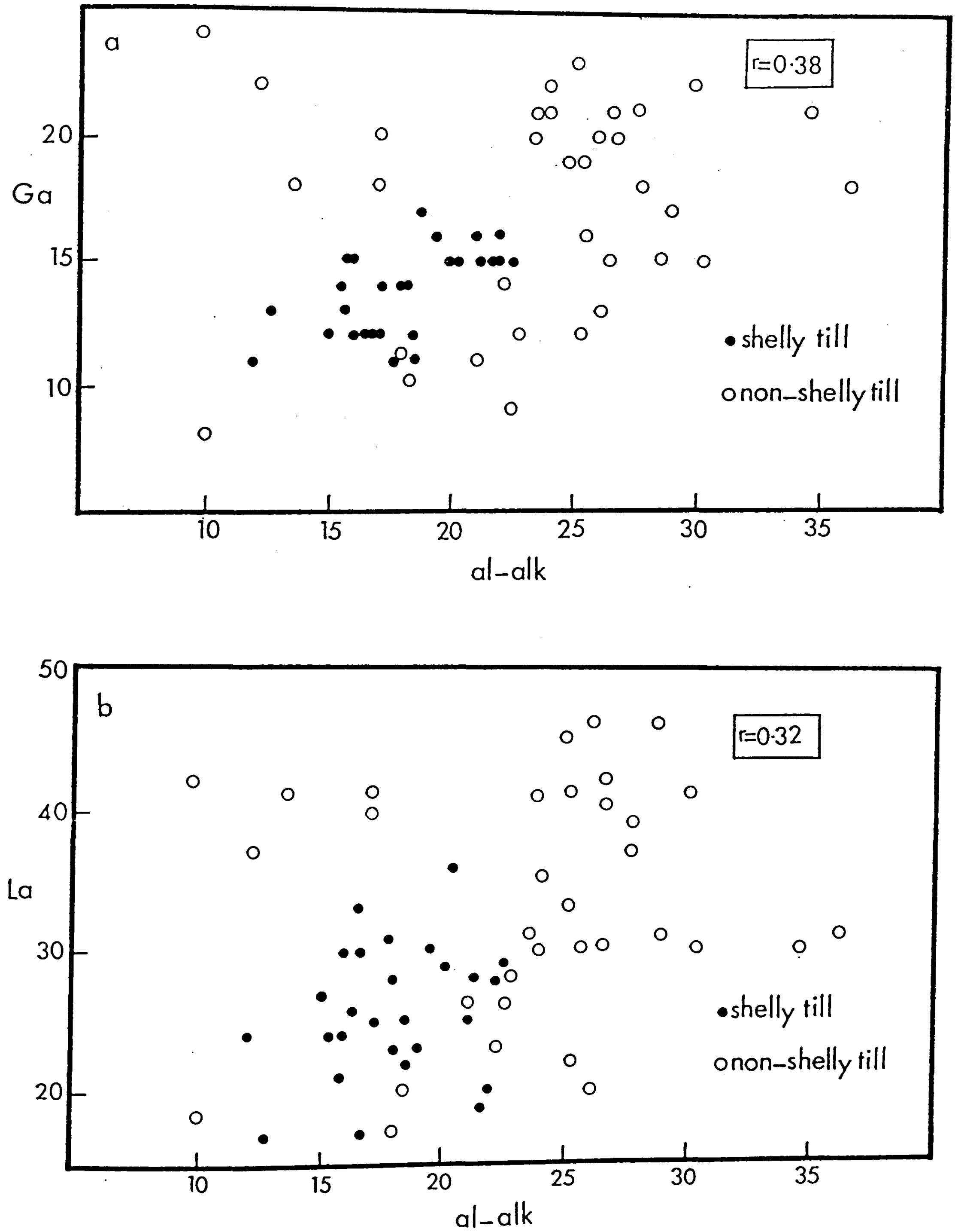
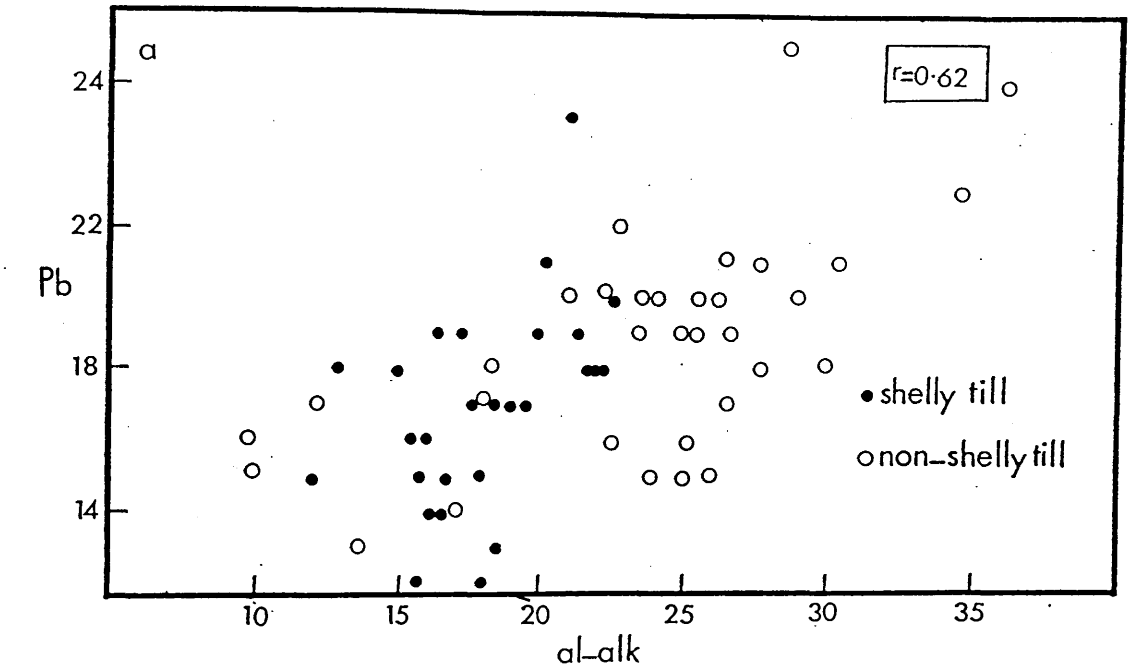


Figure 12.13 Plots of (a) Ga against al-alk, and (b) La against al-alk



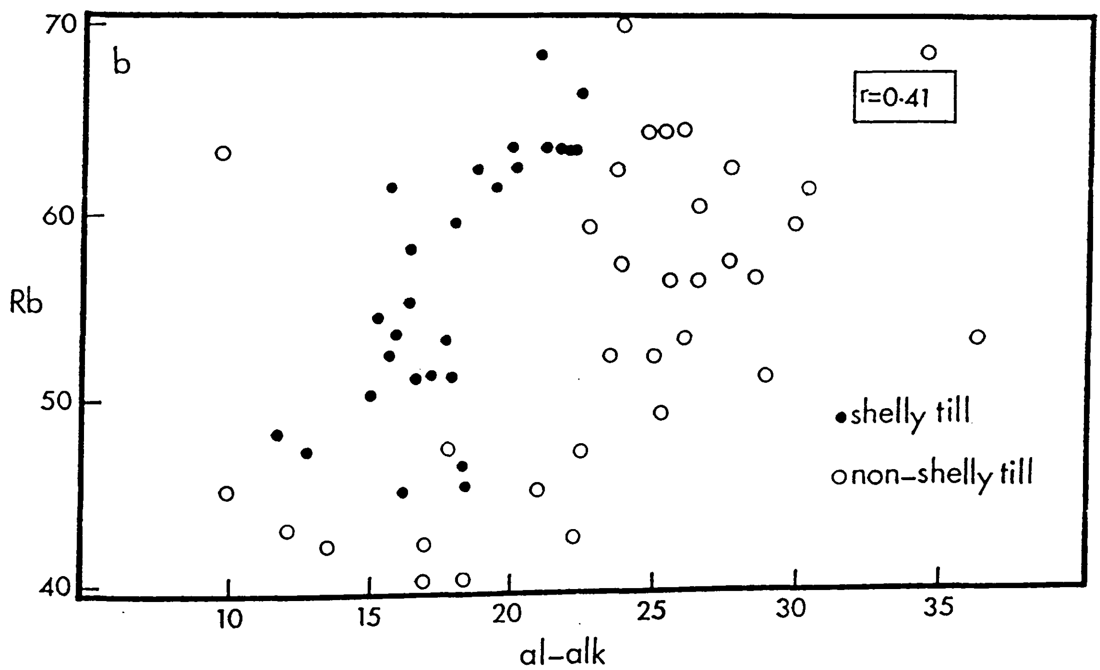
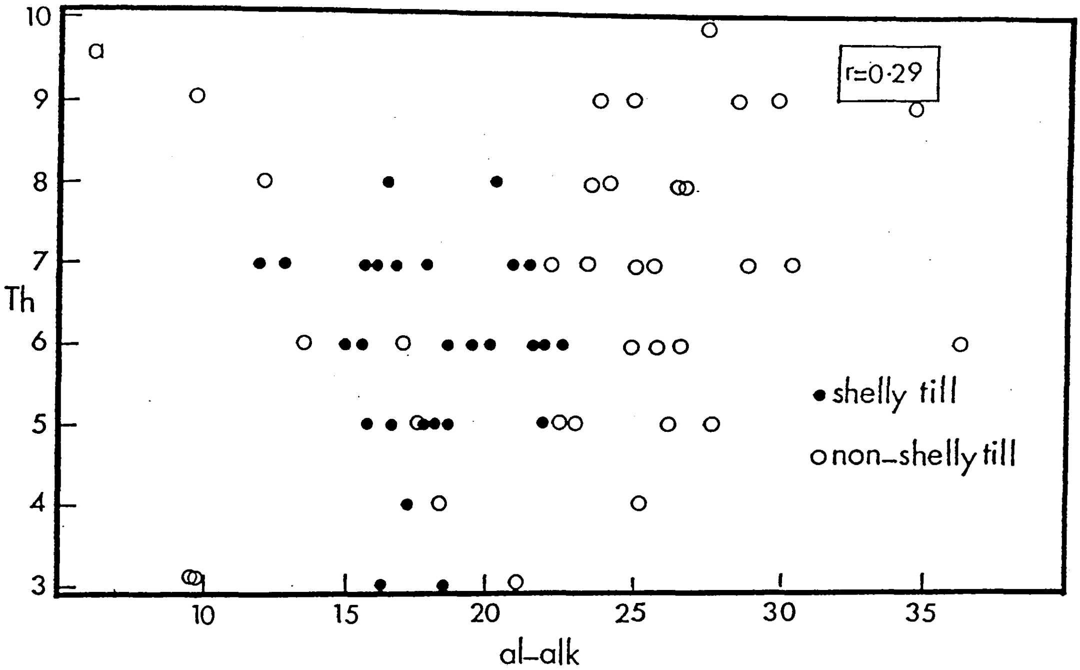


Figure 12.14 Plots of (a) Pb against al-alk, and (b) Rb against al-alk



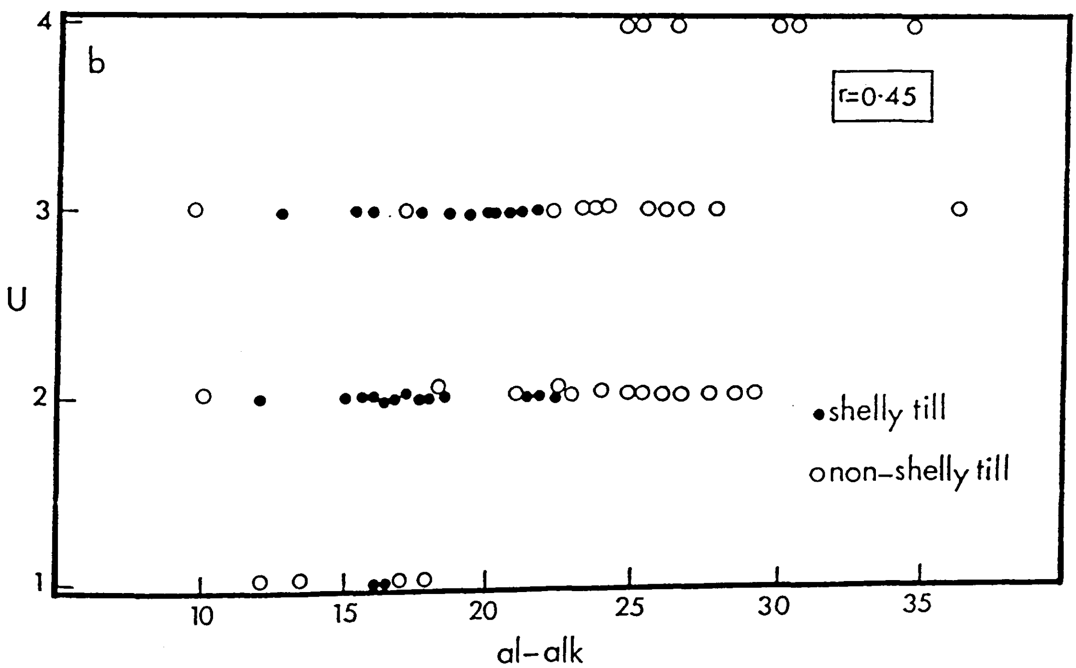


Figure. 12.15 Plots of (a) Th against al-alk, and (b) U against al-alk

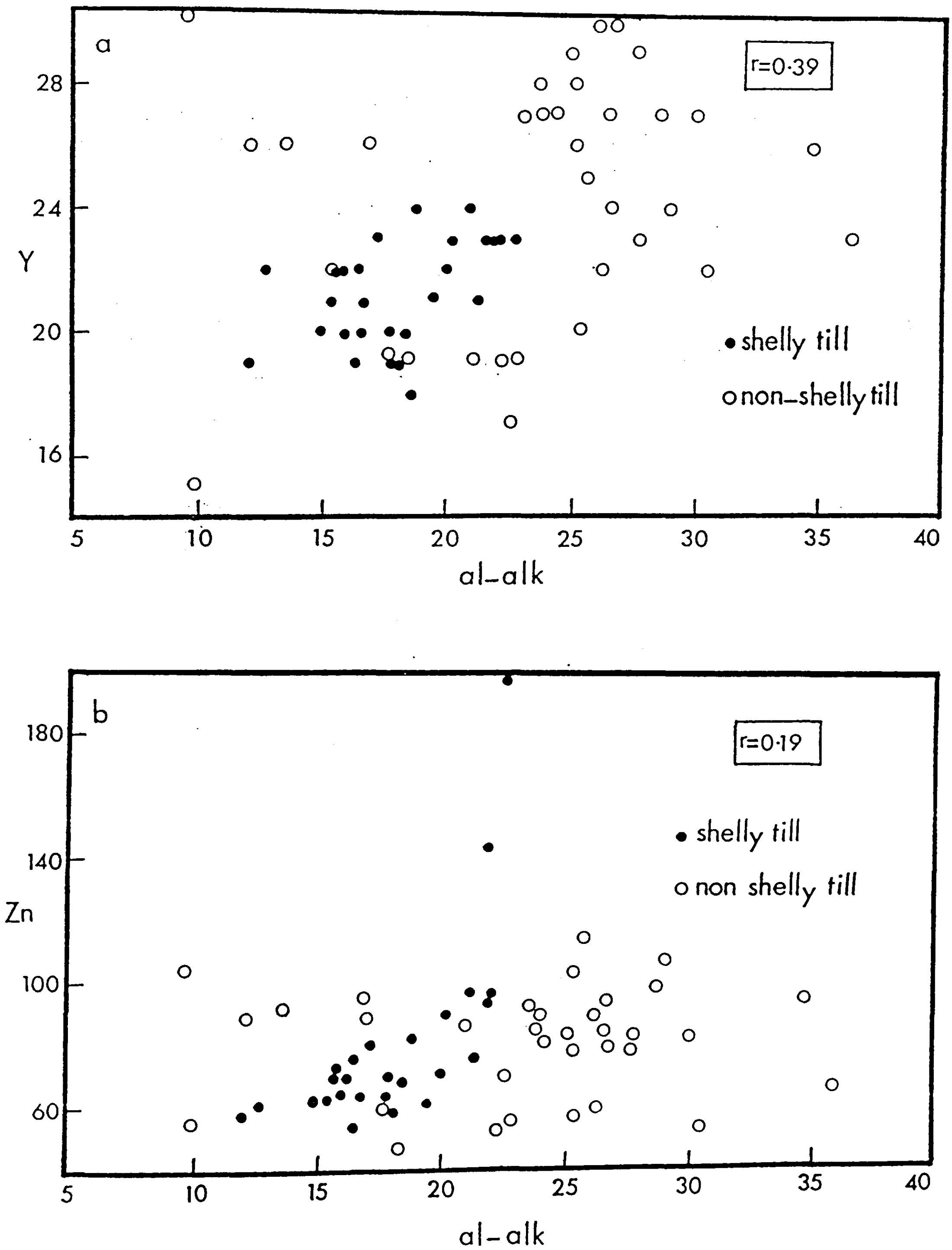


Figure 12.16 Plots of (a) Y against al-alk, and (b) Zn against al-alk

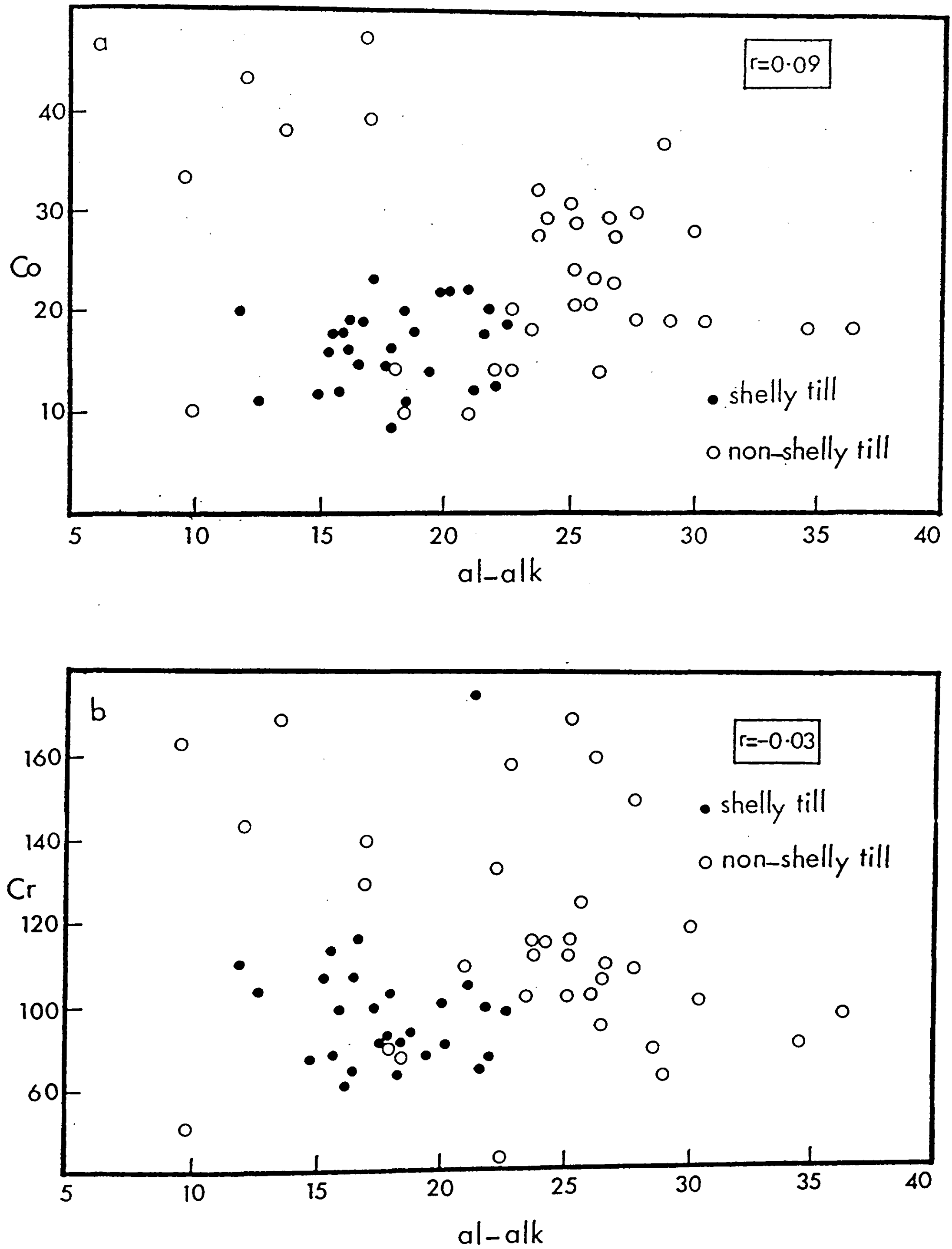


Figure 12.17 Plots of (a) Co against al-alk, and (b) Cr against al-alk

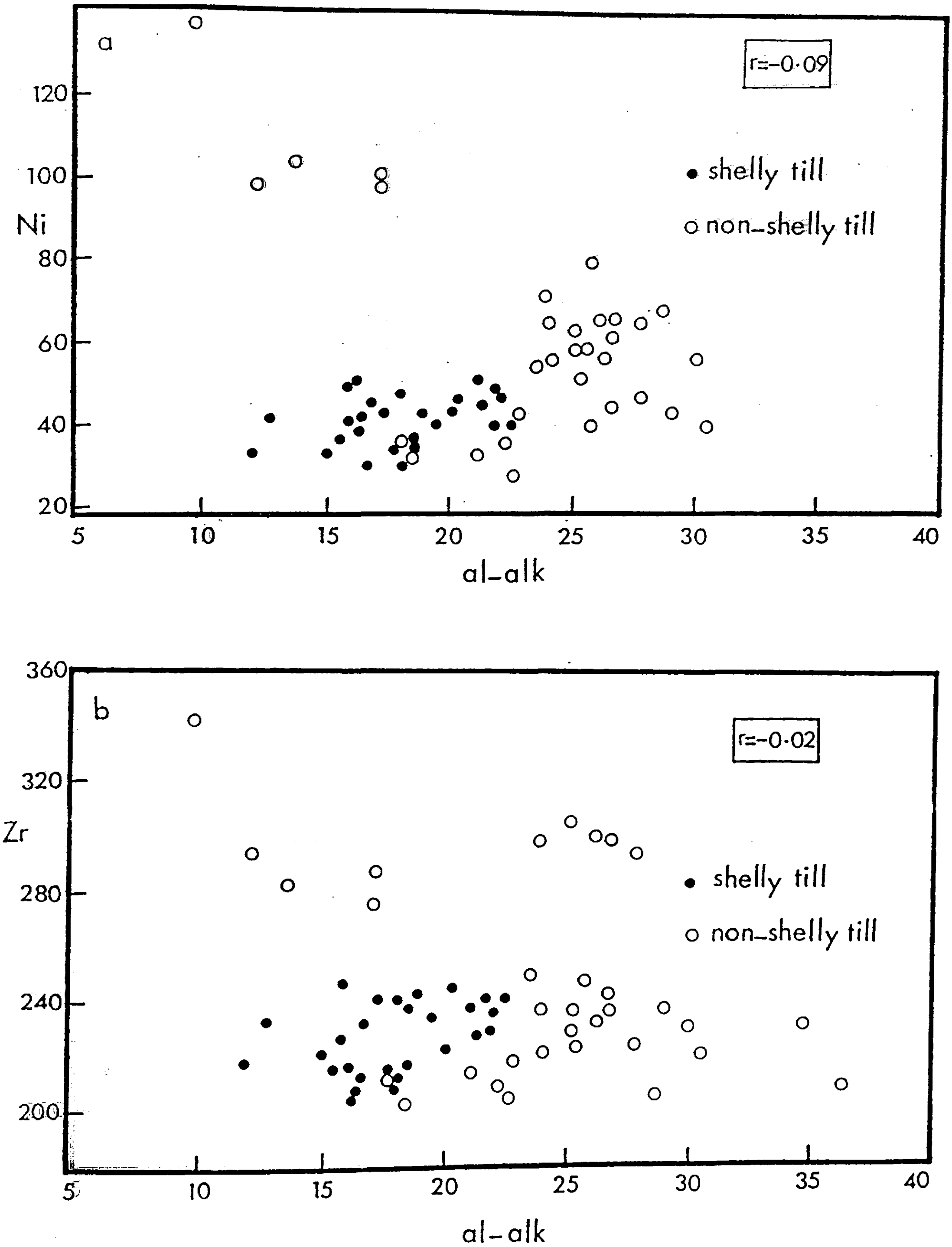
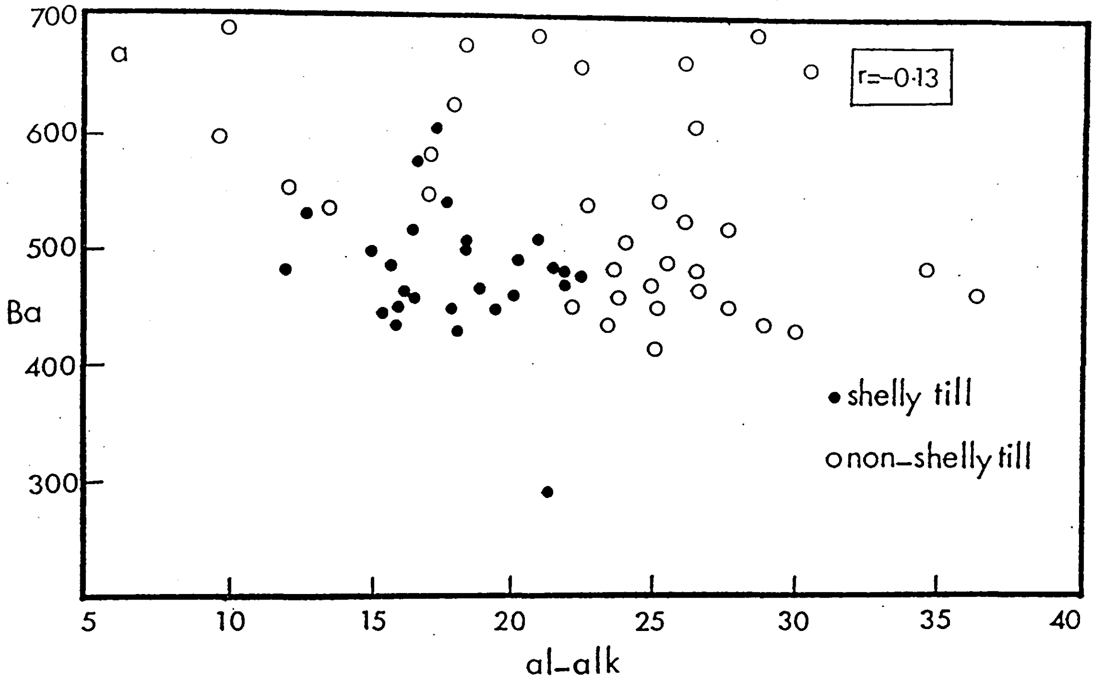


Figure 12.18 Plots of (a) Ni against al-alk, and (b) Zr against al-alk



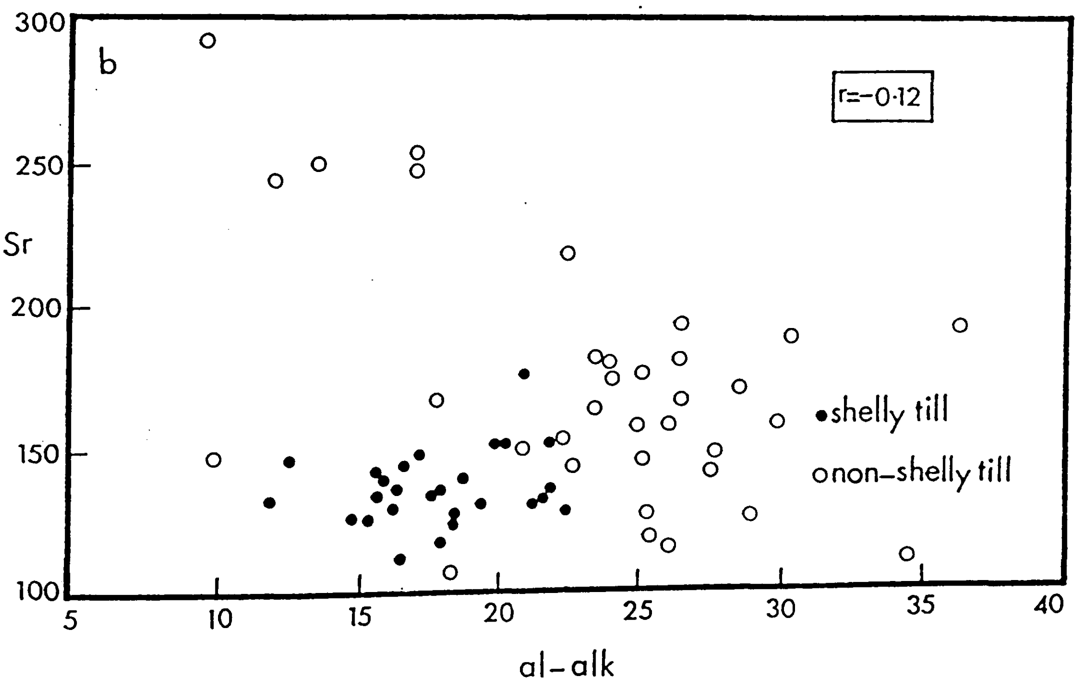


Figure 12.19 Plots of (a) Ba against al-alk, and (b) Sr against al-alk

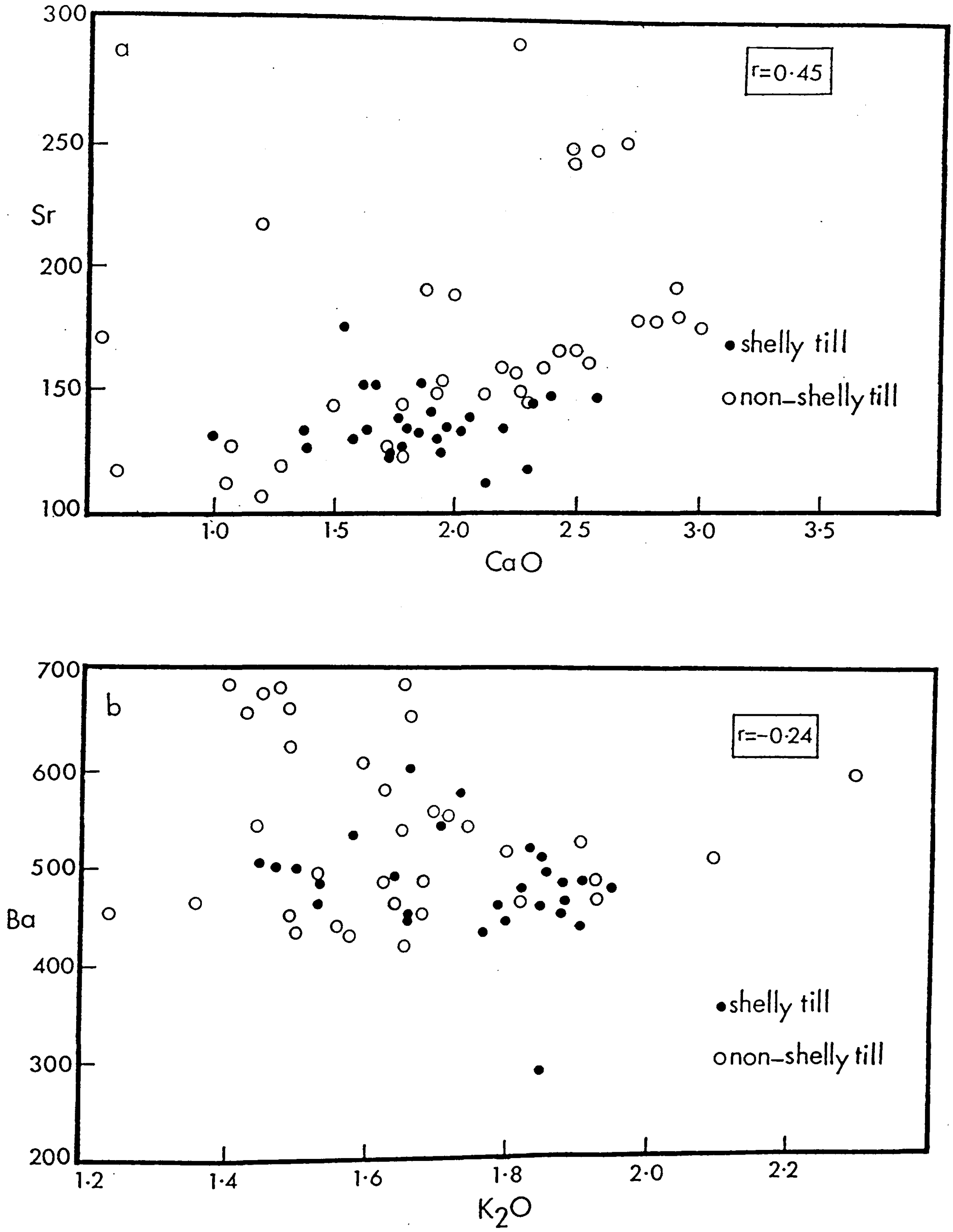


Figure 12.20 Plots of (a) Sr against CaO, and (b) Ba against K_2O

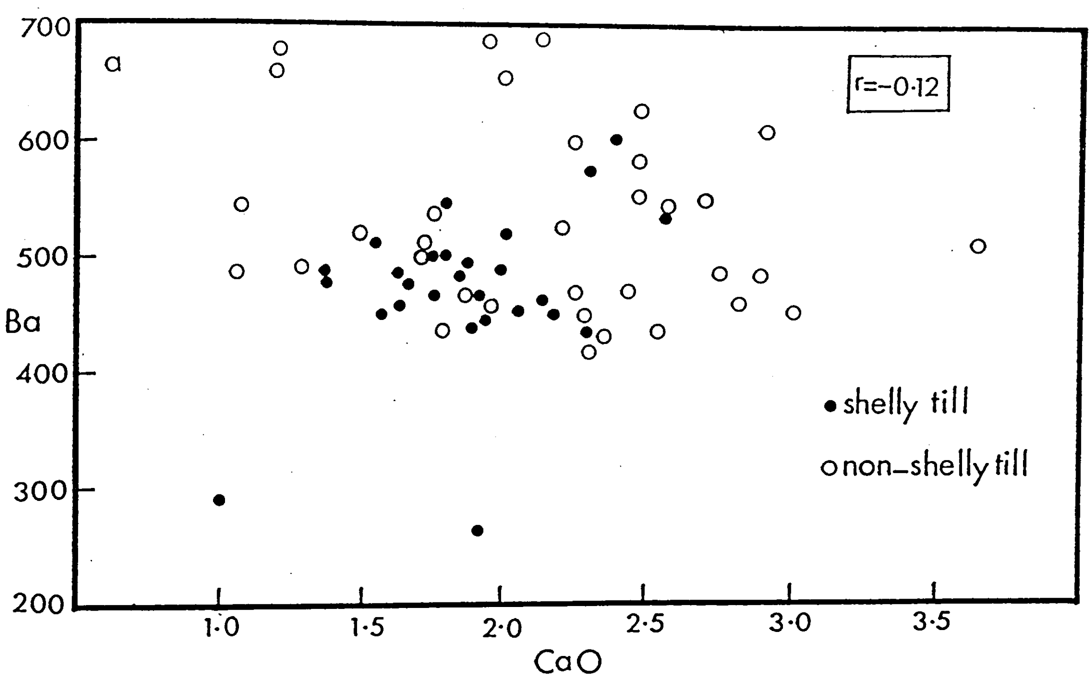


Figure 12.21 Plot of Ba against CaO

Table 12.1 Major element analysis of the till matrix (< 2 mm) of the Northern Ayrshire till samples. Code numbers of Locations and samples correspond with those shown in sketch sections included in the Figures for Chapter 12.

	2-1	2-2	2-3	2-4	2-5
SiO_2	59.82	57.03	61.02	74.73	72.71
TiO_2	1.18	1.17	1.16	0.80	0.75
Al_2O_3	15.86	17.46	15.54	9.66	11.25
Fe_2O_3	4.75	5.53	4.88	4.38	3.17
FeO	2.55	2.30	2.10	0.54	1.16
MnO	0.14	0.13	0.08	0.18	0.07
MgO	2.55	2.52	2.24	1.05	1.00
CaO	2.69	2.71	2.55	1.77	1.99
Na_2O	1.36	0.98	1.61	1.18	0.89
K_2O	2.95	3.09	2.77	1.74	1.66
P_2O_5	0.19	0.19	0.17	0.12	0.12
H_2O	5.04	4.31	3.26	2.18	2.74
CO_2	3.24	3.47	2.66	1.92	2.54
Total	102.32	100.89	100.04	100.25	100.05

	2-6	2-7	2-8	2-9	2-10
SiO_2	69.56	76.14	75.94	75.03	75.66
TiO_2	0.69	0.63	0.74	0.83	0.77
Al_2O_3	12.15	8.20	8.99	9.65	10.11
Fe_2O_3	3.21	3.25	3.78	4.93	5.15
FeO	1.33	0.92	0.72	0.52	0.61
MnO	0.09	0.06	0.08	0.14	0.03
MgO	0.95	0.89	0.98	1.35	1.07
CaO	1.88	1.95	1.94	1.06	0.62
Na_2O	0.66	1.12	1.35	1.03	1.20
K_2O	1.36	1.24	1.47	1.44	1.49
P_2O_5	0.11	0.11	0.13	0.12	0.12
H_2O	4.87	2.93	2.09	2.88	2.86
CO_2	3.84	2.86	1.83	1.55	0.75
Total	100.70	100.30	100.04	100.53	100.44

(Greenock Mains, Location 2)

Table 12.1 (continued)

	6-1	6-2	6-3	6-4
SiO_2	71.95	72.84	71.84	74.27
TiO_2	0.88	0.89	0.89	0.83
Al_2O_3	8.95	9.39	9.47	9.20
Fe_2O_3	4.47	4.00	4.23	4.12
FeO	1.21	1.43	1.30	1.13
MnO	0.09	0.08	0.09	0.08
MgO	1.52	1.74	1.56	1.18
CaO	2.58	2.41	2.32	1.80
Na_2O	2.08	1.52	1.64	1.58
K_2O	1.58	1.66	1.73	1.71
P_2O_5	0.14	0.14	0.15	0.14
H_2O	1.82	2.30	1.80	2.46
CO_2	2.49	2.41	2.13	2.03
Total	99.76	100.81	99.15	100.53

	6-5	6-6	6-7	6-8
SiO_2	77.13	76.67	75.93	76.49
TiO_2	0.85	0.81	0.82	0.85
Al_2O_3	8.48	8.54	8.76	7.84
Fe_2O_3	3.99	3.68	3.94	3.81
FeO	0.84	1.10	1.12	1.16
MnO	0.09	0.08	0.07	0.07
MgO	1.14	1.32	1.40	1.30
CaO	1.78	1.73	1.74	1.85
Na_2O	1.39	1.42	1.92	1.89
K_2O	1.50	1.45	1.47	1.53
P_2O_5	0.13	0.13	0.14	0.15
H_2O	1.90	2.47	1.78	1.62
CO_2	1.32	1.41	1.92	1.61
Total	100.54	100.81	101.01	100.17

(Greenock Mains, Location 6)

Table 12.1 (continued)

	8-1	8-2	8-3	8-4	8-6
SiO_2	72.31	73.35	73.57	73.88	74.80
TiO_2	0.87	0.87	0.89	0.90	0.80
Al_2O_3	10.08	9.36	9.97	9.31	8.97
Fe_2O_3	3.94	4.23	4.07	4.51	3.67
FeO	1.33	1.33	1.23	1.36	1.14
MnO	0.09	0.08	0.07	0.08	0.08
MgO	1.47	1.39	1.70	1.77	1.61
CaO	2.02	1.99	2.19	2.05	1.92
Na_2O	1.97	1.88	1.73	1.68	1.75
K_2O	1.83	1.64	1.66	1.66	1.53
P_2O_5	0.16	0.15	0.14	0.14	0.14
H_2O	2.70	2.39	2.12	1.61	2.68
CO_2	1.99	1.68	1.44	1.70	1.45
Total	100.76	100.34	100.78	100.65	100.54

	8-7	8-8	8-9	8-10
SiO_2	79.24	81.37	76.53	80.83
TiO_2	0.61	0.64	0.69	0.53
Al_2O_3	7.11	6.71	7.35	5.92
Fe_2O_3	3.89	3.77	4.82	3.31
FeO	0.32	0.40	0.40	0.31
MnO	0.06	0.04	0.09	0.04
MgO	0.42	0.34	0.73	0.49
CaO	1.19	1.20	2.48	2.13
Na_2O	0.83	1.07	0.93	1.49
K_2O	1.43	1.45	1.49	1.40
P_2O_5	0.10	0.10	0.10	0.08
H_2O	2.02	1.68	2.34	2.19
CO_2	1.17	1.01	2.27	1.74
Total	98.39	99.78	100.22	100.46

(Merkland Burn, Location 8)

Table 12.1 (continued)

	5-1-1	5-1-2	5-1-3	5-1-4	5-1-5	5-1-6
SiO_2	70.66	75.17	72.47	71.45	71.02	72.83
TiO_2	0.88	0.93	0.93	0.96	0.94	0.90
Al_2O_3	10.65	10.31	10.89	11.05	11.23	10.80
Fe_2O_3	4.02	3.89	4.34	4.25	4.06	4.36
FeO	1.46	1.50	1.31	1.30	1.39	1.24
MnO	0.08	0.07	0.07	0.08	0.08	0.12
MgO	1.58	1.67	1.50	1.53	1.53	1.41
CaO	1.76	1.90	1.58	1.37	1.38	1.00
Na_2O	1.81	2.08	1.84	1.59	1.54	1.69
K_2O	1.88	1.90	1.88	1.91	1.95	1.85
P_2O_5	0.15	0.17	0.15	0.16	0.16	0.14
H_2O	2.81	2.57	1.37	2.82	3.10	1.49
CO_2	2.22	2.03	1.95	1.46	1.79	1.34
Total	99.96	100.59	100.28	99.93	100.17	99.96

	5-2-1	5-2-2	5-2-3	5-2-4	5-2-5	5-3-1	5-3-2
SiO_2	70.53	71.42	70.73	71.65	71.55	69.92	67.06
TiO_2	0.93	0.93	0.96	0.99	0.91	0.89	0.97
Al_2O_3	11.60	11.23	10.79	10.72	11.33	11.88	11.56
Fe_2O_3	5.40	4.27	4.41	4.06	3.75	8.99	5.78
FeO	1.28	1.50	1.51	1.53	1.50	0.32	0.36
MnO	0.10	0.09	0.10	0.08	0.09	0.10	0.09
MgO	1.53	1.63	1.59	1.67	1.58	0.80	1.06
CaO	1.54	1.63	1.87	1.67	1.63	0.55	2.91
Na_2O	1.77	1.85	1.58	1.37	1.67	0.91	0.99
K_2O	1.85	1.85	1.86	1.82	1.88	1.65	1.63
P_2O_5	0.15	0.16	0.16	0.15	0.15	0.16	0.14
H_2O	1.97	2.79	2.59	2.62	2.45	3.18	4.05
CO_2	1.96	1.70	1.92	1.92	1.22	0.82	4.19
Total	100.59	100.28	99.93	100.25	99.71	100.17	100.79

(Sorn Mains, Locations 5-1, 5-2 and 5-3)

Table 12.1 (continued)

	3-1	3-2	3-3	3-4
SiO_2	63.74	64.84	66.69	63.34
TiO_2	1.12	1.13	0.99	1.13
Al_2O_3	13.42	12.88	12.80	13.46
Fe_2O_3	4.07	3.80	3.36	3.97
FeO	2.78	2.77	2.59	2.88
MnO	0.10	0.08	0.08	0.10
MgO	1.73	1.55	1.46	1.76
CaO	2.82	3.01	2.29	2.92
Na_2O	1.75	1.49	1.23	1.30
K_2O	1.64	1.49	1.68	1.59
P_2O_5	0.19	0.19	0.16	0.19
H_2O	3.83	3.68	3.68	3.16
CO_2	2.95	3.50	3.02	3.82
Total	100.14	100.41	100.03	99.62

	3-5	3-6	3-7	3-8
SiO_2	65.81	69.08	71.79	66.77
TiO_2	1.04	0.95	0.94	0.97
Al_2O_3	12.18	11.46	10.76	13.71
Fe_2O_3	4.12	3.31	3.38	2.44
FeO	2.34	2.05	2.10	2.80
MnO	0.11	0.10	0.09	0.09
MgO	1.35	1.21	0.99	1.10
CaO	2.55	1.77	1.28	1.05
Na_2O	1.68	0.99	1.37	1.12
K_2O	1.50	1.56	1.53	1.68
P_2O_5	0.20	0.16	0.14	0.13
H_2O	2.28	2.02	3.27	3.43
CO_2	5.06	5.96	2.42	5.35
Total	100.22	100.62	100.06	100.64

(Sourlie, Location 3)

Table 12.1 (continued)

	13-1	13-2	13-3
SiO_2	75.30	74.39	75.19
TiO_2	0.77	0.80	0.75
Al_2O_3	9.01	9.42	8.58
Fe_2O_3	2.42	2.77	2.68
FeO	1.76	1.65	1.63
MnO	0.07	0.08	0.07
MgO	1.25	1.37	1.19
CaO	2.30	2.14	1.94
Na_2O	1.44	1.79	1.65
K_2O	1.77	1.79	1.80
P_2O_5	0.13	0.15	0.13
H_2O	1.67	2.16	2.53
CO_2	2.51	2.07	1.95
Total	100.40	100.58	100.09

	13-4	13-5	13-6
SiO_2	59.79	61.90	61.03
TiO_2	1.14	1.18	1.18
Al_2O_3	14.53	13.86	14.75
Fe_2O_3	4.02	4.85	3.81
FeO	2.60	3.52	3.07
MnO	0.13	0.10	0.10
MgO	2.58	1.64	1.79
CaO	3.64	2.30	2.36
Na_2O	1.45	1.56	1.28
K_2O	2.09	1.66	1.57
P_2O_5	0.19	0.20	0.20
H_2O	2.04	4.85	5.62
CO_2	4.70	3.52	2.96
Total	98.90	101.14	99.72

(Sourlie, Location 13)

Table 12.1 (continued)

	5B-1	5B-2	5B-3	5B-4	5B-5
SiO_2	62.45	61.57	62.82	60.16	60.68
TiO_2	1.76	1.80	1.77	1.91	1.46
Al_2O_3	12.18	11.58	10.53	13.22	14.24
Fe_2O_3	8.54	8.54	8.56	8.59	5.98
FeO	0.92	0.98	0.95	1.18	2.15
MnO	0.10	0.13	0.12	0.12	0.12
MgO	3.17	3.20	3.39	3.52	2.31
CaO	2.48	2.58	2.48	2.71	2.76
Na_2O	2.00	2.47	2.25	2.25	1.56
K_2O	1.62	1.65	1.70	1.71	1.92
P_2O_5	0.32	0.32	0.32	0.34	0.25
H_2O	3.08	3.59	3.98	3.59	4.15
CO_2	1.40	1.12	1.13	1.18	3.21
Total	100.02	99.53	100.00	100.48	100.79

	5B-6	5B-7	5B-8	7B-1	7B-2
SiO_2	62.57	61.64	63.21	60.82	60.97
TiO_2	1.41	1.40	1.34	1.84	1.32
Al_2O_3	14.27	14.09	14.07	10.98	14.06
Fe_2O_3	5.58	5.77	6.66	8.53	5.23
FeO	2.23	1.99	1.03	1.63	2.19
MnO	0.09	0.13	0.12	0.15	0.12
MgO	1.85	2.00	1.64	2.83	2.00
CaO	2.25	2.21	1.49	2.26	2.45
Na_2O	1.62	1.36	1.45	2.69	1.30
K_2O	1.93	1.90	1.80	2.29	1.82
P_2O_5	0.24	0.24	0.23	0.33	0.22
H_2O	3.46	4.27	3.12	3.77	4.45
CO_2	3.10	3.33	3.83	1.02	4.22
Total	100.60	100.33	99.99	99.14	100.35

(Tayburn, Locations 5B and 7B)

Table 12.2 Trace element contents (in ppm) of the Northern Ayrshire till samples. Code numbers of Locations and samples correspond with those shown in sketch sections included in the Figures for Chapter 12.

	2-1	2-2	2-3	2-4	2-5
Ba	702	770	699	536	653
Ce	83	84	78	55	69
Co	32	28	23	20	19
Cr	138	132	125	157	100
Cu	33	39	35	19	25
Ga	23	23	23	12	15
La	38	33	37	28	30
Ni	59	70	63	42	39
Pb	31	27	26	22	21
Rb	103	115	102	59	61
Sr	170	183	176	143	188
Th	11	9	11	5	7
U	4	3	4	2	4
Y	30	33	32	19	22
Zn	107	108	101	54	52
Zr	239	234	255	217	219

	2-6	2-7	2-8	2-9	2-10
Ba	462	450	681	541	660
Ce	74	47	48	50	53
Co	18	14	10	21	14
Cr	97	132	108	168	159
Cu	21	23	17	21	23
Ga	18	14	11	12	13
La	31	23	26	22	20
Ni	42	35	32	58	56
Pb	26	20	20	19	20
Rb	53	42	45	49	53
Sr	191	152	149	126	116
Th	6	7	3	4	5
U	3	3	2	2	2
Y	23	19	19	20	22
Zn	65	51	85	56	59
Zr	208	208	213	223	230

(Greenock Mains, Location 2)

Table 12.2 (continued)

	6-1	6-2	6-3	6-4
Ba	535	603	577	543
Ce	44	55	55	51
Co	11	23	19	15
Cr	104	100	116	91
Cu	16	20	20	17
Ga	13	14	12	11
La	17	25	17	31
Ni	41	42	45	34
Pb	18	19	15	17
Rb	47	51	51	53
Sr	147	148	145	134
Th	7	4	7	7
U	3	2	2	3
Y	22	23	21	20
Zn	60	79	64	63
Zr	232	241	231	214

	6-5	6-6	6-7	6-8
Ba	500	503	502	482
Ce	43	47	52	47
Co	11	20	12	20
Cr	91	84	87	110
Cu	20	15	17	17
Ga	12	11	12	11
La	25	22	27	24
Ni	35	34	33	32
Pb	13	17	18	15
Rb	45	46	50	48
Sr	126	125	126	132
Th	5	3	6	7
U	2	2	2	2
Y	20	18	20	19
Zn	66	66	62	58
Zr	237	216	219	217

(Greenock Mains, Location 6)

Table 12.2 (continued)

	8-1	8-2	8-3	8-4	8-6
Ba	518	489	450	452	461
Ce	61	48	48	61	50
Co	19	18	16	18	16
Cr	84	113	92	99	81
Cu	16	19	22	25	15
Ga	12	13	14	15	12
La	33	24	28	30	26
Ni	41	49	47	50	38
Pb	19	12	15	16	14
Rb	55	52	51	53	45
Sr	134	134	135	139	130
Th	8	7	5	7	8
U	1	2	2	2	1
Y	22	22	19	20	19
Zn	75	70	70	64	69
Zr	207	226	207	216	205

	8-7	8-8	8-9	8-10
Ba	656	673	624	687
Ce	48	48	43	32
Co	14	10	14	10
Cr	62	87	90	70
Cu	16	15	15	13
Ga	9	10	11	8
La	26	20	17	18
Ni	27	32	34	20
Pb	16	18	17	15
Rb	47	40	47	45
Sr	217	106	166	147
Th	5	4	5	3
U	2	2	1	2
Y	17	19	19	15
Zn	68	46	58	54
Zr	205	201	210	185

(Merkland Burn, Location 8)

Table 12.2 (continued)

	5-1-1	5-1-2	5-1-3	5-1-4	5-1-5	5-1-6
Ba	468	441	449	485	478	289
Ce	55	52	58	55	62	62
Co	18	12	14	18	19	12
Cr	93	88	88	85	98	174
Cu	19	20	20	20	24	21
Ga	17	15	16	15	15	15
La	23	21	30	19	29	28
Ni	43	40	40	39	39	45
Pb	17	15	17	18	20	19
Rb	62	61	61	63	66	63
Sr	138	141	131	133	129	131
Th	6	5	6	6	6	7
U	3	3	3	2	2	3
Y	24	22	21	23	23	21
Zn	81	71	61	143	198	75
Zr	242	246	233	240	241	227

	5-2-1	5-2-2	5-2-3	5-2-4	5-2-5	5-3-1	5-3-2
Ba	509	459	493	474	483	684	481
Ce	60	63	54	50	53	93	70
Co	22	22	22	13	20	37	23
Cr	104	101	90	87	99	88	94
Cu	27	18	17	21	23	37	24
Ga	16	15	15	16	15	15	15
La	25	29	36	28	20	46	30
Ni	51	44	46	47	48	67	44
Pb	25	19	21	18	18	27	21
Rb	68	63	62	63	63	56	56
Sr	176	152	152	152	134	170	192
Th	7	6	8	5	6	9	8
U	3	3	3	2	3	2	2
Y	24	22	23	23	23	27	24
Zn	96	70	89	94	93	98	82
Zr	237	222	244	235	229	205	239

(Sorn Mains, Locations 5-1, 5-2 and 5-3)

Table 12.2 (continued)

	3-1	3-2	3-3	3-4
Ba	457	448	448	604
Ce	72	74	73	71
Co	28	24	19	29
Cr	114	112	148	105
Cu	27	31	22	33
Ga	21	19	18	20
La	30	33	37	40
Ni	64	51	46	60
Pb	20	16	18	17
Rb	57	52	57	56
Sr	178	175	147	180
Th	9	7	5	6
U	3	4	3	4
Y	27	26	23	27
Zn	83	102	78	92
Zr	235	235	223	235

	3-5	3-6	3-7	3-8
Ba	435	435	488	483
Ce	59	60	65	72
Co	18	19	21	18
Cr	101	82	124	90
Cu	27	26	17	24
Ga	20	17	16	21
La	31	31	30	30
Ni	53	42	39	45
Pb	19	20	20	23
Rb	52	51	56	68
Sr	163	125	118	111
Th	7	7	7	9
U	3	2	3	4
Y	27	24	25	26
Zn	89	106	113	92
Zr	248	236	246	230

(Sourlie, Location 3)

Table 12.2 (continued)

	13-1	13-2	13-3
Ba	431	460	447
Ce	57	54	51
Co	9	15	16
Cr	103	107	107
Cu	18	16	20
Ga	14	12	14
La	23	30	24
Ni	30	30	36
Pb	12	14	16
Rb	59	58	54
Sr	117	112	125
Th	5	5	6
U	2	2	3
Y	19	20	21
Zn	58	54	62
Zr	211	211	215

	13-4	13-5	13-6
Ba	505	413	429
Ce	71	81	78
Co	29	29	28
Cr	114	114	117
Cu	32	29	26
Ga	22	23	22
La	35	41	41
Ni	55	58	55
Pb	15	19	18
Rb	70	64	59
Sr	176	145	158
Th	8	6	9
U	2	2	4
Y	27	28	27
Zn	82	78	81
Zr	220	227	229

(Sourlie, Location 13)

Table 12.2 (continued)

	5B-1	5B-2	5B-3	5B-4	5B-5
Ba	579	534	550	546	482
Ce	73	83	76	85	87
Co	39	38	43	47	32
Cr	139	168	142	129	112
Cu	32	31	33	32	33
Ga	18	18	22	20	21
La	40	41	37	41	41
Ni	99	103	97	98	71
Pb	14	13	17	14	20
Rb	42	42	43	40	62
Sr	248	248	243	251	179
Th	6	6	8	6	8
U	3	1	1	1	3
Y	26	26	26	26	28
Zn	88	91	88	94	88
Zr	285	281	293	275	297

	5B-6	5B-7	5B-8	7B-1	7B-2
Ba	468	523	518	595	465
Ce	81	99	89	98	83
Co	31	23	30	33	28
Cr	101	102	108	163	108
Cu	25	25	27	38	25
Ga	19	20	21	24	21
La	45	46	39	42	42
Ni	62	65	64	136	65
Pb	15	15	21	16	19
Rb	64	64	62	63	60
Sr	157	158	143	291	166
Th	9	6	10	9	8
U	4	3	2	3	3
Y	29	30	29	30	30
Zn	81	88	80	103	80
Zr	304	299	293	341	297

(Tayburn, Locations 5B and 7B)

Table 12.3 Range, average ($\overline{X}$) and standard deviation (S) of major element data for the shelly till, non-shelly tills and "shelly till" at Location 2.

		SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O	CO_2
N Ayrshire shelly till	Range	70.53 to 77.13	0.75 to 0.99	7.84 to 11.60	2.42 to 5.40	0.84 to 1.76	0.07 to 0.12	1.14 to 1.77	1.00 to 2.58	1.37 to 2.08	1.45 to 1.95	0.13 to 0.17	1.37 to 3.10	1.22 to 2.51
(N = 27)	$\overline{X}$	73.18	0.88	9.85	3.98	1.34	0.08	1.49	1.86	1.71	1.74	0.15	2.44	1.84
	S	1.99	0.06	1.12	0.59	0.20	0.01	0.17	0.34	0.62	0.15	0.01	0.48	0.35
N Ayrshire non-shelly tills	Range	59.79 to 81.37	0.53 to 1.91	5.92 to 14.75	2.44 to 8.99	0.31 to 3.52	0.03 to 0.18	0.34 to 3.52	0.55 to 3.64	0.66 to 2.69	1.24 to 2.29	0.08 to 0.34	1.68 to 5.62	0.75 to 5.96
(N = 34)	$\overline{X}$	67.83	1.10	11.58	5.05	1.55	0.10	1.59	2.10	1.41	1.64	0.18	3.27	2.74
	S	6.77	0.39	2.45	1.93	0.98	0.03	0.86	0.71	0.47	0.21	0.08	0.95	1.41
"Shelly till" at Greenock Mains, Location 2	Range	57.03 to 61.02	1.16 to 1.18	15.54 to 17.46	4.75 to 5.53	2.10 to 2.55	0.08 to 0.14	2.24 to 2.55	2.55 to 2.71	0.98 to 1.61	2.77 to 3.09	0.17 to 0.19	3.26 to 5.04	2.66 to 3.47
(N = 3)	$\overline{X}$	59.29	1.17	16.29	5.05	2.32	0.12	2.44	2.65	1.31	2.94	0.19	4.20	3.12
	S	2.05	0.01	1.03	0.42	0.23	0.03	0.17	0.09	0.32	0.16	0.01	0.89	0.42

Table 12.4 Correlation coefficients of sand, silt and clay with the major oxides in the combined shelly till (N = 27) and non-shelly till (N = 34) samples from Northern Ayrshire.

Major oxide	sand (2.0 - 0.063mm)	silt (0.063 - 0.002mm)	clay (< 0.002mm)
SiO_2	0.77	-0.57	-0.72
TiO_2	-0.57	0.45	0.49
Al_2O_3	-0.84	0.66	0.72
Fe_2O_3	-0.29	0.25	0.20
FeO	-0.66	0.50	0.58
MnO	-0.47	0.34	0.47
MgO	-0.45	0.40	0.32
CaO	-0.21	0.10	0.32
Na_2O	-0.19	0.28	-0.11
K_2O	-0.58	0.60	0.22
P_2O_5	-0.54	0.42	0.46
H_2O	-0.52	0.29	0.68
CO_2	-0.39	0.21	0.52

Table 12.5 Correlation coefficients of sand, silt and clay with the trace elements in the combined shelly till (N = 27) and non-shelly till (N = 34) samples from Northern Ayrshire.

Trace element	sand (2.0 - 0.063mm)	silt (0.063 - 0.002mm)	clay (<0.002mm)
Ba	0.44	-0.45	-0.16
Ce	-0.74	0.54	0.70
Co	-0.55	0.42	0.48
Cr	-0.13	-0.02	0.34
Cu	-0.57	0.41	0.56
Ga	-0.78	0.55	0.78
La	-0.66	0.50	0.59
Ni	-0.46	0.32	0.47
Pb	-0.18	0.13	0.16
Rb	-0.68	0.65	0.36
Sr	-0.21	0.07	0.37
Th	-0.65	0.56	0.45
U	-0.39	0.28	0.37
Y	-0.81	0.63	0.70
Zn	-0.44	0.46	0.15
Zr	-0.58	0.47	0.45

Table 12.6 Correlation coefficients for the Northern Ayrshire shelly till (N = 27) and non-shelly till (N = 34) major element data.

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O	CO_2
SiO_2	1.00												
TiO_2	-0.85	1.00											
Al_2O_3	-0.90	0.62	1.00										
Fe_2O_3	-0.54	0.78	0.31	1.00									
FeO	-0.62	0.30	0.70	-0.23	1.00								
MnO	-0.61	0.59	0.50	0.50	0.19	1.00							
MgO	-0.74	0.91	0.50	0.66	0.27	0.53	1.00						
CaO	-0.54	0.43	0.32	0.11	0.42	0.27	0.51	1.00					
Na_2O	-0.27	0.55	0.02	0.40	0.08	0.20	0.69	0.28	1.00				
K_2O	-0.45	0.44	0.43	0.26	0.28	0.41	0.48	0.12	0.46	1.00			
P_2O_5	-0.83	0.99	0.58	0.78	0.28	0.56	0.91	0.44	0.60	0.43	1.00		
H_2O	-0.70	0.52	0.67	0.33	0.45	0.33	0.35	0.27	-0.08	0.06	0.49	1.00	
CO_2	-0.46	0.06	0.55	-0.27	0.62	0.20	-0.06	0.39	-0.36	-0.01	0.02	0.31	1.00

Table 12.7 Range, average ($\overline{X}$) and standard deviation (S) of trace element composition (in ppm) of Northern Ayrshire shelly till, non-shelly till and "shelly till" at Location 2.

	shelly till			non-shelly tills			"shelly till", Location 2		
	Range	$\overline{X}$	S	Range	$\overline{X}$	S	Range	$\overline{X}$	S
Ba	289 - 603	481	56	413 - 687	535	87	699 - 770	724	40
Ce	43 - 63	54	6	32 - 99	69	16	78 - 84	82	3
Co	9 - 23	17	4	10 - 47	24	10	23 - 32	28	5
Cr	81 - 174	99	18	62 - 168	115	28	125 - 138	132	7
Cu	15 - 27	19	3	13 - 38	25	6	33 - 39	36	3
Ga	11 - 17	14	2	8 - 24	17	4	23 - 23	23	0
La	17 - 36	26	5	17 - 46	33	8	33 - 38	36	3
Ni	30 - 51	41	6	20 - 136	58	25	59 - 70	64	6
Pb	12 - 25	17	3	13 - 27	19	3	26 - 31	28	3
Rb	45 - 68	56	7	40 - 70	54	8	102 - 115	107	7
Sr	112 - 176	136	13	106 - 291	171	44	170 - 183	176	7
Th	3 - 8	6	1	3 - 10	7	2	9 - 11	10	1
U	1 - 3	2	1	1 - 4	3	1	3 - 4	4	1
Y	18 - 24	21	2	15 - 30	24	4	30 - 33	32	2
Zn	54 - 198	78	30	46 - 113	80	18	101 - 108	105	4
Zr	205 - 246	225	13	185 - 341	244	38	234 - 255	243	11
	(N = 27)			(N = 34)			(N = 3)		

Table 12.8 Correlation coefficients for major and trace element data, shelly till (N = 27) and non-shelly tills (N = 34) of Northern Ayrshire.

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Ba	Ce	Co	Cr	Cu	Ga	La	Ni	Pb	Rb	Sr	Th	U	Y	Zn	Zr
SiO_2	1.00																										
TiO_2	-0.85	1.00																									
Al_2O_3	-0.90	0.62	1.00																								
Fe_2O_3	-0.54	0.78	0.31	1.00																							
FeO	-0.62	0.30	0.70	-0.23	1.00																						
MnO	-0.61	0.59	0.50	0.50	0.19	1.00																					
MgO	-0.74	0.91	0.50	0.66	0.27	0.53	1.00																				
CaO	-0.54	0.43	0.32	0.11	0.42	0.27	0.51	1.00																			
Na_2O	-0.27	0.55	0.02	0.40	0.08	0.20	0.69	0.28	1.00																		
K_2O	-0.45	0.44	0.43	0.26	0.28	0.41	0.40	0.12	0.46	1.00																	
P_2O_5	-0.83	0.99	0.58	0.78	0.28	0.56	0.91	0.44	0.60	0.43	1.00																
Ba	0.23	-0.07	-0.33	0.28	-0.51	-0.16	-0.16	-0.12	-0.20	-0.24	-0.06	1.00															
Ce	-0.86	0.76	0.81	0.61	0.44	0.57	0.56	0.26	0.12	0.42	0.74	-0.08	1.00														
Co	-0.80	0.86	0.63	0.79	0.23	0.58	0.77	0.37	0.31	0.28	0.85	0.08	0.78	1.00													
Cr	-0.33	0.45	0.22	0.41	0.04	0.51	0.44	0.06	0.26	0.11	0.43	-0.09	0.33	0.38	1.00												
Cu	-0.80	0.75	0.70	0.67	0.36	0.51	0.63	0.33	0.19	0.32	0.74	0.01	0.80	0.80	0.40	1.00											
Ga	-0.93	0.75	0.88	0.40	0.70	0.53	0.63	0.42	0.21	0.43	0.72	-0.33	0.83	0.68	0.31	0.80	1.00										
La	-0.80	0.73	0.75	0.56	0.44	0.53	0.55	0.29	0.12	0.33	0.72	-0.09	0.88	0.75	0.23	0.71	0.73	1.00									
Ni	-0.75	0.92	0.51	0.85	0.15	0.60	0.82	0.29	0.50	0.38	0.91	0.09	0.74	0.83	0.57	0.81	0.69	0.66	1.00								
Pb	-0.03	-0.21	0.24	0.00	-0.03	0.13	-0.34	-0.39	-0.49	-0.09	-0.25	0.09	0.20	0.04	-0.03	0.14	0.13	0.09	-0.09	1.00							
Rb	-0.35	0.05	0.57	-0.15	0.50	0.25	0.02	-0.08	-0.05	0.73	0.01	-0.38	0.36	0.02	-0.05	0.20	0.44	0.25	0.01	0.31	1.00						
Sr	-0.58	0.71	0.29	0.73	-0.04	0.44	0.64	0.45	0.33	0.17	0.72	0.27	0.56	0.71	0.33	0.65	0.47	0.51	0.78	-0.07	-0.17	1.00					
Th	-0.61	0.44	0.60	0.33	0.38	0.37	0.28	0.16	0.13	0.39	0.42	-0.24	0.61	0.49	0.13	0.55	0.62	0.53	0.42	0.30	0.43	0.28	1.00				
U	-0.28	0.02	0.44	-0.25	0.53	-0.02	-0.10	0.05	-0.15	0.14	-0.01	-0.23	0.25	-0.02	0.01	0.20	0.37	0.22	-0.01	0.23	0.46	-0.02	0.37	1.00			
Y	-0.93	0.76	0.89	0.52	0.59	0.54	0.58	0.33	0.18	0.46	0.73	-0.16	0.88	0.73	0.25	0.78	0.91	0.78	0.70	0.18	0.44	0.45	0.68	0.35	1.00		
Zn	-0.41	0.37	0.43	0.23	0.27	0.21	0.30	-0.03	0.13	0.39	0.35	-0.13	0.36	0.34	-0.02	0.40	0.40	0.29	0.28	0.19	0.36	0.18	0.25	0.05	0.47	1.00	
Zr	-0.74	0.87	0.56	0.66	0.23	0.55	0.71	0.27	0.44	0.52	0.84	-0.07	0.69	0.65	0.37	0.60	0.68	0.61	0.79	-0.12	0.21	0.56	0.46	0.17	0.77	0.38	1.00

Table 12.9 Range, average ($\overline{X}$) and standard deviation (S) of major element data for the shelly till, "shelly till" at Location 2 and marine clays at Afton Lodge.

		SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O	CO_2
N Ayrshire shelly till (N = 27)	Range	70.53 to 77.13	0.75 to 0.99	7.84 to 11.60	2.42 to 5.40	0.84 to 1.76	0.07 to 0.12	1.14 to 1.77	1.00 to 2.58	1.37 to 2.08	1.45 to 1.95	0.13 to 0.17	1.37 to 3.10	1.22 to 2.51
	$\overline{X}$	73.18	0.88	9.85	3.98	1.34	0.08	1.49	1.86	1.71	1.74	0.15	2.44	1.84
	S	1.99	0.06	1.12	0.59	0.20	0.01	0.17	0.34	0.62	0.15	0.01	0.48	0.35
"Shelly till" at Greenock Mains, Location 2 (N = 3)	Range	57.03 to 61.02	1.16 to 1.18	15.54 to 17.46	4.75 to 5.53	2.10 to 2.55	0.08 to 0.14	2.24 to 2.55	2.55 to 2.71	0.98 to 1.61	2.77 to 3.09	0.17 to 0.19	3.26 to 5.04	2.66 to 3.47
	$\overline{X}$	59.29	1.17	16.29	5.05	2.32	0.12	2.44	2.65	1.31	2.94	0.19	4.20	3.12
	S	2.05	0.01	1.03	0.42	0.23	0.03	0.17	0.09	0.32	0.16	0.01	0.89	0.42
Marine clay at Afton Lodge (N = 3)	Range	56.89 to 60.41	0.96 to 1.28	14.36 to 16.37	2.60 to 4.78	2.37 to 3.08	0.08 to 0.12	2.30 to 2.50	2.79 to 3.44	1.60 to 3.06	2.23 to 2.50	0.14 to 0.23	3.67 to 5.10	3.28 to 3.58
	$\overline{X}$	58.81	1.08	15.47	3.76	2.68	0.11	2.38	3.11	2.18	2.39	0.18	4.43	3.43
	S	1.78	0.17	1.02	1.10	0.36	0.02	0.11	0.33	0.77	0.14	0.05	0.72	0.15

CHAPTER 13

RESULTS OF ANALYSIS OF TILLS OF NORTHERN AYRSHIRE IN RELATION TO SPECIFIC AIMS OF THE PROJECT

13.1 Introduction

Aim 7 of the research project, presentation of grain-size, clay mineralogical and geochemical data for the tills of Northern Ayrshire, and general discussion of these data, is fulfilled in Chapters 10, 11 and 12, above. The purpose of this chapter is to consider the same data collectively in relation to the more specific Aims, 8 to 13, of the research project.

13.2 Mineralogical and geochemical properties of the shelly till (Aims 8 and 11)

In March 1986, when the project was extended to include Northern Ayrshire, samples of shelly till were collected at three Sites, Greenock Mains, Merkland Burn and Sorn Mains. The intention was to compare the properties of the shelly till matrix (a) at Locations 2 and 6 at Greenock Mains and at Locations 5-1 and 5-2 at Sorn Mains, and (b) between the three Sites. In June 1986, it was discovered that shelly till also occurs at Sourlie, a Site that is located c. 30km to the NW of the other three Sites. A further Aim (11) therefore became that of comparing the matrix of the shelly till at Sourlie with that of the shelly till at the other three sites. In the course of laboratory analysis it became clear that the samples of "shelly till" that had been collected at Greenock Mains, Location 2, on the grounds that this deposit had been identified as shelly till by Holden (1977), differ markedly in grain size and in geochemical contents and to a lesser extent in clay mineralogy from the samples of shelly till collected at other Locations in N Ayrshire. Comparison of this deposit with the shelly till at Greenock Mains, Location 6, as a means of assessing the properties of the shelly till at more than one Location within a Site, therefore became irrelevant.

Comparison of the data for Locations 5-1 and 5-2 at Sorn Mains has established that, at that Site, the shelly till matrix is essentially uniform in its mineralogical and chemical composition. Similar comparison of the relevant data for the Greenock Mains Site (represented only by the till at Location 6), Merkland Burn Site and the Sorn Mains Site shows that the shelly till matrix is remarkably uniform in grain size, clay mineralogy and major and trace element contents within the part of Ayrshire where these sites occur, and the collective data for Sourlie, Location 13, demonstrate that there is no significant difference between the properties of the shelly till matrix at Sourlie and at the other three sites.

From the above, it may be said that the matrix of the shelly till appears to be singularly uniform over a wide area of Northern Ayrshire. The properties of the shelly till matrix may be summarised as follows:

1) The samples have their modal class in the fine sand fraction (2ø - 3ø), and the sand-silt-clay composition ranges between silty sand and silty mud.
2) Mean size (Mz) usually ranges from 3.9ø to 4.8ø (very fine sand to coarse silt).
3) Sorting(σ_I) usually exceeds 2ø, ranging from 2.22ø to 2.67ø (very poorly sorted).
4) Skewness (Sk_I) usually ranges from -0.01 to 0.27 (nearly symmetrical to fine skewed).

5) Kurtosis (K_G) usually ranges from 0.74 to 0.94 (mostly platykurtic).

6) The clay fraction is dominated by kaolinite (average 39.6%) and illite (32.0%), with subordinate chlorite (15.8%) and minor amounts of montmorillonite (10.2%).

7) Geochemically, there is a high percentage of silica (average 73.18), showing that there is a significant component of quartz, believed to be derived from sandstone bedrock.

8) SiO_2 is preferentially concentrated in the sand fraction, but Al_2O_3, Fe_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O and P_2O_5 and all trace elements except Ba occur preferentially in the silt and clay fractions.

9) The oxides Al_2O_3, Fe_2O_3, FeO, MgO and K_2O are contained mainly in the clay minerals.

13.3 Other N Ayrshire tills possibly resembling the shelly till of that area (Aim 9)

Comparison of grain-size, clay mineralogical and major element data for the matrices of the grey and red tills at Tayburn, Locations 5B and 7B, and Sorn Mains, Location 5-3, with corresponding data for the shelly till of N Ayrshire as a whole (Table 13.1) shows that none of the other four till units resembles the shelly till in all three aspects - grain size distribution, clay mineralogy and geochemistry. Clay mineralogy gives some support to the suggestion (Chapter 11. 3.2, above) that the (upper) grey till at Tayburn resembles the shelly till, but both grain size and major element data do not support this premise.

Trace element data were not included in the comparison since they have a lower level of significance in relation to this particular problem.

13.4 Comparison of the mineralogy and geochemistry of the Upper and Lower grey tills at Sourlie (Aim 10)

For the purposes of this comparison, the data for the Upper grey till at Sourlie, Location 13, have been disregarded since the three samples concerned were collected in the lowermost 0.5m of the till unit, directly above shelly till.

From Table 13.2 it is clear that there is a fair degree of similarity between the matrices of the two grey tills at Location 3 in sand-silt-clay distribution and values of grain-size parameters (except skewness). Also, the tills have the same clay mineral assemblages. However, the proportion of kaolinite is higher in the Upper grey till and the proportion of montmorillonite higher in the Lower grey till. Geochemically, with the exception of CaO and MgO, the major element data also show a similarity between the tills. These results suggest that the matrices of the two grey tills at Sourlie had similar sources.

13.5 Changes through vertical profiles in the tills of Northern Ayrshire (Aim 12)

As noted in Chapter 10, changes in the sand-silt-clay distribution through the profiles of the shelly till at Greenock Mains, Location 6, and Sorn Mains, Location 5-1, and through the Upper grey till at Sourlie, Location 3, and the (lower) red till at Tayburn, Location 5B, show clearly that the fine material (silt and clay) tends to increase gradually downwards. This probably reflects gradual downward leaching of the fine material during and after deposition.

Several of the tills show weathering of clay minerals through the profile. The alteration of illite, chlorite and, occasionally, vermiculite to montmorillonite through mixed-layer illite-montmorillonite and vermiculite-montmorillonite and/or with vermiculitization, has been detected in: the Upper till at Greenock Mains, Location 2; the shelly till at Greenock Mains, Location 6, and at Sorn Mains, Location 5-1; the Upper and Lower grey tills at Sourlie, Location 3, and the shelly till at Sourlie, Location 13; the (upper) grey till at Tayburn, Location 5B.

In relation to Aim 12(a) (Chapter 4.1.2), the changes noted above are regarded as evidence of weathering having occurred in some of the sampled till profiles.

In relation to Aim 12(b), it is of importance to note that there is evidence of weathering in the profiles of the following tills: shelly till at Greenock Mains, Location 6; Lower grey till at Sourlie, Location 3; shelly till at Sourlie, Location 13. In the first two of these, the till that shows weathering is overlain directly by stratified sand and gravel deposits, while in the last case the till that shows weathering is overlain directly by another till (the Upper grey till at Sourlie). The significance of these observations is discussed in Chapter 14.

13.6 Comparison of the shell-bearing (marine) clays at Afton Lodge with other shell-bearing deposits (Aim 13)

The sand-silt-clay distribution, clay mineral assemblage and major element data for samples of the shell-bearing (marine) clays at Afton Lodge are given in Table 13.3, where they are compared with the same data for all the shelly till samples from N Ayrshire and the "shelly till" at Greenock Mains, Location 2. The table shows that in all three aspects the "shelly till" at Greenock Mains, Location 2, is closely similar to the marine clays at Afton Lodge. On the other hand, the shelly till of N Ayrshire as a whole differs markedly from the other two deposits in sand-silt-clay distribution and major element contents. Although there are minor variations in the proportions of clay minerals present, all three deposits have the same clay mineral assemblage. This resemblance is to be expected if the source or part of the source of the shelly till was a marine clay such as that at Afton Lodge.

The results show that there is an obvious dissimilarity between the "shelly till" deposit at Greenock Mains, Location 2, and the shelly till of N Ayrshire, and a similarity between the deposit at Greenock Mains and the marine clay at Afton Lodge.

Table 13.1 Summary statistics of sand-silt-clay percentages, grain-size parameters, clay mineral compositions and major oxides contents for the matrices of the shelly till of Northern Ayrshire, the grey and red tills at Tayburn and the grey and red tills at Sorn Mains, Location 5-3. N gives the number of samples.

Variable	All shelly till samples (N = 27)	All grey till at Tayburn (N = 5)	All red till at Tayburn (N = 5)	Grey till at Loc. 5-3 (N = 1)	Red till at Loc. 5-3 (N = 1)
sand	50.13 ± 5.36	35.68 ± 1.82	46.07 ± 4.89	43.88	47.57
silt	43.29 ± 5.20	50.43 ± 3.07	42.27 ± 2.38	48.92	45.18
clay	6.56 ± 1.65	13.89 ± 2.37	11.66 ± 2.63	7.20	7.25
Mz	4.32 ± 0.24	5.04 ± 0.20	4.42 ± 0.28	4.60	4.53
σ_I	2.46 ± 0.10	2.76 ± 0.12	3.04 ± 0.11	2.55	2.46
Sk_I	0.14 ± 0.08	-0.12 ± 0.06	-0.04 ± 0.12	-0.02	0.12
K_G	0.83 ± 0.05	0.83 ± 0.03	0.82 ± 0.03	0.79	0.82
kaolinite	39.6 ± 6.72	51.9 ± 9.88	19.7 ± 7.43	67.6	64.1
illite	32.0 ± 3.40	18.2 ± 5.63	12.6 ± 2.17	27.0	25.0
chlorite	15.8 ± 7.96	6.3 ± 5.93	-	-	-
montmor.	10.2 ± 4.76	10.5 ±14.59	67.9 ± 6.15	5.4	10.3
vermiculite	-	13.1 ±12.74	-	-	-
SiO_2	73.18 ± 1.99	61.81 ± 1.07	61.56 ± 1.11	67.06	69.92
TiO_2	0.88 ± 0.06	1.39 ± 0.06	1.82 ± 0.06	0.97	0.89
Al_2O_3	9.85 ± 1.12	14.15 ± 0.10	11.70 ± 1.05	11.56	11.88
Fe_2O_3	3.98 ± 0.59	5.84 ± 0.53	8.55 ± 0.02	5.78	8.99
FeO	1.34 ± 0.20	1.92 ± 0.50	1.13 ± 0.30	0.36	0.32
MnO	0.08 ± 0.01	0.12 ± 0.02	0.12 ± 0.02	0.09	0.10
MgO	1.49 ± 0.17	1.96 ± 0.25	3.22 ± 0.26	1.06	0.80
CaO	1.86 ± 0.34	2.23 ± 0.47	2.50 ± 0.16	2.91	0.55
Na_2O	1.71 ± 0.62	1.46 ± 0.13	2.33 ± 0.26	0.99	0.91
K_2O	1.74 ± 0.15	1.87 ± 0.06	1.79 ± 0.28	1.63	1.65
P_2O_5	0.15 ± 0.01	0.24 ± 0.01	0.33 ± 0.01	0.14	0.16

Table 13.2 Summary statistics of sand-silt-clay percentages, grain-size parameters, clay mineral compositions and major oxides contents for the matrices of the Upper Grey till and Lower Grey till at Sourlie, Location 3. N gives the number of samples.

Variable	Upper Grey till at Sourlie, Location 3 (N = 5)	Lower Grey till at Sourlie, Location 3 (N = 3)
sand	42.95 ± 2.73	44.53 ± 4.17
silt	44.74 ± 1.92	44.20 ± 2.83
clay	12.31 ± 1.37	11.26 ± 1.47
Mz	4.83 ± 0.20	4.73 ± 0.25
σ_I	2.71 ± 0.11	2.68 ± 0.06
Sk_I	0.01 ± 0.12	0.11 ± 0.07
K_G	0.79 ± 0.02	0.75 ± 0.03
kaolinite	56.4 ± 7.86	40.7 ± 8.52
illite	25.2 ± 8.19	25.8 ± 4.70
chlorite	13.9 ± 1.11	15.8 ± 5.61
montmorillonite	4.6 ± 1.51	17.6 ± 3.41
SiO_2	64.88 ± 1.40	69.21 ± 2.51
TiO_2	1.08 ± 0.06	0.95 ± 0.02
Al_2O_3	12.95 ± 0.52	11.98 ± 1.54
Fe_2O_3	3.86 ± 0.31	3.04 ± 0.52
FeO	2.67 ± 0.21	2.32 ± 0.42
MnO	0.09 ± 0.01	0.09 ± 0.01
MgO	1.57 ± 0.18	1.10 ± 0.11
CaO	2.72 ± 0.29	1.37 ± 0.37
Na_2O	1.49 ± 0.23	1.16 ± 0.19
K_2O	1.58 ± 0.08	1.59 ± 0.08
P_2O_5	0.19 ± 0.02	0.15 ± 0.02

Table 13.3 Summary statistics of sand-silt-clay percentages, clay mineral compositions and major oxides contents for the matrices of the shell-bearing marine clay at Afton Lodge, shelly till of Northern Ayrshire and the "shelly till" at Greenock Mains, Location 2. N gives the number of samples.

Variable	Marine clay at Afton Lodge (N = 3)	All shelly till samples of N. Ayrshire (N = 27)	"Shelly till" at Greenock Mains, Location 2 (N = 3)
sand	8.08 ± 2.38	50.13 ± 5.36	6.08 ± 3.38
silt	77.84 ± 2.26	43.29 ± 5.20	78.12 ± 2.11
clay	14.08 ± 0.21	6.56 ± 1.65	15.79 ± 1.33
kaolinite	34.3 ± 2.64	39.6 ± 6.72	27.5 ± 1.42
illite	40.1 ± 1.70	32.0 ± 3.40	45.6 ± 1.60
chlorite	15.8 ± 0.38	15.8 ± 7.96	14.7 ± 1.40
montmorillonite	9.7 ± 1.75	10.2 ± 4.76	12.1 ± 1.21
SiO_2	58.81 ± 1.78	73.18 ± 1.99	59.29 ± 2.05
TiO_2	1.08 ± 0.17	0.88 ± 0.06	1.17 ± 0.01
Al_2O_3	15.47 ± 1.02	9.85 ± 1.12	16.29 ± 1.03
Fe_2O_3	3.76 ± 1.10	3.98 ± 0.59	5.05 ± 0.42
FeO	2.68 ± 0.36	1.34 ± 0.20	2.32 ± 0.23
MnO	0.11 ± 0.02	0.08 ± 0.01	0.12 ± 0.03
MgO	2.38 ± 0.11	1.49 ± 0.17	2.44 ± 0.17
CaO	3.11 ± 0.33	1.86 ± 0.34	2.65 ± 0.09
Na_2O	2.18 ± 0.77	1.71 ± 0.62	1.31 ± 0.32
K_2O	2.39 ± 0.14	1.74 ± 0.15	2.94 ± 0.16
P_2O_5	0.18 ± 0.05	0.15 ± 0.01	0.19 ± 0.01

PART IV

APPLICATION OF TILL MINERALOGY AND GEOCHEMISTRY TO QUATERNARY STRATIGRAPHY, AND GENERAL CONCLUSIONS

CHAPTER 14

APPLICATION OF THE PROJECT'S RESULTS TO QUATERNARY STRATIGRAPHY

14.1 Introduction

The purpose of this chapter is to suggest briefly how the results of the mineralogical and geochemical studies of the tills and associated deposits of the NW Glasgow area and Northern Ayrshire may contribute towards the tackling of problems of Quaternary stratigraphy in these parts of south-western Scotland.

14.2 NW Glasgow area

Three ways in which the laboratory analyses of the matrices of the Red, Weathered Grey and Grey tills of the NW Glasgow area may contribute towards interpretation of the Quaternary stratigraphy of that area are discussed below.

14.2.1 Sources of the Red and Grey tills

Determination of the sources of the Red and Grey tills is of importance since this information may help to clarify the direction(s) of ice movement and indicate whether the Red and Grey tills are of the same or different ages. Analyses of the matrices of the Red and Grey tills (Chapters 5, 6 and 7) and of bedrock samples (Chapter 9), together with data presented on pebble lithology by Menzies (1981, 160-161 and Figs. 4 and 5), indicate that both the matrix and the clast fraction of (a) the Grey till were derived largely from Carboniferous shales and sandstones, and (b) the Red till were derived largely from Devonian (O.R.S.) bedrocks.

14.2.2 Red and Grey 'facies' of the Wilderness Till

In an attempt to systematise the Quaternary stratigraphy of the Glasgow area, Browne & McMillan (1985, Table 1) suggested that the 'Wilderness Till' of that area is a lithological unit (Formation) that was deposited during the main Late Devensian glaciation. They distinguished two 'facies' of the Formation (Browne & McMillan 1985, 17), a red and a grey, that correspond to the Red and Grey tills studied in this project. These authors discussed several characteristics of the Wilderness Till but they did not define the properties of the matrices of the two facies. This project therefore contributes substantially to the definition of the properties of the Wilderness Till by presenting data on the sand-silt-clay distribution, grain-size parameters, clay mineral assemblages, and major oxides and trace elements contents of the matrices of the Red and Grey tills of the NW Glasgow area in Table 14.1.

14.2.3 Zone of overlap of Red and Grey tills

It has long been thought that a zone where both Red till and Grey till are present occurs in the NW Glasgow area (see Chapter 3.2, above). The results of the laboratory analyses described in this thesis show clearly that such a zone does exist and that within this zone there are several places where Red, Weathered Grey and Grey till occur close together.

Location A at the Veterinary College (Chapter 8.6.2), where Red till rests directly on Grey till gives support to the report by Menzies (1976, 152) that, 'In a section in the stoss end of a drumlin in Maryhill (567 689) red till was observed overlying grey till. The boundary between the two tills although not sharp was distinct. This red till approached the reddish brown till in colour but did not appear to be weathered grey till'. Menzies (1981, 161) and Browne &

McMillan (1985) held the view that the Red till and Grey till are the products of a single ice advance, presumably accepting the superimposition of Red upon Grey till as a product of glacial deposition of debris that was derived from the west and north-west, where both O.R.S. sandstones and Carboniferous shales and sandstones are the bedrocks.

Evidence from Cleveden School, Location A, and Broomhill Cross (see Chapter 8.6.3) raises doubts about the course of events in the NW Glasgow area being as simple as suggested above. It has been shown by this study that, at both these sites, Red, Weathered Grey and Grey till are all present in close proximity to each other, and field records of the 1960s (Dr W.G. Jardine, personal communication) show that Red till samples were collected from immediately above Weathered Grey till samples. This poses a problem since such evidence suggests that at least a short period of exposure of the Grey till occurred at these sites before the Red till was deposited on top of its altered upper part.

14.3 Northern Ayrshire

14.3.1 Introduction

Previous studies of tills in Northern Ayrshire, on which interpretations regarding the Quaternary stratigraphy of that area have been based (see Chapter 3.3, above), appear to have been concerned mainly with the clast fraction (> 2mm). In this study, on the other hand, analysis was confined to the matrices (fraction < 2mm) of the tills. The results of these two different types of study may be expected to give agreement in some cases and to be conflicting in others. This point must constantly be borne in mind in the discussion below where the results of the mineralogical and geochemical studies of the matrices of tills and associated deposits are considered in relation to four aspects of the Quaternary stratigraphy of Northern Ayrshire.

14.3.2 The shelly till

On the basis of the presence or absence of shell fragments in the clast fraction, two till units, shelly and non-shelly, were distinguished in the past in Northern Ayrshire. The shelly till was thought to have originated largely from Quaternary shell-bearing marine clays that were picked up by ice from the floor of the Firth of Clyde (Eyles et al. 1949, 124-127) or perhaps from the area of the Clyde Estuary (cf. Holden 1977).

In the course of the present study, the shelly till was found to have a fairly uniform composition throughout the area sampled, despite the fact that three of the samples analysed were from the site at Sourlie in the north-western part of the area and the 24 other samples were from three sites, Greenock Mains, Merkland Burn and Sorn Mains, located fairly close together in the south-eastern part of the area. The analyses established that the shelly till matrix has a high silica content (c. 73%), which is present mainly as quartz in the sand fraction, and the sand fraction constitutes c. 50% of the matrix, the clay fraction constituting only around 6.5%. These results suggest that, contrary to the views of Eyles et al. (1949) and Holden (1977), the shelly till matrix consists of a fairly high proportion of sandstone and a relatively small amount of marine clay. This point is of importance in relation to the evidence of direction of ice movement (discussed below, section 14.3.5) provided by the distribution of shelly till and high-level Quaternary marine clays in Northern Ayrshire.

14.3.3 High-level marine clays

Shell-bearing Quaternary clays at Afton Lodge (c. 85m above Ordnance Datum, Newlyn, i.e. above present sea level) and at other sites in south-western Scotland have been regarded recently as marine in origin and preserved *in situ* (Holden 1977, 108-111; Sutherland 1981, 248-249). The present study has indicated clearly (Chapter 13.6) that the so-called "shelly till" at Greenock Mains, Location 2 (Fig. 10.21), is not part of the shelly till of Ayrshire, and more probably is a marine clay (*in situ*) similar to that at Afton Lodge.

The altitude of this shell-bearing deposit at Greenock Mains, Location 2, is c. 180m above O.D., considerably higher than the altitude of the Quaternary marine clays at Afton Lodge and those identified elsewhere in SW Scotland, but lower than the altitude of c. 300m above O.D. that Smith (1898, 113) considered a possible maximum limit of Quaternary marine submergence in Ayrshire. Also, the Greenock Mains site is located c. 30km inland from the present coast, much further inland than the Afton Lodge and other clays previously identified as *in situ* Quaternary shell-bearing marine deposits. If the shell-bearing clays at Location 2 are indeed *in situ* marine deposits, the possibility of Quaternary marine submergence in Ayrshire to altitudes much higher, and marine incursion to distances much further inland, than those envisaged recently must be considered seriously.

It should be noted that this study has not established the age relationship of the shell-bearing clays at Greenock Mains, Location 2, to the shell-bearing marine clays at Afton Lodge. Amino acid D/L ratios for the shell component in these two deposits would be of use in this respect.

14.3.4 Sedimentary successions

Stratigraphy relies to a large extent on the correlation and interpretation of successions of sedimentary units. Sedimentary successions established at three sites in N Ayrshire, and of interest in this context, are summarised and their significance discussed below.

Greenock Mains (combined evidence from Locations 2 and 6; see also Figs. 10.21 and 10.22)

Upper till; shows weathering of clay minerals		5-6m
Sand and gravel		4-18m
Shelly till; shows weathering of clay minerals and downwash of silt and clay fractions	at least	7m

Merkland Burn (Location 8; see also Fig. 10.30)

Upper red till		5m
Sand and gravel		1m
Shelly till	up to	6.5m
Lower red till	at least	1.5m

Sourlie (combined evidence from Locations 3 and 13; see also Fig. 10.38)

Upper grey till; shows weathering of clay minerals and downwash of silt and clay fractions	up to	12+m
Shelly till; shows weathering of clay minerals	up to	3.5m
Sand and organic-rich clay and silt	up to	1.5m
Sand and gravel	up to	9m
Lower grey till; shows weathering of clay minerals	up to	7.5m

Several points that may be noted in, or arise from, the successions given above appear to have stratigraphical significance:

1) At Greenock Mains, weathering of clay minerals and downwash of the silt and clay fractions in the shelly till suggest at least a short period of exposure of the shelly till before deposition of the overlying sand and gravel unit.

2) At Sourlie, weathering of clay minerals suggests (a) at least a short period of exposure of the Lower grey till before deposition of the overlying sand and gravel unit, and (b) a similar event after deposition of the shelly till but before deposition of the Upper grey till.

3) The Upper till at Greenock Mains, as shown in Chapter 11.8, may be part of the same till unit as the Upper red till at Merkland Burn, and the source of these tills may have been similar to that of the Lower red till at Merkland Burn. Holden (1977, 37) did not record the presence of this Lower red till, but the Greenock Mains and Merkland Burn sites were included within the area (between Sorn and Muirkirk; Fig. 1.3) where he noted that the shelly till is overlain by till that he claimed is local in origin.

It is interesting to compare the combined information given by the till successions at Greenock Mains and Merkland Burn with the till succession recorded at Sourlie:

Succession at Greenock Mains and Merkland Burn	Succession at Sourlie
Upper red till	Upper grey till
Sand and gravel	Shelly till
Shelly till	Organic-rich sediments dated c. 30,000 years B.P. resting on sand and gravel
Lower red till	Lower grey till

The following comments may be made:

1) In each succession three tills are present, the shelly till being both underlain and overlain by non-shelly till units.

2) Laboratory studies have shown that at Sourlie the matrices of the Upper and Lower grey tills are similar, suggesting similar sources for these tills. The matrices of the Upper and Lower red tills of the Greenock Mains and Merkland Burn sites also appear to have similar sources to each other.

3) Although the matrix of the shelly till at Sourlie closely resembles the matrix of the shelly till at Greenock Mains and Merkland Burn, this does not necessarily mean that the shelly till at Sourlie is of the same age as the shelly till at the other two sites. The shelly till at Sourlie has been proved to be younger than c. 30,000 years B.P. on the basis of radiocarbon dating (Jardine & Dickson 1987), and amino acid D/L ratios for shell fragments in this till confirm a Late Devensian age for this till unit (D.Q. Bowen & G.A. Sykes, personal communication). It would be useful to obtain amino acid D/L ratios for shell fragments from the shelly till at Greenock Mains and Merkland Burn, with a view to establishing whether the shelly till at these sites is of the same age as, or a different age from, the shelly till at Sourlie.

14.3.5 Directions of ice movement

Suggestions regarding directions of ice movement in Northern Ayrshire have been based in the past partly on the orientation of drumlins and glacial striae, and partly on the distribution of erratic clasts in the tills, especially Highland (metamorphic) rocks and fragments of marine shells (see Chapter 3.3, above). Of relevance here is that Richey et al. (1930) and Eyles et al. (1949) claimed that the presence of shelly till in inland parts of Ayrshire is evidence of west-to-east movement of ice (from the Firth of Clyde), whereas Goodlet (1970) and Holden (1977) were of the opinion that ice movement was mainly from the north. Holden discounted the view that the shells that occur in the Ayrshire shelly tills were picked up by ice from the floor of the Firth of Clyde. He implied, although he did not state, that the shells in the shelly tills were derived from the north, presumably from the area of the Clyde Estuary.

In the course of this study it has been shown that a hitherto unrecognised deposit of shell-bearing marine clay, similar to that at Afton Lodge, is present at Greenock Mains, Location 2. The fact that this deposit was previously regarded as part of the shelly till of Ayrshire and that its recognition as a marine clay rather than till was firmly established only through analysis of the <2mm size fraction suggests that there may be several other, as yet undiscovered, locations in Ayrshire where at least small pockets of shell-bearing deposits are marine clays rather than shelly till. Also, and perhaps of greater importance, the discovery at Greenock Mains suggests that, prior to the glaciation or glaciations during which the shelly tills were formed, there may have been present at inland sites in Ayrshire numerous small areas of shell-bearing marine clays. It follows from these possibilities that it may be unnecessary to suppose that the sources of the relatively small amounts of shell-bearing marine clay (see section 14.3.2, above) that became mixed with other material to form the shelly till were derived from either the Firth of Clyde or the Estuary of the Clyde. If this is indeed the case, the presence of shell-bearing clay in the shelly till may not be indicative of any particular direction of ice movement, since the shell-bearing clay may have been picked up locally within inland Ayrshire.

Table 14.1 Summary statistics of sand-silt-clay percentages, grain-size parameters, clay mineral compositions, major oxides contents and trace elements contents for the matrices of the Red till and Grey till of the NW Glasgow area. For completeness, comparable statistics for the Weathered Grey till of the same area are also given. N gives the number of samples.

Variable	Red till (N = 20)	Grey till (N = 19)	Weathered Grey till (N = 10)
sand	59.38 ± 7.67	41.50 ± 4.16	53.31 ± 3.24
silt	34.24 ± 6.79	47.26 ± 3.62	41.11 ± 3.28
clay	6.81 ± 1.69	11.24 ± 1.49	5.68 ± 1.18
Mz	3.96 ± 0.30	4.85 ± 0.29	4.16 ± 0.23
σ_I	2.51 ± 0.18	2.64 ± 0.09	2.60 ± 0.10
Sk_I	-0.28 ± 0.11	0.16 ± 0.11	-0.13 ± 0.11
K_G	0.85 ± 0.22	0.74 ± 0.04	0.75 ± 0.05
kaolinite	42.01 ± 9.05	58.67 ± 8.87	59.88 ± 3.83
illite	21.42 ± 6.12	22.61 ± 4.85	17.15 ± 2.76
vermiculite	33.90 ± 6.90	9.81 ± 3.45	21.96 ± 4.54
chlorite	—	9.19 ± 2.86	—
SiO_2	70.92 ± 4.88	63.76 ± 2.80	66.32 ± 4.19
TiO_2	0.98 ± 0.25	0.88 ± 0.09	0.84 ± 0.06
Al_2O_3	11.63 ± 2.51	13.34 ± 1.57	13.27 ± 1.53
Fe_2O_3	5.05 ± 1.30	3.10 ± 0.95	4.46 ± 0.37
FeO	0.86 ± 0.54	2.42 ± 0.74	0.67 ± 0.16
MnO	0.08 ± 0.03	0.10 ± 0.02	0.08 ± 0.03
MgO	1.12 ± 0.43	1.65 ± 0.33	1.21 ± 0.59
CaO	0.73 ± 0.47	1.79 ± 0.46	1.04 ± 0.85
Na_2O	1.31 ± 0.39	1.17 ± 0.54	0.95 ± 0.25
K_2O	1.50 ± 0.18	1.74 ± 0.22	1.57 ± 0.16
P_2O_5	0.14 ± 0.04	0.16 ± 0.02	0.13 ± 0.03
CO_2	1.88 ± 1.19	5.91 ± 1.02	5.12 ± 1.46
H_2O	3.62 ± 0.93	4.43 ± 0.91	4.69 ± 0.61

Table 14.1 (continued)

Variable	Red till	Grey till	Weathered Grey till
Ba	425.5 ± 58.1	436.4 ± 66.1	404.4 ± 82.9
Ce	64.3 ± 13.2	73.4 ± 9.6	78.2 ± 8.9
Co	12.6 ± 5.2	14.2 ± 4.3	9.8 ± 3.8
Cr	111.1 ± 20.8	112.5 ± 13.1	113.2 ± 15.2
Cu	14.2 ± 4.0	14.6 ± 3.4	12.8 ± 3.4
Ga	13.5 ± 2.7	16.4 ± 2.4	16.8 ± 2.7
La	35.3 ± 5.7	39.4 ± 5.8	42.8 ± 5.8
Ni	31.1 ± 10.2	36.8 ± 8.2	32.2 ± 12.4
Pb	14.6 ± 4.0	16.0 ± 3.3	17.9 ± 3.0
Rb	53.6 ± 10.3	67.0 ± 9.9	67.2 ± 6.9
Sr	116.1 ± 27.2	140.5 ± 30.9	115.2 ± 29.0
Th	6.5 ± 2.9	7.6 ± 1.6	8.8 ± 1.9
U	2.3 ± 1.2	2.4 ± 1.0	3.1 ± 0.7
Y	23.9 ± 4.3	25.0 ± 2.5	26.3 ± 2.5
Zn	59.5 ± 19.8	64.0 ± 10.7	61.2 ± 10.3
Zr	257.8 ± 27.5	248.0 ± 23.9	271.5 ± 28.5

CHAPTER 15

C O N C L U S I O N S

15.1 Introduction

The work discussed in this thesis has consisted mainly of an analytical study of the matrices of tills in two areas of south-western Scotland - NW Glasgow and Northern Ayrshire. The intention has been to present detailed data for the tills of these areas and to discuss the significance of these data in defining the properties of these tills. Further aims have been to determine the possible bedrock sources of the Red and Grey tills of the NW Glasgow area and to examine the relevance of the results of the analytical studies in relation to interpretation of Quaternary stratigraphy in the areas studied.

15.2 NW Glasgow area

Three categories of till have been distinguished in the NW Glasgow area, Red, Weathered Grey and Grey. The following general conclusions result from analysis of samples from sites distributed widely throughout the area, together with analysis of samples from two vertical profiles through Red till and two through both Grey and Weathered Grey till.

15.2.1 Grain-size distribution

1) Mechanical analyses of the till matrices shows that the Red till generally displays a coarser grained composition than the Grey till.

2) The average percentages of the sand-silt-clay fractions of the Red and Weathered Grey tills are fairly close. Distinction between these two categories of till therefore is difficult on the basis of grain-size distribution alone.

3) Plotting of the sand-silt-clay contents of the three categories of till on a triangular diagram is of great value in demonstrating the distinction between the Grey till on the one hand and the Red and Weathered Grey till on the other.

4) Of the grain-size parameters, mean size and skewness appear to be the most diagnostic for distinguishing between the Grey till on the one hand and the Red till and Weathered Grey till on the other. All three categories of till are very poorly sorted. Also, most of the samples have platykurtic distribution.

5) Downward leaching of finer-grade material has taken place in both Red till profiles and profiles through both the Grey and Weathered Grey till.

15.2.2 Clay mineralogical analysis

1) Analysis shows pronounced dissimilarities between the clay mineralogy of the Red and Weathered Grey tills on the one hand and the Grey till on the other. Kaolinite, illite and vermiculite are present in all samples. Chlorite is present only in Grey till samples. The presence of chlorite therefore may be used as a diagnostic property in identification of the Grey till.

2) The percentage of kaolinite is much lower, and the percentage of vermiculite is higher, in the Red till than in the Weathered Grey till. Thus, the relative proportions of these two minerals can be used to distinguish between these two categories of till.

3) The clay mineralogy changes vertically in till profiles. In the case of profiles through both Grey and Weathered Grey till,

chlorite disappears up the profile, and the amount of vermiculite increases up the profile at the expense of chlorite and illite. Although it is difficult to distinguish between weathered Red till and non-weathered Red till in the same profile, it is obvious that the amount of vermiculite increases upwards at the expense of illite.

4) There are three probable modes of origin of the clay minerals in the tills: (a) direct inheritance; (b) pre-glacial weathering; (c) pedogenesis since till deposition.

15.2.3 Geochemistry

1) In comparison with the Grey till, the average major element composition of the Red till is richer in SiO_2, TiO_2, Fe_2O_3 and Na_2O and poorer in Al_2O_3, FeO, MnO, MgO, CaO, K_2O and P_2O_5.

2) All three categories of till have a high SiO_2 content. This is consistent with these tills having a source in the local sandstone bedrocks, which are enriched in SiO_2.

3) A higher abundance of Fe_2O_3 and lower abundance of FeO in the Weathered Grey till than in the Grey till suggests that oxidation of FeO started after deposition of the Grey till.

4) With the exception of Sr, Rb, Ba and Ce, the average trace element contents of the Red and Grey tills show close similarity. The content of Sr, Rb and Ba is higher in the Grey till. This correlates well with the higher K_2O and CaO content in the Grey till than in the Red till.

5) Except for Zr, all the trace elements are preferentially concentrated in the silt and clay fractions of the tills, Ce, La, Ga, Y and Rb being contained in the clay fraction. Zr appears to occur both in clay minerals and in the sand fraction as detrital zircon; Sr is concentrated in the Ca minerals and Ba in the

K-feldspars.

6) The ratios $Ga:Al_2O_3$, $MgO:Ni$, $FeO:Co$ and $Ni:Co$ can be used to detect weathering trends in both the Grey and Red till profiles.

15.2.4 Bedrock sources of the tills

The provenances of the Grey and Red tills can be established on the basis of differences in the mineralogical composition of the local bedrocks. As noted above, the Red till contains a higher percentage of silica than the Grey till. Also, chlorite is present in the latter till but absent in the former. The presence of chlorite in the shales and, to a lesser extent, in the sandstones of Carboniferous age, together with the lower quartz content in the Carboniferous sandstones than in the O.R.S. sandstones, suggests that the Grey till has been derived mainly from Carboniferous shales and sandstones, while the Red till has been derived mainly from Devonian (O.R.S.) sandstones.

15.3 Tills of Northern Ayrshire

Analysis of 61 samples of the matrices of two groups of tills, shelly and non-shelly, showed that both groups have high SiO_2 content, reflecting quartz-rich source rocks. Surprisingly, the matrices of the non-shelly tills have higher CaO and CO_2 contents than the matrix of the shelly till. This may be due to the presence of fine ground limestone in the non-shelly till matrices.

15.3.1 Characteristics of the shelly till

Marked similarities in sand-silt-clay composition, clay mineralogy and major elements contents of shelly till matrices from three sites (Greenock Mains, Merkland Burn and Sorn Mains) in the south-eastern part, and one site (Sourlie) in the north-western part of Northern

Ayrshire were recorded. In particular, it was noted that the shelly till has a high silica content and a low clay content, which suggests that the proportion of shell-bearing marine clay in the shelly till is not nearly as great as suggested by previous, less detailed studies.

15.3.2 Shell-bearing marine clays

Analyses of shell-bearing marine clays from Afton Lodge compared with those of the Ayrshire shelly till as a whole and those of a shell-bearing deposit at Greenock Mains, Location 2, showed clearly that the last of these deposits is not a shelly till (as formerly thought). However, there is a strong possibility that this deposit is a shell-bearing marine sediment, similar in composition to the deposit at Afton Lodge.

15.3.3 Till deposits at Sourlie

Three superimposed tills, Upper grey, shelly and Lower grey, are present at Sourlie. In terms of grain-size distribution, clay mineral composition and most of the major element data, the matrices of the Upper and Lower grey tills are sufficiently similar to suggest that they had similar sources, possibly the local Carboniferous shales and sandstones. The properties of the shelly till matrix are remarkably similar to those of the shelly till at other sites that were studied in Northern Ayrshire.

15.3.4 The red till at Tayburn

The matrix of the (lower) red till at Tayburn is distinctly different in its clay mineralogy from that of all the other tills studied in Northern Ayrshire. It is characterised by a very high content of montmorillonite, which is most likely derived from basic igneous rocks, such as basalt, which is the local bedrock.

15.4 Relevance to Quaternary stratigraphy

15.4.1 NW Glasgow area

Three ways in which the laboratory studies of the Red, Weathered Grey and Grey tills of the NW Glasgow area have contributed to interpretation of Quaternary stratigraphy in that area are:

1) It is confirmed that Devonian (O.R.S.) sandstones are the main source rocks of the Red till, and Carboniferous shales and sandstones are the main source rocks of the Grey till. Directions of ice movement therefore may be established on the basis of the spatial distribution of the Red till, Grey till and Devonian and Carboniferous bedrocks.
2) The properties of the matrices of the red and grey facies of the 'Wilderness Till', a lithological Formation proposed by Browne & McMillan (1985), can be defined on the basis of the laboratory-determined properties of the matrices of the Red and Grey tills.
3) A zone of overlap between outcrops of Red till and Grey till in the NW Glasgow area is confirmed. Within this zone, Weathered Grey till overlain by Red till is present in places, suggesting at least a short period of exposure of Grey till before deposition of Red till on top of it. A satisfactory explanation of this relationship has still to be given.

15.4.2 Northern Ayrshire

The results of the laboratory studies are relevant to four aspects of Quaternary stratigraphy in Northern Ayrshire:

1) Contrary to previous views, the shelly till matrix consists of a high proportion of sandstone, probably local bedrock, and a

relatively small amount of shell-bearing marine clay.

2) The discovery of the presence of shell-bearing marine clays at Greenock Mains at c. 180m above present sea level and c. 30km inland from the present coast, suggests that recent views regarding the maximum elevation and maximum extent of marine incursion in Ayrshire in Quaternary times may have to be modified.

3) In comparing till successions at Greenock Mains, Merkland Burn and Sourlie, it was noted that (a) weathering of lower till units at Greenock Mains and Sourlie occurred prior to deposition of overlying sediments, and (b) the shelly till is not necessarily the same age throughout Northern Ayrshire.

4) The sources of the small amounts of shell-bearing marine clay incorporated into the shelly till need not have been the Firth of Clyde or the Clyde Estuary, as previously suggested. There may have been small pockets of these clays present at inland locations prior to the glaciation(s) that produced the shelly till. It follows that the presence of shell-bearing clay in the shelly till may not be indicative of any particular direction of ice movement, since the shell-bearing clay may have been picked up locally within inland Ayrshire

15.5 Future research

As a result of the work carried out in the course of this project, it has become obvious that further research would be useful as follows:

1) Detailed field recording of the nature of, and relationships between, the various deposits that occur at Greenock Mains, Locations 2 and 6.

2) Collection of shell fragments from exposures of shelly till at several locations throughout Ayrshire with a view to age

determination of these fragments by amino acid and radiocarbon methods, where possible.

3) Determination of the bedrock sources of the major till units of Northern Ayrshire.

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