THE LENNOXTOWN ESSEXITE ERRATICS TRAIN, CENTRAL SCOTLAND.

RICHARD ALAN SHAKESBY

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I declare that the research for,
and composition of this thesis
are my own work.

ABSTRACT

This thesis is an investigation of glacial erratics derived from two small, adjacent, distinctive outcrops of essexite near Lennoxtown, Central Scotland.

Analysis of till samples has revealed that rock fragments and sand-size particles of essexite are absent up-ice of the essexite outcrops and scarce in a down-ice direction. Using dry stone walls as random samples of glacially transported stones, classic erratics train patterns of the distribution of erratics from both outcrops have been derived. The close spacing of joints on one outcrop has led to the rapid disappearance of its erratics in the walls with distance from the source due to glacial crushing. Crushing is also shown by a size reduction of erratics from the other outcrop in the walls in a down-ice direction.

Measurement of size and morphometric properties of essexite erratics has revealed that crushing is the dominant and abrasion a subsidiary process in glacial transport, whilst abrasion is dominant for particles that have undergone fluvioglacial and beach transport. Roundness appears to be the best measure differentiating between processes acting in the glacial, fluvioglacial and beach environments. Tests of compressive strength and experimental abrasion of essexite have been carried out to aid interpretation of the results.

Till-particle preferred orientations, striae and the long axes of ice-moulded features show a similar

direction to that of the major axis of the train.

From the evidence available it is suggested that the essexite wall stones underwent englacial transport in the lower layers of the last active ice and were deposited as an ablation mantle. A position of transport at the base of the ice is invoked for essexite particles in the till. The lateral spreading of essexite erratics down-ice of the source is attributed to divergence of basal ice flow around subglacial obstacles.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

CHAPTER 1

INTRODUCTION

> "If we take the case of a hill,... isolated amid other kinds of rock, and if from this well defined source we find issuing a stream of... boulders... then we can tell with certainty which way the ice travelled." (Cadell,1913,p.110)

This is a study of various aspects of the Lennoxtown essexite erratics train and of the relationship of this train to glacial processes and glacier ice movement. Detailed analysis of the distribution pattern of glacially transported fragments from two small, adjacent, distinctive outcrops of essexite in the Central Lowlands of Scotland forms the basis of the investigation from which the other aspects have evolved. Although a small topic within the broader field of glacial geomorphology it was hoped that many inferences that might be made from the investigation would be applicable to the subject as a whole and lead to a better understanding of glacial processes.

The different aspects of the study have developed in response to the following five questions. Firstly, and fundamentally, what is the distribution pattern of the essexite fragments down-ice of the outcrops? Secondly how have the size and morphometric properties of erratic essexite stones been affected by glacial transport and transport in other environments? Thirdly, in view of the likelihood of essexite stones being subject to crushing and abrasion during transport, what is the nature of the distribution pattern of fine essexite particles in till and fluvioglacial deposits? Fourthly how does ice movement direction shown by other geomorphological evidence compare with the alignment of the erratics train? Fifthly, and more tentatively, what processes can be inferred from the form of the erratics train?

After a review of the literature on erratics in chapter 2, an outline of the geology and glacial geomorphology of the study area in chapter 3 and a description of a pilot study in the first section of chapter 4, the second section of chapter 4 and chapters 5 to 9 are concerned with these five questions. The second section of chapter 4 deals with the distribution of essexite fragments within till in the vicinity of the outcrops. Another approach to the question of determining the distribution pattern of essexite fragments is given in chapter 5. Dry stone walls in the neighbourhood of the essexite outcrops are regarded as legitimate, unbiased samples of glacially transported stones and they have been used to analyse the train of essexite erratics. Chapter 6 deals with the size and morphometry of essexite erratics. Data derived from the measurement of these properties for stones that have been transported glacially and fluvioglacially and others that have undergone beach processes are discussed. The probable reasons for, and implications arising from differences in the size and morphometry of stones within and between these three environments are analysed. In chapter 7 an account is given of the distribution pattern in till and fluvioglacial deposits of sand-size, distinctive mineral grains occurring within both essexite outcrops. This part of the investigation was carried out in response to the third question. Chapter 8 details the relationship of ice movement direction shown by striae, ice-moulded features and the preferred orientations of till particles to the alignment of the essexite erratics train. Chapter 9 is in a sense a synthesis in that it is primarily concerned with suggesting glacial processes responsible for the formation of the erratics train. In chapter 10 the main conclusions arising from the investigation are restated.

C H A P T E R 2

A REVIEW OF LITERATURE ON THE ORIGIN, TRANSPORT AND DEPOSITION OF GLACIAL ERRATICS

> "It has been said that we 'only see what we look for'; so that 'knowing what to look for' is half the battle. Equipped with the knowledge accumulated by our predecessors we have the immense advantage of being able to begin where they left off." (Harrison, 1894, p.118)

At the beginning of the nineteenth century the existence of former glaciers in Britain had not been contemplated; glaciers were regarded as phenomena of high latitudes and altitudes. By the end of that century, however, most geologists regarded them as powerful agents in the production of landforms far away from modern glaciers. Glacial erratics provided a major line of evidence for the transporting power and former widespread existence of glacier ice. The importance of erratics was reflected in the formation of committees in Switzerland, England and Scotland devoted to their study, and the existence of the journal "Zeitschrift für Geschiebeforschung" published between 1925 and 1942.

Erratics and development of the "Glacial Theory"

Early geologists regarded the widely distributed deposits of clays, sands, gravels and boulders that covered much of Britain as a hindrance in the examination of the underlying solid rock. When interest in these superficial deposits was finally stirred, it was the large boulders that first attracted attention. They often contrasted in colour and texture with the underlying soils and bedrock and appeared to be strewn randomly over plains and mountains. It was soon recognised that erratic blocks, as these boulders were called, were fragments of rock that were not _in situ_ but had been transported by some means from their source. Folk legends regarded them as being brought by giants, dwarfs, the devil and other fantastic beings. In Scotland, names such as the Giant's Putting Stone, Heathens and Deil's Stones give some idea of how they were popularly thought to have originated (Milne-Home,1872).

Erratic blocks were regarded by geologists as distinct in origin from the apparently disorganised unstratified clays, sands and gravels with which they were often associated. The sheer size and distance from the possible source of many erratics baffled those seeking to assign a transporting agent. Very large erratics weighing thousands of tons have been reported from North America and Europe (e.g. Rutherford,1942; Herrmann,1930). In England a village is sited on an erratic (Cameron,1893). In Scotland a number of large erratics have been reported (e.g. Geikie,1900; Milne-Home,1884; Campbell & Anderson,1910), one being of sufficient size to be worked as a quarry (Carruthers,1911).

The size of such erratics suggested a transporting agent of tremendous power, yet capable of placing a very large boulder such as the Giant's Putting Stone near Ardentinny "as if a push would roll it over" (Milne-Home,1872,p.703). The agent also had to account for the transportation of inherently fragile erratics intact to their point of deposition. For instance an erratic in S.W. Ohio is c.½ha in extent, weighs some 13,500 tonnes, has been carried at least 7km, yet has a thickness varying from only 2m to 5½m (Wolford,1932). Similar examples have been recorded in Britain (e.g. Reade,1882).

Nineteenth century scientists were faced with apparently conflicting evidence. The transporting agent was powerful, yet it could deposit extremely fragile boulders without damage. There appeared to be no obvious limitation in the height to which erratics were carried. Some could only wonder at the phenomenon. "C'est un des phénomènes les plus généraux, les plus frappans et les plus inexplicables de la géologie" (Brongniart,1828, p.7). Others put forward explanations almost as fanciful as the folk legends. The more acceptable hypotheses included torrents of water, icebergs floating across a submerged land surface and "land-ice" (Hansen,1970).

Swedenborg in 1719 was the first to attempt a scientific explanation and concluded that the sea had been responsible for distributing erratics (North, 1943). In 1740 tilas observed that erratics decreased in frequency away from their source (Ødum,1945). At this time scientific views had not broken loose from religious dogma which maintained that creation began in 4004 B.C. (Chorley et al.,1964). It was a natural impulse therefore to ascribe erratic blocks along with the clays, sands and gravels to a catastrophic flood (Howorth,1893). De Saussure in 1779 was an exponent of the Deluge or Débâcle as this flood was known (Wendt, 1970). In Britain, Buckland's work of 1823 assigned the derivation of erratic blocks to the Noachian Deluge (Harrison,1894). Theories of the"Diluvialists",as exponents of the Deluge became known, however, did not go entirely unchallenged (Playfair,1802; Brongniart,1828).

Lyell (1837) in "Principles of Geology" argued that the most serious obstacle to unravelling the correct history of the earth was literal acceptance of the Bible. However he still upheld the view that the land surface had been submerged at some time in the recent geological past. To explain the movement of large erratics he introduced the concept of icebergs floating across the submerged land. This became known as the "Drift Theory" and it overcame many of the problems associated with the Diluvial Theory. Previously it had been difficult to explain the apparently chaotic nature of the "diluvium" (as the clays, sands, gravels and boulders were known) if it was to be regarded as a marine deposit. However this was more readily accounted for if floating icebergs had dropped debris from their bases on to the bedrock surface. The angularity of rock fragments and the occurrence of huge erratic boulders could also be explained better (Hansen,1970). The Drift Theory became strengthened following discovery of sea-level changes relative to the land by the reports of men like Parry, Ross and Scoresby who described the calving of Greenland glaciers. Papers advocating the Drift Theory to account for phenomena of the diluvium or "drift" persisted until the last quarter of the nineteenth century.

For Darwin(1842,1848) the Drift Theory explained the uplift of boulders in Glen Roy. Coastal ice crept inland as the land submerged. With subsequent re-emergence of the land the erratic boulders carried by the ice were left 250m higher on the mountainside "in the same manner as would have happened with so much drift timber" (Darwin,1848,p.319). Murchison(1867), Reade(1882,1883), Mackintosh(1874,1879), Martin(1856), Ricketts(1885) and Maw(1864) were amongst other proponents of the Drift Theory in Britain. Iceberg transportation was invoked to explain the presence of Scandinavian erratics along the east coast of Britain (Trimmer, 1851; Ricketts,1885; Phemister,1926; Bremner,1934).

It was understandable that the supposition of a former extension of land-ice to explain all the phenomena of the drift should have been pioneered in countries where modern glaciers existed. Venetz in 1822 was followed by Charpentier in 1835 and Agassiz in 1837 in proposing a former extension of glaciers in Switzerland (Harrison,1894). As long ago as 1707 Scheuchzer had already observed the flow and transporting power of glaciers (Charlesworth,1957). Esmark(1827) realised that a great ice sheet had covered Norway and transported boulders and other debris, smoothed rock surfaces and excavated fjords.

Prior to 1840 little serious thought was given to the action of glaciers in accounting for features in Britain that are today unhesitatingly assigned to a glacial origin. This stemmed mainly from an absence of modern glaciers and an ignorance of the deposits formed by such glaciers in other countries. In 1840 however Agassiz visited Scotland to see for himself the glacial traces that had been described to him by Buckland who became converted to the "Glacial Theory" as a result of a trip to glaciers in Switzerland in 1838 with Agassiz. Agassiz read a summarised version of his "Études sur les glaciers" before the Glasgow meeting of the British Association (White,1970). The views of Agassiz were not immediately universally accepted and some scientists like Darwin, Lyell, Crosskey, Murchison and Woodward remained sceptical, merely modifying their views within the older iceberg-marine theory (Hansen,1970).

In Scotland the evidence for valley glaciers was clearer than in much of the rest of Britain, and as a result the Glacial Theory was more readily accepted there. Chambers(1853) advocated land-ice rather than icebergs to account for the ridge and trough forms of the Lothians. Jamieson(1862) wrote on the "ice-worn rocks of Scotland" and in 1863 demonstrated that the parallel roads of Glen Roy and neighbouring glens were the result of glacial damming. The general acceptance of the Glacial Theory in Scotland however can be traced to a paper by A. Geikie(1863) "on the phenomena of the glacial drift in Scotland".

Yet some geologists were still not convinced that an ice sheet had covered Scotland. Instead the Drift Theory was expanded to include local glaciers on high ground, since their former existence could no longer be denied. With a whole range of agents, including glaciers, icebergs, terrestrial meltwater, ocean currents and combinations of these it was not difficult to "explain" all the phenomena of the drift (Hansen,1970). If the erratics were small, rounded and distant from their source, the ocean currents might account for them. If, on the other hand, they were large, angular and near their source they must have been carried on icebergs (e.g. Hopkins,1851). The Drift Theory survived until the late nineteenth century chiefly as a result of this flexibility.

The interest aroused by erratic blocks led to a more intensive study of their nature and distribution with committees set up especially to investigate them. The Scottish Boulder Committee was set up by the Royal Society of Edinburgh in 1871 with the object "first to ascertain the districts in Scotland where any remarkable boulders were situated; and, second, to select those which might be deemed worthy of preservation" (Milne-Home,1872,p.703). Ten reports were published in all and they provided geologists with considerable information about erratic boulders. The largest recorded erratic boulder was estimated to weigh 800 tonnes.

Summarising the work, Milne-Home(1884), noted the main conclusions arising out of the reports. Granite formed the largest boulders and greenstone boulders were the most numerous. Generally boulders were either soft, friable and angular and transported over short distances, or they were tough, homogeneous and rounded and had travelled far.

Although the reports gave rise to considerable evidence in favour of former glaciation, Milne-Home still advocated the Drift Theory. The existence of erratics at 950m could be explained by the submergence of the land beneath the sea to that level. Submergence was indicated by sands and gravels up to 650m and sea shells to 175m. Changes in the direction of striae around high ground could be accounted for by ocean currents, whose presence was confirmed by kames in the Scottish Central Lowlands.

Milne-Home's was a minority view. As early as 1865 A. Geikie had summed up the situation in the following manner. "After long years of doubt and discussion, geologists are at length led to believe that during a comparatively recent geological period the whole of the northern half of Great Britain was cased in ice" (Geikie, 1865,p.78). It was in part the tangible evidence afforded by the transport of erratic blocks that steered nineteenth century scientific thinking away from notions of a Deluge to icebergs floating over a submerged land surface, and finally to the acceptance of the former existence of ice sheets in Britain.

Origin of erratics

Before the transporting powers of glaciers were more fully realised, the huge erratics were often thought to represent the remnants of denuded geological strata (e.g. Greenough,1819). Complex faulting and folding of bedrock was also suggested (Seeley,1864,1865, 1868; Woolacott,1921). Overthrust faulting was once invoked to explain the north-south line of huge blocks of quartzite that make up the Foothills erratics train in the Calgary area, Canada (Hume,1931). The blocks were thought to represent erosion remnants of a now denuded fault plate. Recent study however has demonstrated a glacial origin for these blocks (Stalker,1956; Morgan,1969).

Following the general acceptance of the Glacial Theory interest was centred on the manner in which blocks of rock could be prised from their source by ice. From observation of modern glaciers it was noted that material could be introduced subglacially at the bedrock-ice interface or on to the ice surface. An exception occurred for material that was entrained from large bedrock obstructions in the path of the ice. Trains of debris were seen to be carried out horizontally into an englacial position from such prominences (e.g. Chamberlin,1895).

Material introduced on to the ice surface consists almost entirely of frost-shattered rock fragments (Sharp,1949; Boulton,1970a; Carson,1971). The transport of erratics by this means has been suggested for some erratics trains (Geinitz,1923; Morgan,1969). However a far larger proportion of bedrock erosion takes place beneath the ice. The ability of ice sheets to remove bedrock became apparent in Britain when sections into glacial deposits were carefully examined. Injection of till between bedrock strata involving tremendous pressures was noted (Milne-Home,1869; Marr,1887; Dwerryhouse,1893). Large slabs of rock still connected to bedrock were observed jutting out into till apparently in the process of removal (Crosskey,1882; Hershey,1897; Sardeson,1905). Similar slabs also appeared to have been folded as a result of ice pressure (Hershey,1897; Thwaites,1921).

Not all material incorporated by ice need be freshly eroded bedrock. It may be derived from older tills (Johnson,1971), from preglacial stream deposits (Heiche,1937), from former beaches (Grönwall,1900) or from other preglacial deposits (Krumbein,1933). Removal of this overburden by ice will lead to contact with the underlying bedrock.

Glacial erosion of bedrock is thought to operate in two distinct ways: by abrasion of rock surfaces to give them a smoothed or striated appearance, and by plucking or quarrying (Embleton & King,1975). The latter is clearly the process involved in the removal of erratics since abrasion gives rise to silt and clay size particles. Quarrying is also quantitatively more effective than abrasion in removing bedrock (Henderson, 1959; Flint,1971). The ability of ice to quarry bedrock increases with closer spacing of the joints (Harker,1899; Cailleux,1952; Henderson,1959). Matthes(1930) illustrated this in the narrowing of the lower Yosemite valley into the Merced Gorge which marks the point where well jointed rocks terminate and massive, unquarriable granite begins. Although the quarrying process unquestionably takes place, the lack of direct observation has given rise to a number of theories to explain the phenomenon.

One suggestion is that preglacial preparation of bedrock is important. Demorest(1939,1943) considered that the supply of pluckable material depends on the depth of unconsolidated or loosely jointed rock existing in preglacial times. Boyé(1950,1968) developed this idea by specifically assigning freeze-thaw action to this task where a sufficient supply of moisture was available. Bedrock material is broken up prior to removal by ice as a result of water percolating into the pre-existing joints and cracks in the rock. With successive freeze and thaw the joints are weakened and prised apart (Chamberlin,1893; Chapman & Greenfield,1949). The existence of weathered rock in till supports the idea of preglacial preparation of bedrock (Goldthwait & Kruger,1938). Birot(1968) however argued that the depth of the preglacial permafrost would not have been deep enough to prepare sufficient quantities of material. Feininger(1971) favoured deep chemical weathering of crystalline rocks to account for large-scale glacial removal.

Another proposed mechanism for glacial quarrying involves freeze-thaw action in a subglacial environment. Carol(1947) observed subglacial water in the lee of a roche moutonnée and favoured freeze-thaw action to account for the plucked appearance of the rock surface. Holmes(1944) considered that subglacial freeze-thaw might result from fluctuations in pressure due to variations of the stress in the overlying ice. McCall(1960) favoured subglacial freeze-thaw to explain observed phenomena beneath a cirque glacier in Norway. Basal melting is characteristic of temperate glaciers as direct observation has shown (Kamb & LaChapelle,1964). On the other hand modern high latitude glaciers are composed chiefly of ice that is below the melting point. Recent cores into some of these glaciers however indicate that the presence of subglacial meltwater at the bedrock-ice interface is not uncommon (Fisher,1955; Gow _et al._,1968; Stupavsky & Gravenor,1974). It has been suggested that this is a result of pressure melting and that only in the terminal zones is basal ice below the melting point (Weertman,1961). Weertman and Boulton(1972) suggested that such glaciers might provide a good model for major Quaternary ice sheets, with basal ice at the melting point in their internal parts and bordered marginally by a wedge of colder ice. The subglacial freeze-thaw process therefore cannot be discarded in explaining quarrying on the grounds that the Quaternary ice sheets were non-temperate.

Another possible mechanism of glacial quarrying involves the action of pressure release beneath thick ice. For example, Lewis(1954) and Linton(1963) pointed out that when bedrock is removed by a glacier the ice replacing rock is only about one-third of the density of the rock. This might lead to the development of dilatation joints paralleling the bedrock surface. Quarrying by this means would help to explain the pronounced ability of ice to erode vertically producing deep valleys (Holmes,1937; Wyllie,1958; Spreitzer,1963; Gjessing,1966). Confirmation of this pressure release process has come from quarrying and mining operations where rock is known to expand following the removal of overlying rock (Bain,1931; Jahns,1943). Jahns(1943) observed that the parallelism of the sheets was independent of rock structure and that the dilatation joints were spaced at progressively greater distances with depth and became parallel to the surface.

An hypothesis has been suggested that facilitates the creation of jointing in rocks by pressure release. Glacier thinning would not only lead to a greater release of pressure creating dilatation joints, but would also mean that meltwater activity could create opportunities for freeze-thaw action to work on joints (Lewis,1954; Harland,1957; Henderson,1959; Birot,1968). Following a re-advance, loosened bedrock would already be prepared for removal by the glacier ice. It has recently been suggested by Trainer(1973) that moving ice can itself open up joints along pre-existing zones of weakness. He points out that pressure release joints cannot be the whole answer to glacial quarrying since high angle joints are needed to break up rock into blocks. Boulton (1972,1974) suggests that bedrock can be crushed by ice in subglacial cavities due to lateral expansion of rock in response to stresses set up by the overlying ice.

The importance of glacial quarrying in relation to the study of frequency, size and shape of erratics is axiomatic. The ease with which glacier ice can incorporate bedrock material will control the frequency of erratics down-ice of the outcrop. The shape and size of erratics will be affected by the original bedrock jointing characteristics. The influence of bedrock jointing on the size and shape of erratics is well known (Shaler, 1893; Charlesworth,1924; Drake,1970; Henderson,1972; Gry,1974; Krüger,1974). This does not however rule out quarrying of bedrock along lines of weakness induced by dilatation or pressure of ice since, during glacial transport rock fragments will in any case tend to be crushed into joint-controlled blocks.

Distribution of erratics

The possible ways in which erratic material can be incorporated, transported and deposited in the glacial environment will be discussed in this section. The incorporation of erratics into glacier ice and aspects of their vertical distribution will be discussed, followed by the horizontal component in their distribution.

Apart from their size, a particular feature of erratic blocks that puzzled early nineteenth century scientists was the heights to which they had been lifted above their sources. Many instances of uplift of erratics have been documented in the British Isles. In Arvon, Ordovician shale has been lifted 30m in 3km (Greenly,1941). Hollingworth(1931) noted the transport of Shap granite boulders to higher levels in the Lake District. On the Isle of Man granite boulders weighing 2tonnes have been raised some 170m. In Scotland, erratics of Torridonian Sandstone have been carried up some 450m (Peach et al.,1913). In Glen Orchy a mass of kentallenite has left a well marked train of boulders leading to a point 170m above the parent rock (Kynaston & Hill,1908). Rannoch Moor granite erratics have been lifted some 650m from their source (Peach et al.,1913; Bailey & Maufe,1916). In the Shetland Isles stones in till have been carried at least 200m up the shoulder of Saxavora Hill (Peach & Horne,1879).

It is acknowledged that moving ice can provide the means for carrying and depositing material to higher levels than its source. The elevation of erratics is only part of the wider question of how the upward transport of glacial material is performed.

Evidence for the upward transport of material on modern glaciers and ice caps is abundant. Forbes(1847) observed that the greater part of the surface of the Rhône glacier was free of stones. Towards the snout However many stones appeared at the glacier surface.

Forbes suggested that this resulted from retardation of the snout due to increased friction, thus causing stones from the bedrock-ice interface to be "actually introduced into the ice by friction at the bottom of the glacier, and forced upwards by the action of the frontal resistance" (Forbes,1847,p.152). Similar conclusions for the derivation of observed supraglacial debris were drawn by Salisbury(1896), Garwood and Gregory(1898) and Garwood (1899). The material arriving at the surface of the glacier had apparently been dragged up so-called shear planes formed where active ice overrode a wedge-shaped, stagnant, frontal zone (Worcester,1939; Goldthwait,1951; Sharp,1954; Bishop,1957; Souchez,1966,1967,1971; Clayton,1967; Stewart & MacClintock,1971). Shearing of debris has also been postulated for situations where the lower layers of ice have been retarded by topographical obstructions (e.g. Lewis,1887; Woodward,1897; Flint et al.,1942; Parizek, 1969). Pebbles observed emerging from shear planes at the glacier surface have been water-worn (Kendall,1894; Garwood & Gregory,1898; Ray,1935; Chamberlin,1936) and striated (Visser,1935; Sharp,1949). From observations Goldthwait(1951) considered that dirty shear planes in the Barnes ice cap would intersect with the ground some 480m back under the ice. Swinzow(1962) observed horizontal dirt bands at this approximate distance.

Pirie(1913) though noting an upward inclination of strata towards the glacier snout could find no evidence of shearing. Chamberlin(1928) found that shear plane movement was only slight. More recently Weertman(1961) and Hooke(1968,1973) have objected to the concept of discrete shear planes formed at the margin between active and stagnant ice. Hooke(1973) and Anderton(1973) consider that the upward transport of debris is merely a passive response to surface ablation.

Whether or not shear planes are an important method of ice movement, transport of debris solely by this means at the margin of a glacier or an ice sheet cannot account for the known travel of debris up to 800km from its source (Goldthwait,1971). Some other method of incorporation and transport of debris therefore seems likely and a number of alternative hypotheses have been proposed. Campbell(1891) considered that glaciers would conform to the laws of fluid action and that just as rivers carry material from their base to the surface so too must glaciers, except that the debris does not return to the base in a glacier. Hollingworth(1931) suggested a process whereby cross currents at different levels in the ice were capable of thrusting up material. Case(1895) and Sollas(1895) both demonstrated by means of models how debris might follow an upward trajectory when a glacier was forced to rise over a bedrock obstacle.

Following observation of subglacial meltwater at the base of modern cold and temperate glaciers, a method of incorporation of material by freezing of water on to the bottom of an ice sheet was proposed (Weertman,1961, 1966). Weertman considered that the position where the 0°C isotherm coincided with the base of the ice would shift in response to a change in the thickness of the ice. As a result of a repetition of this process alternating layers of clear ice (representing frozen meltwater) and debris would be frozen to the base of the ice.

Boulton(1972) proposed a similar process to account for the quarrying of large erratics. Where the depth of freezing in subglacial materials coinciding with major joints or planes of weakness the material might be carried forward by the glacier.

Boulton(1970a), noting that pressure melting and regelation occurred around an obstruction on a glacier bed, considered that basal debris might be carried to a relatively greater height because of the formation of regelation ice beneath it in the lee of the obstruction. However he added that vertical mobility by this means is limited to around 10cm (Boulton,1975).

Boulton(1974) has observed how plastic flow of ice enables large boulders to be tightly gripped by a glacier. Beneath the Glacier d'Argentière the closure of a cavity led to ice flowing firstly around boulders and then transporting them.

Although these suggestions indicate how material can be incorporated into the base of a glacier of ice sheet, none of them appears to account for the uplift of erratics by hundreds of metres over short distances. Shear or thrust planes however provide the steep upward trajectory necessary. Although it seems unlikely that material can be"dragged up from the base of the glacier along thrust planes" (Clayton,1967,p.42), shearing has been observed carrying material already incorporated by the regelation process to higher levels in the ice (Boulton, 1970a).

A specialised manner in which basal debris can be lifted by glacier ice concerns the interaction of two ice streams. Bonney(1889) observed how two glaciers converged, the smaller ponding against the other and being forced to rise. Since the sole of the smaller glacier carried with it basal debris which was deposited on to the surface of the other glacier, Bonney considered that this process might throw light on the way in which "blocks of rock in past geological ages may sometime have been carried uphill by glaciers" (Bonney,1889,p.391). Similar observations of overriding glacial streams were made by Visser(1932,1935) and Klebelsberg(1939).

Not only are erratics distributed at various levels in the landscape but there is also some evidence to suggest that they may be separated according to distance of transport in any vertical sequence of glacial deposits. For instance Goodchild(1875) found that the higher of two divisions of glacial deposits contained larger, more angular blocks with a more distant origin than material in the lower division. Calhoun(1906) and Mölder(1950) noted that boulders lying on the surface had travelled farther than material in the underlying till. Ramsay(1912), Charlesworth(1924), Stather(1929) and Vincent(1969) have also noted separation of deposits containing certain erratics. Sauramo(1924) found a till sheet containing predominantly granite-gneiss material overlying another that was chiefly composed of micaschist. Since the granite-gneiss had a more distant source he argued that a process of sequential deposition had operated. Boulton(1970b) also noted that the upward sequence of debris deposited from an englacial position reflected in reverse order the lithologies over which the ice had moved. Hyvarinen et al.(1973) have shown quantitatively that the amount of material with a long transport history increases higher up in a till sequence. Flint(1957) suggested that this phenomenon of sequential deposition resulted from the deposition of till formed by the glacier stirring up local material which protected the ground from further erosion and permitted the subsequent deposition of far-travelled material.

Other work however has reflected the remarkable extent to which ice has mixed material of local and far-travelled origins. Milthers stated that "it only very seldom happens that boulders of one origin... occur in a special geological horizon, and that boulders of another origin... lie in another separate horizon" (Milthers,1909, p.33). Davies(1876) and Hyyppä(1948) concurred with this view.

Having dealt with the vertical aspects of the transportation and deposition of erratics, the horizontal component of their distribution will now be discussed. In the lee of bedrock outcrops lines of erratics extend downstream in the direction of ice movement. If an outcrop is small, hard, suitable for quarrying and sufficiently distinctive for easy identification, a stream of erratics may be traced. Characteristically, lines drawn from the localities of a number of erratics to their source form a fan with the apex centred on the source. Early workers referred to them as boulder trains but boulders are only one of many particle sizes that constitute the material eroded from an outcrop. The term indicator fans has been used to describe streams of erratics of all particle sizes, but for the present investigation the term erratics trains is preferred.

Erratics trains form "perhaps the best available index of the local direction of flow of an ice sheet" (Flint,1957,p.123). Other indicators of ice movement direction, such as striae, drumlins and crag-and-tails, show the movement of the base of an ice sheet at a particular point or time. The direction of the major axis of an erratics train, however, represents the culmination of an infinite number of changes in ice movement direction over a large area through phases of ice advance, retreat and stillstand.

An erratics train can be almost linear as in the case of the train from Snake Butte, north central Montana (Knechtel,1942), or it may form an extremely wide fan such as the 80 degree arc from a quartzite outcrop in the Waterloo area (Buell,1895). The fragments generally become fewer with distance from their outcrop, as Tilas noted in 1740, and fewer away from the major axis of the train. The distance over which erratics are spread is limited by the distance from the source to the margin of the ice mass and the ability of the fragments to survive weathering and erosion during transport (Price,1973).

Erratics often become smaller, more spherical and rounded with distance from their outcrop.

The earliest train of erratics to be noted in Scotland is the train of dolerite fragments from Corstorphine Hill in Edinburgh (Maclaren,1852). Hopkins(1852) noted the southward spread of erratics from Glen Fyne to the Clyde estuary. The Lennoxtown boulder train mapped by Peach(1909) is by far the best known train of erratics in Scotland (Fig.3.2). Erratics trains have also been studied in North America (e.g. Perry,1870; Benton,1878; Shaler,1893; Buell,1895; Taylor,1910; Knechtel,1942; Stalker,1956; Morgan,1969; Dionne,1973) and Scandinavia (e.g. Hausen,1914; Hucke,1937; Saksela,1949; Mölder,1950; Edelman,1951; Gillberg,1965,1967,1968a; Rui,1972). Mickelson(1971) actually observed a train of marble erratics on stagnant ice of the Burroughs glacier, Alaska.

The sharp rise in the frequency of erratics on approaching an outcrop from a down-ice direction has given rise to the use of erratics trains in prospecting for ore bodies covered by glacial deposits. This method has had a long history in Scandinavia (e.g. Tilas,1740; Sauramo,1924; Högbom,1931; Lundqvist,1935; Ødum,1945; Hyyppä, 1948; Grip ,1953; Kauranne,1958; Krüger,1974). Similar uses of erratics trains in prospecting have been made in North America (e,g. Moore,1940; Dreimanis,1956,1958; Lee,1963; Gunn,1968). In Scandinavia dogs have been specially trained to locate individual sulphide- and graphite-rich erratic boulders (Hyvarinen <u>et al.</u>,1973). In Ireland dry stone walls have been used as locations for tracing erratic boulders (Morrissey & Romer,1973). Not only boulders have been used in tracing ore bodies in glacial drift prospecting. In the 1930's mineral composition of till was included followed by X-ray diffractometers and various rapid chemical analysers in the 1940's (Shilts,1971). Geochemical methods are commonly used (Cazalet,1973; Eriksson,1973; Govett,1973; Nilsson,1973; Shilts,1973a; Szabo <u>et al.</u>,1975). In Sweden extensive uranium prospecting has brought about the use of magnetic, radon, radiometric and electromagnetic surveys as well as more traditional methods for tracing glacial erratics (Lundberg,1973).

The rapid decline in the amount of erratic material with distance from its source had been noted by nineteenth century observers. Benton reported that boulders of chloritic schist near their source were "abundant... while on passing along the train to the south-east, a well marked... diminution in their number may be observed" (Benton,1878,p.28). Shaler recorded for the Iron Hill boulder train, Rhode Island that "the average distance between the pebbles of ore rapidly increases as we depart from the source of the train" (Shaler,1893,p.198). Salisbury(1900) theoretically determined the dilution of material in till. However Krumbein(1937) was the first to attempt to define mathematically the dilution in the amount of erratic material with distance from the source. He used a map of individual erratic boulders to derive measures of boulders per unit area at five points vary-in distance from the source (Fig.2.1a). He showed that the decrease in the concentration of boulders per unit area could be expressed as a negative exponential function of the form

$$Y = mb^{-ax}$$

where m is the value of Y when x=0, b is the base of the exponential function and a is a constant.

Dreimanis(1956) illustrated the percentage of rock fragments in till against distance from the source for a number of different rock types (Fig.2.1b). All the curves resemble the curve of Krumbein(1937) in that the rate of decline is high near the outcrop after which each curve flattens out.

Gillberg(1965,1967,1968a) fitted curves based on the function introduced by Krumbein to the dispersion of various lithologies within till in southern Sweden. Dionne (1973) has also derived curves representing the decay in the percentage of ordovician pebbles in fluvioglacial material and till in Quebec.

The shape of these decay curves varies for different particle sizes in till or fluvioglacial material, and between material of the same size and lithology in till and fluvioglacial deposits.

Lee(1965) investigated the effects of fluvioglacial deposition on the dilution of different sizes and types of minerals in the Munro esker, Canada. By sampling the esker at intervals he found that the maximum abundance of any mineral did not occur at the outcrop but some distance downstream. The larger particles tended to approach their maximum abundance more quickly than finer particles.

Similar results have been obtained by Shilts and McDonald (1975) for the Windsor esker, southern Quebec.

Hellaakoski(1931) made observations on material comprising the esker at Laitila, Finland. The esker runs almost parallel to neighbouring striae and overlies an outcrop of Rapakivi granite for 27km of its length. The percentage of Rapakivi stones was counted both in the drift alongside the esker and in the esker itself from a point where it crossed on to the Rapakivi outcrop. The percentage counts at sample points along the route of the esker are shown in Fig.2.2. At a distance of 1.5km from the proximal contact with the Rapakivi granite, this rock amounts to 50 per cent of the stones in the drift. However, in the esker Rapakivi stones only start to appear at 5 to 8km. The maximum abundance of Rapakivi granite in the drift occurs at 15km from the proximal contact compared with a higher maximum abundance at 20km for esker material. Hellaakoski argued that the drift acted as the source of Rapakivi stones for the esker thus explaining the greater distance before maximum abundance is reached in the latter.

The far-travelled nature of esker material has also been noted by Virkkala(1958), Matisto(1961), Gillberg (1968b) and Szabo <u>et al.</u>(1975).

A number of studies involving various size grades of a particular rock type have indicated that the fine material persists for greater distances within till than the coarser component (e.g. Crampton,1959; Bayrock,1962; Gillberg,1968a; Pettersson,1968; Szabo <u>et al.</u>,1975).

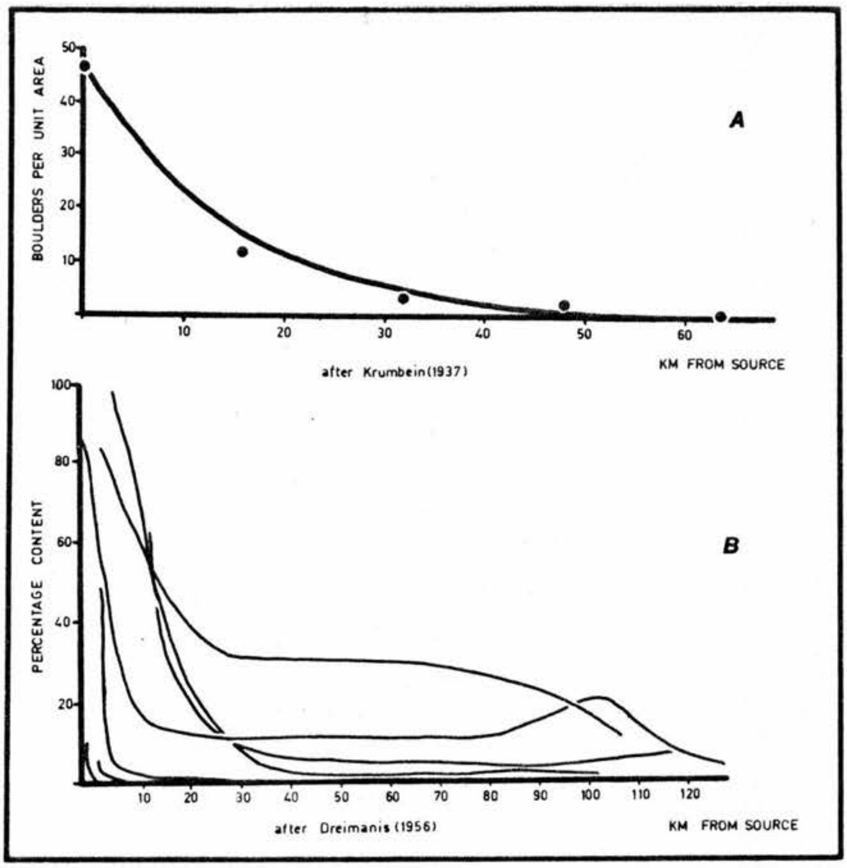


Figure 2.1

Distance decay curves for A) erratics from Mount Ascutney and B) a number of erratics trains.

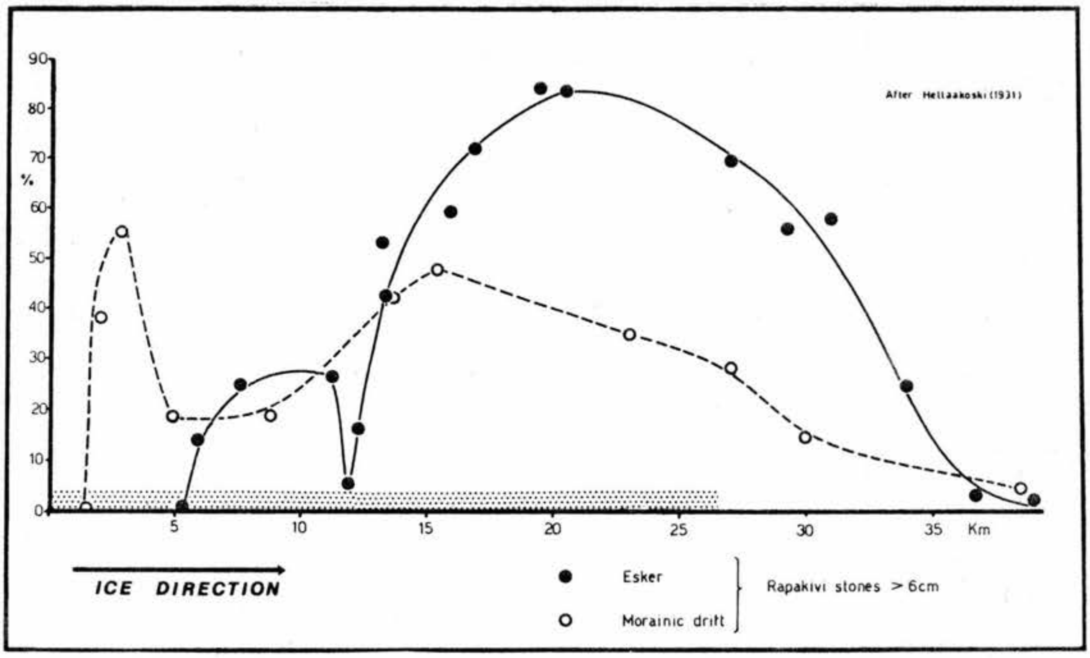


Figure 2.2

Distance decay curves for Rapakivi granite erratics in morainic drift and esker material. Stippled area represents extent of the Rapakivi outcrop.

Dreimanis and Vagners(1965,1969,1971,1972) investigated this phenomenon in some detail. They considered that for mono-mineralic rocks in till there is a bi-modal distribution of partical sizes; a matrix mode in the fine fraction and a clast-size mode formed by rock fragments. In multi-mineralic rocks, matrix modes will correspond to each constituent mineral. The matrix mode forms the "terminal grade" to which rock fragments are eventually reduced and beyond which comminution of the material no longer takes place. At the source the clast-size mode is larger than the matrix mode. However with "increasing distance of glacial transport away from the source, the matrix modes grow larger, recording increasing comminution of clast-size particles" (Dreimanis & Vagners,1971, p.242). In the case of the frequency distribution of dolostone-dolomite, the matrix mode attains over 30 per cent of total dolomite after 75km and 70 per cent after 300 to 500km transport. In contrast to this view, a few workers considered that both fine and coarse till material undergoes short glacial transport (e.g. Donovan & James,1967; Shilts,1973b).

The dispersion of erratic material from its source along a line in the direction of ice movement presents a comparatively straightforward situation. The introduction, however, of a third dimension, by building up a pattern of the dispersion along an infinite number of lines radiating from the source, leads to a far more complex picture. A number of factors that affect the dispersion of erratic material are known, but their contribution has not been quantified. Anderson(1955) has grouped these factors under the four headings of provenance, lithology, glacial processes and dilution. Similar lists of factors affecting the dispersion of erratic material were produced by Flint(1971) and Holmes(1960).

Provenance refers to the source of an erratic. The size and proximity of an outcrop affect the amount of material from that source in the glacial deposits. Eskola (1933) found that the percentage of rock types in till was similar to the percentage area of Finland underlain by that rock type. Harrison(1960) found a similar relationship of bedrock area to till content for Wisconsin till in Central Indiana. The topographic position of the source outcrop also affects the number of erratic fragments produced. The source of the Iron Hill boulder train is in the form of a "unique boss of rock rising from the tolerably level country" (Shaler,1893,p.189). However, less prominent rock masses can also give rise to well-defined fans of erratics (Sauramo,1924). The depth of cover by older glacial deposits or weathered material can also affect the amount of erratic material (Krumbein,1933; Gillberg, 1965).

Under the heading of lithology, Anderson(1955) considered the durability, jointing, massiveness and weathering products as being important. Jointing has already been discussed earlier in this chapter in connection with glacial quarrying. The efficiency of quarrying at the source affects the amount of erratic material in glacial deposits. Durability in transport, i.e. resistance to crushing and abrasion, is also an important factor. Non-durable rock types such as sandstones, shales and schists die out quickly in transport (Holmes,1960; Flint,1971). On the other hand granites and other hard igneous rocks often tend to comprise the far-travelled portion of glacial deposits as a result of their durability (Anderson, 1957; Beaumont,1967; Marcussen,1973). If the bedrock can be effectively weathered preglacially then the ice can incorporate considerably more material (Krumbein,1933; Feininger,1971).

Glacial processes have already been discussed in the context of incorporation and upward transport of rock fragments. The main factors under this heading that affect the amount of erratic material in glacial deposits are the thickness, load and rate of movement, which dictate the eroding powers of glacier ice, and the mode of transport, which affects the distribution.

Dilution represents the effect on the amount of erratic material by the addition of other lithologies. This is superimposed on all the foregoing factors and is of major importance in interpreting the distribution of any erratic material.

Theories relating to the formation of erratics trains

Having considered the nature of, and factors affecting the decline of erratic material with distance from the source attention will now be turned to the problem of explaining the fan shape of an erratics train.

In most cases the major axis of an erratics train coincides fairly closely with the direction of ice movement as shown by striae, drumlins etc. in the vicinity. However the processes responsible for carrying erratics obliquely across the ice flow lines reflected by the ice direction indicators are points of conjecture. Any hypothesis must account not only for varying widths of trains but also for a general decrease in erratic material down-ice of the source and away from the major axis until the occurrence of the erratics becomes sporadic. The main hypotheses in the literature can be grouped under the headings of divergent flow of ice, changing direction of ice movement, wandering centre of ice motion and glacial meltwater.

It seems reasonable to infer that a fan of erratics can result from "the divergent flow inherent in the spreading of glacier ice" (Flint,1957,p.123). An illustration of this natural spreading action by ice is the Wadena drumlin field (Wright,1957). Since drumlins are elongated hills streamlined by the basal motion of ice, their long axes reflect the direction of ice movement. The Wadena drumlin field indicates that the ice lobe responsible for their formation spread across an arc of 130 degrees over a distance of 115km. Goldthwait(1971) considered that the typical erratics train suggests some basal mechanism of lateral dispersion in the ice. He advocated the theory of regelation around small basal obstructions and divergent flow around larger obstacles to explain intricate lateral dispersion beneath even unidirectional upper ice. Boulton(1975) has studied in some detail the streaming of basal debris around small bedrock obstacles (Fig.2.3). He regards the extent of lateral mobility as being limited to c.10cm.

Another proposed hypothesis accounting for the observed spreading of erratics away from their source involves an ice stream following a different path either during separate glaciations or phases of the same glaciation. Hausen(1914) considered that the wide fan of erratics from Sweden and Finland spreading to the south-east and south had resulted from two separate ice movements, the "grosse Vereisung" and "jungere baltische Glaziation". The former had travelled from north-west to south-east while the latter had involved a north to south movement. Buell(1878), Petersen(1899) and Ramsay(1912) also advocated separate directions of ice movement to explain the shapes of erratics trains. Hyvarinen et al.(1973) consider that the width of a train is dependent on whether more than one glaciation has been responsible for their distribution. Mountjoy(1958) expressed caution in interpreting ice direction from the Foothills erratics train in case other glaciations had been instrumental in spreading the material. Different directions of ice movement have given rise to intercrossing of erratics on a local scale (Horne,1899). Many, however, have argued that the speed of weathering in some rocks means that it is impossible for two glaciations to be responsible for the resulting erratics trains (e.g. Hyyppä,1948).

There is considerable support for the view that changing ice direction during various phases of a single glaciation has been responsible for creating the fan shape of a typical erratics train. Edelman(1951), considering the origin of a train of sandstone boulders, with one periphery of the train more distinct than the other, favoured this view. "If the ice moved in different directions at separate times it is clear that the boulders quarried by the last ice stream were transported along an almost straight line,[accounting for the distinct boundary] whereas boulders quarried during earlier stages had possibilities of being transported several times in different directions" [accounting for the sporadic occurrence of boulders along the other boundary] (Edelman,1951,p.160). Milthers(1913) suggested that the Baltic ice must have changed direction to some extent at times to account for Danish erratics discovered on the Norfolk coast. Hucke (1937) referred to the possibility of changing ice direction during the "Diluvium" explaining the distribution of erratics in a fan. Gillberg(1965) regarded the fan of Cambro-silurian material in the highlands of Sweden as being formed by separate ice movements at different times. Rui cited the remarkably confined nature of two parallel erratics trains in the Rorøs district of Norway as evidence of "the constancy...of movement of the ice-sheet in its final dynamic stage" (Rui,1972,p.17). Furthermore, both Rui and Holmsen(1964) considered that the ice must have been thick since "the direction of the latest glacial flow was toward NW, independent of local topography"

(Holmsen,1964,p.160).

However in most cases it seems that ice direction is very much controlled by topography. Horberg and Anderson(1956), considering Pleistocene ice lobe movements in central U.S.A., argued that the larger and broader the valleys, the less ice flow was diverted. Where there was only a small angle between ice movement direction and valley alignment, the divergence was more efficient. The influence of topographic irregularities in directing ice movement becomes greater as an ice sheet wastes, as Perry(1870) realised in attempting to account for trains of boulders in Berkshire County, Massachussetts being diverted around hill masses. Saksela(1949) agreed with this view. "Offenbar hat... die Topographie der Unterlage einen merkbaren Einfluss auf die Bewegungen des Inlandeises und somit auch auf die Form des Geschiebefächers ausgeübt" (Saksela,1949,p.51). He also offered an explanation of the wide arc encompassing many erratics trains by arguing that "in einem hügeligen Gelände... breitet sich der Fächer schnell aus, wenn man sich von Mutterfelsen nach der Bewegungsrichtung des Inlandeises entfernt" (Saksela,1949,p.51). With the alignment of landforms approximately the same as that of ice movement, the train would remain the same width, but on flat topography the train would broaden.

Lundqvist(1935) proposed a mechanism for producing the observed fan shape of an erratics train illustrated by the two diagrams shown in Fig.2.4. The left-hand diagram illustrates the flow of ice around upstanding hill

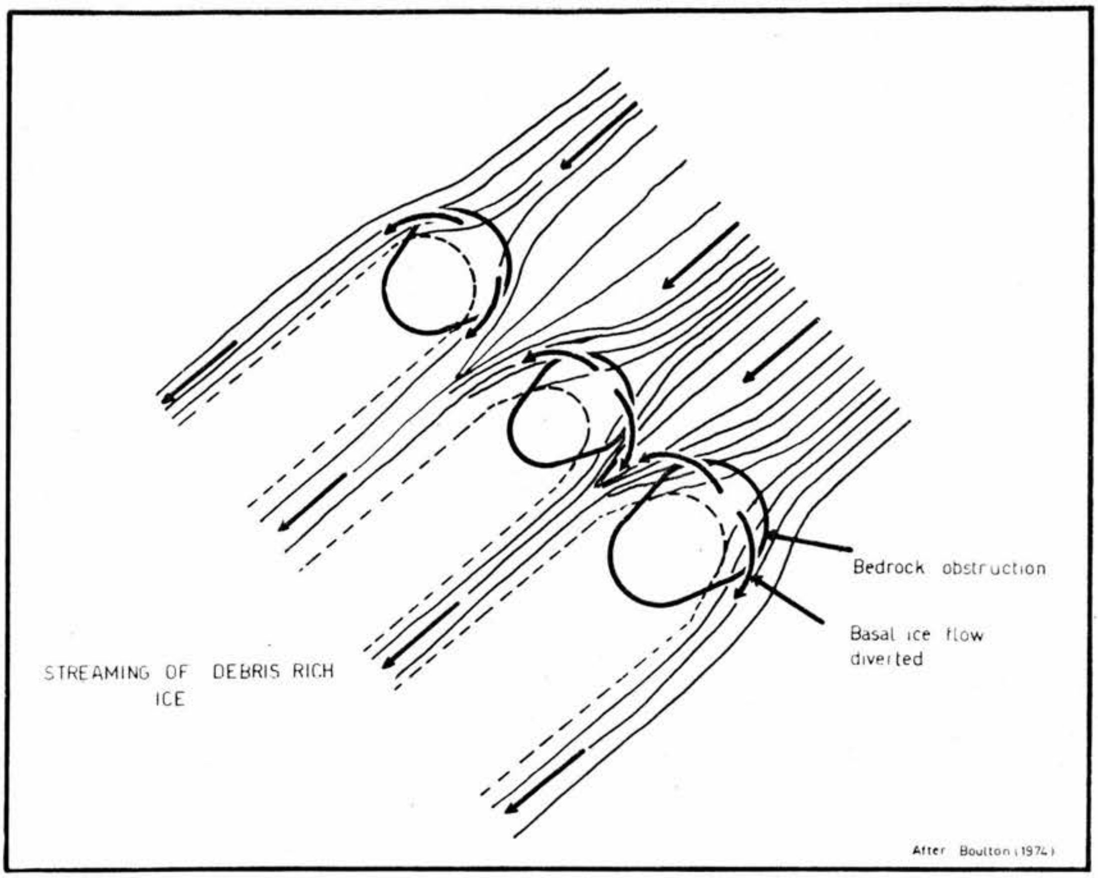


Figure 2.3

Paths followed by debris-rich basal ice around bedrock obstructions according to Boulton(1974).

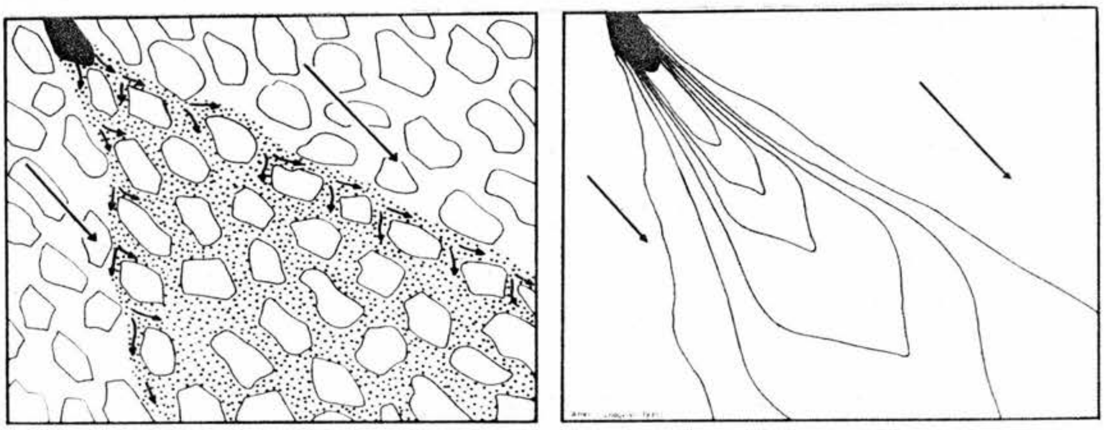


Figure 2.4

Formation of an erratics train by streaming of thin ice around isolated hills (left-hand diagram) to leave a classic erratics train pattern (right-hand diagram) according to Lundqvist(1935). Arrows represent direction of ice movement.

masses at a stage when ice is thin. Each upstanding hill deflects the ice which carries with it erratics from the source in the top left-hand corner of the diagram. When the ice has wasted the isolines of erratic density will be as shown in the right-hand diagram of Fig.2.4.

Sauramo(1924) favoured the idea of topography influencing ice direction during the later stages of ice wastage to explain fans of erratics. However, he also considered the changing ice direction at successive ice margins as the ice sheet retreated. Fig.2.5 shows two stages of retreat (A & B) in an ice lobe. Since the ice flow turns nearly at right angles to the ice margin, ice direction will change from the direction of arrow b to that of arrow a as the ice retreats from area B to area A. Fig.2.6 shows directions of ice movement towards six ice margins during late glacial times in Western Finland. The configuration of the margin constantly changed in response to factors such as relief and ice supply. Since ice direction at each margin would correspondingly change, erratics would undergo a wide variety of directions of transport immediately prior to deposition. Milthers(1909) agreed broadly with this view to account for the fanning of erratics in Scandinavia.

Shaler(1893) objected to this means of explaining the spread of boulders from Iron Hill, Rhode Island. He maintained that "the difficulty with this hypothesis is that it will not account for the gradual and essentially uniform widening of the train from its source" (Shaler, 1893,p.202). He also thought that the "variations in the

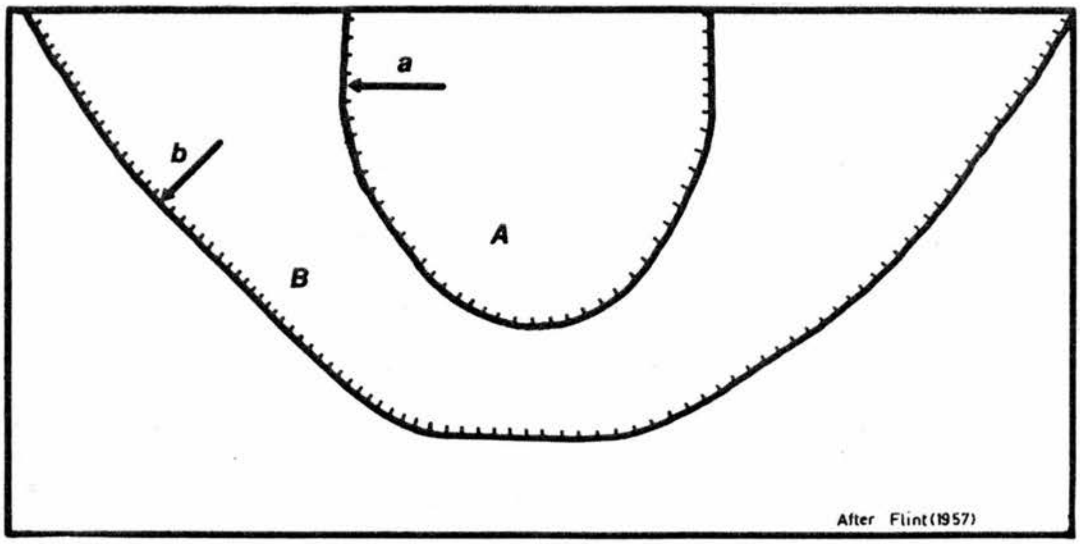


Figure 2.5

Changing direction of movement at ice margin during retreat.

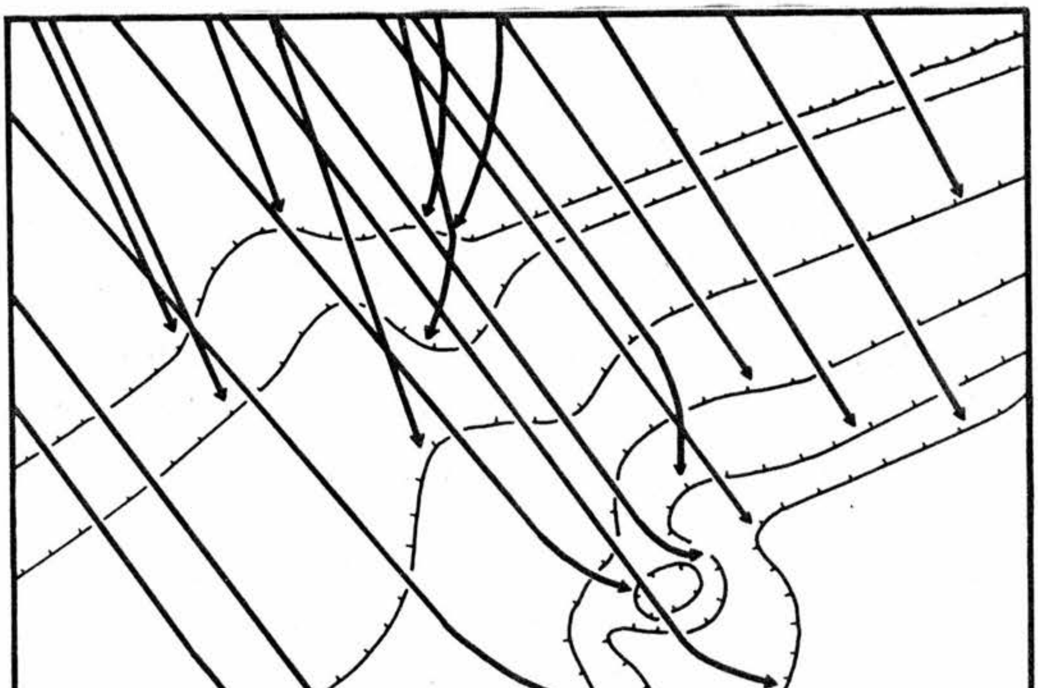


Figure 2.6

Ice movement directions and ice margins in W. Finland.

position of the ice front amounted to only a few hundred feet of distance in the axis of motion" (Shaler,1893,p. 201) such that a wide fan of erratics could not form.

An hypothesis related to the changing direction of ice movement, but alleging a cause inherent to the ice itself, was proposed by Teumer(1927). He argued that " Inlandeis... kann immer nur ein bestimmt begrenztes Geschiebestreubild erzeugen"(Teumer,1927,p.28). Thus in order to form a fan shape to the spread of an erratics train he maintained that a wandering centre of ice motion was necessary. With the centre of motion at A in Fig.2.7 a distribution of erratics in the shaded sector W would be formed. With the centre of motion successively at points B,C and D, sectors X,Y and Z respectively would be strewn with erratics. It follows that the nearer the outcrop is to the ice centre the wider the arc over which the erratics are spread. Other authors have referred to shifting centres of glacial outflow to explain changing ice direction (e.g. Goldthwait,1951; Flint,1951). Furthermore the migration of ice centres as a result of growth or wastage of an ice sheet is established. The North American ice sheets grew eastwards from the Cordillera (Charlesworth,1957). The Greenland ice cap is known to be complex. It is characterised by a number of low domes and local ice caps, up to 60km or more in diameter, that during ice shrinkage apparently have a positive regimen (Flint,1971). During the Pleistocene the juxtaposition of such features may well have had an important effect on the direction of ice motion in the vicinity of an erratics source (Holmsen,1964).

Another possible mechanism that could lead to a fan of erratics is the action of subglacial meltwater. Shaler considered "the horizontal dispersion of the materials contained in the boulder train from Iron Hill to have been mainly brought about by the violent movements of subglacial water" (Shaler,1893,p.205). Hucke thought that "die Schmelzwasser wirkten auf eine Durchmischung des Geschiebebestandes hin" (Hucke,1937,p.51). Lister (1973), considering the origin of proglacial boulders, proposes discrete but temporary subglacial channels to account for this debris. He envisages channels emanating from the glacier snout at high velocity with the streams intermittently changing their position of outflow.

Kummerow(1925) discussed the work of both subglacial and marginal streams in spreading erratics. Tyrrell(1898) favoured the idea of boulders being carried beyond the limit of glaciation by streams. Bergesen(1973) considers that till stones can be transported at variance to the general ice direction as a result of intermediate transport by englacial or supraglacial streams.

Size, shape and roundness changes of erratics during glacial and fluvioglacial transport

Morphological change of rock fragments during transport in a glaciated region has been to a large extent a neglected topic. This has resulted from the difficulty of obtaining a controlled situation in the field. For example, the effect of lithology must be controlled and a single size range of material should be used. Efforts have therefore been concentrated on attempting to define the characteristic size, shape and roundness of fragments for a particular mode of glacial transport (e.g. Mansfield, 1907; Von Engeln,1930; Wentworth,1936; King & Buckley,1968; Bergesen,1973; Gregory & Cullingford,1974). Alternatively the controlled situation has been reached by subjecting material to simulated processes in the laboratory (Wentworth,1919; Krumbein,1941b; Sarmiento,1945; Beaumont,1967; Drake,1968).

However the main characteristics of the change in the morphometric properties of erratics during glacial transport were realised at the beginning of the nineteenth century. The decrease in the size of material away from its source was observed by Greenough(1819). He noted that the "largest masses are found nearest the parent rock, and they diminish in size according to their distance" (Greenough,1819,p.369). Hopkins(1852) observed that the granite erratics emanating from the Loch Etive and Loch Fyne areas diminished in size southwards. Shaler(1893) remarked on the decrease in the size of material away from the outcrop and attempted to define the characteristic size of erratics at various distances from the source. Benton(1878) and Taylor(1910) noted a decrease in the size of material in the direction of transport for the Richmond erratics trains. Drake(1972) measured the size of basal till pebbles for 29 lithologies in an area of east-central New Hampshire. He found that size decreased with distance from the source.

That the shape of fragments was influenced by crushing during transport along incipient bedrock fractures and fissile material therefore does not undergo prolonged travel was also realised by Greenough. "Substances breaking into cubic or hexagonal blocks are found at a greater distance than those which break into fragments with acute angles. Hence the reason why granite is found at such a distance from the parent rock" (Greenough,1819, p.369). During the first quarter of the nineteenth century the agency responsible was thought to be the Deluge. Nevertheless the observations were extremely astute and were not improved upon by Benton(1878) nearly half a century later when considering the effect of glacial transport on boulders forming the Richmond boulder trains. He remarked that "many... of the fragments torn off by the ice contained incipient fissures, which were afterwards developed by the crushing force of the glacier" (Benton, 1878,p.37).

With the fuller knowledge of glaciers and ice sheets accumulated since those early accounts, we are better able to distinguish between the characteristic processes acting in the subglacial, englacial, supraglacial and fluvioglacial environments. The following discussion will deal with the changes in shape and roundness of rock fragments as a result of processes acting in these environments.

Geikie noted the major effects of subglacial processes on the morphological properties of erratics with distance from the source. "The large boulders in the boulder-clay are all from rocks of the neighbourhood, and they become larger in size, less rounded and worn... the nearer they approach to the parent masses from which they have been detached" (Geikie,1863,p.38). Mansfield described typical glacial pebbles as having "Facetted, rounded edges, snubbed ends, polished and striated surfaces" (Mansfield,1907,p.533). Von Engeln(1930) found pebbles in the subglacial till of central New York that were typically striated and of a "flat-iron" shape. Ovoid-shaped pebbles, he felt, were a secondary till-stone type formed by rotation within the till. The facetted parts of the flat-iron pebbles resulted from the fragments being held against the bedrock over which the ice was moving. Wentworth(1936) looked for these characteristic features in till pebbles of the Wisconsin area. He found that the flat-iron description of glacial pebbles was "surprisingly correct". Facetting as a feature of glacial pebbles, although at present out of favour has nevertheless recently been described for till stones (Boulton,1970b). Dreimanis(1956) illustrated the increase in roundness of ore pebbles with distance away from the outcrop.

Quantitative analysis on glacial till stone shapes was first undertaken by Holmes(1960). He examined 3,234 pebbles and cobbles from unleached till in central New York. From the study he concluded that crushing and abrasion affected subglacially transported stones. He considered that facetting resulted from abrasion along pre-existing flat surfaces such as would result from jointing in the rock and maintained that abrasion was concentrated in the rounding of edges and corners of till stones. Ovoid-shaped pebbles, and to a lesser extent discoid-tabular-shaped pebbles, increased with distance from the source and conversely the numbers of wedge forms and rhomboids decreased. These results led Holmes to disagree with Von Engeln(1930) and to argue that the ultimate form to which till stones were abraded in the absence of crushing was the ovoid.

Drake(1968,1972) analysed 1,852 basal till pebbles from 19 sites in east-central New Hampshire. He determined the sources of the pebbles and measured their shape, roundness, amount of breakage, weathering and distance from source. He agreed with Holmes(1960) that crushing and abrasion are the dominant processes affecting pebble morphology in the subglacial environment. He found that roundness increased rapidly within a short distance of transport from the bedrock source. Thereafter mean roundness values maintained an equilibrium. According to Drake, this indicated that the pebbles had undergone continuous crushing and abrasion until final deposition. He also noted the breakage on pebbles. Freshly broken pebbles disappeared most rapidly and those showing no break persisted the farthest. Drake argued that some ultimate shape was being produced that could resist further crushing.

The shape of pebbles was measured and each pebble assigned to one of four shape categories introduced by Zingg(1935). These are rods, blades, spheres and discs. In order to determine the initial shape of the fragments, large unweathered boulders of each lithology represented by the pebbles were fragmented with a sledge hammer (Drake,1970). He considered that these artificially crushed bedrock fragments would be equivalent to the shapes of fragments quarried by basal ice. Assuming this artificially crushed bedrock as representative of the original shapes, he found that over a distance of c.30km "basal till spheres increased by one-half; blades decreased by one-half; rods decreased by one-sixth; and discs increased one-tenth" (Drake,1972,p.2163). These results indicate the effect of the subglacial processes. "With regard to crushing, the elongate pebbles (blades and rods) would clearly be most susceptible to failure and the spheres the least susceptible" (Drake,1972,p.2164). Not only are spheres and discs resistant to crushing and formed by abrasion, but these shapes are actually produced by the crushing of more susceptible blades and rods. Thus the preferential shapes produced by subglacial processes according to Drake are spheres, and to a lesser extent discs. He then agrees broadly with Holmes(1960) who maintained that the ultimate till stone form was the ovoid.

Measurements of pebble weathering made by Drake(1968) indicated that the most weathered, and hence, most readily crushed material tended to be reduced in comparison with the harder pebbles of the same lithology. He concluded that the harder material, being more resistant to crushing, was able to survive longer transport in the subglacial environment. These results support the view of a selective process of subglacial crushing in the production of pebble shape.

Drake assumed that the 29 lithologies represented by the pebbles analysed were essentially similar in their responses to crushing and abrasion, although he did acknowledge that the long transport of certain pebbles could be attributed to their exceptional durability. However resistance to crushing and abrasion varies considerably between rock types which must affect pebble-shape production. In eastern Durham, Beaumont(1967) found that resistant metamorphic and igneous till pebbles with a distant source were more rounded than locally derived, relatively soft sandstone pebbles. He considered that "it might well be that these sub-rounded sandstone fragments represent some kind of semi-equilibrium form which changes little as the dimensions of the particles are reduced" (Beaumont,1967, p.398). He concluded that a "process seems to operate whereby the softer rocks are eliminated and the more resistant rocks rounded to varying degrees" (Beaumont, 1967,p.434). He therefore stressed more strongly than Drake the effect of abrasion. Whereas Drake regarded similar values for roundness with distance from the source as indicative of a state of dynamic equilibrium due to the combined effects of crushing and abrasion, Beaumont regarded this situation as representative of a steady state, abrasion merely reducing the size of fragments. A more important result of the analysis by Beaumont is that stones of different lithologies respond to subglacial processes in different ways.

Comparable detailed analysis on the shape of rock fragments inferred to have been transported in an englacial position has not been carried out. However, observations on debris in modern glaciers allow an assessment of the active englacial processes to be made. Garwood & Gregory(1898) noted englacial material to be rounded and striated. Striated rock fragments from an englacial position have been noted by Phillipp(1920), Visser(1935), Sharp(1949) and Boulton(1970b). Many consider that such evidence of abrasion reflects subglacial rather than englacial processes. Henderson(1972) noted the angularity of till stones in Newfoundland and argued that having undergone englacial transport they had suffered little grinding and crushing prior to deposition. Upham(1891) distinguished between subglacial and englacial till pebbles on the basis of the greater angularity of the latter. Lister(1958) found that the grain-size of englacial debris gradually became smaller at higher levels within the ice, and on the assumption that the higher bands were the farthest travelled, he suggested that there is a gradual mechanical breakdown of debris transported englacially. Others have stressed the less intense nature of both crushing and abrasion on fragments in an englacial position (Elson,1961; Matisto,1961; Andrews,1963; Dreimanis & Vagners,1969; Marcussen,1973; Gry,1974).

At the ice margin, surface ablation will lead to englacially transported fragments attaining a supraglacial position. Immediately prior to, and following emergence of the fragment from the ice it can undergo considerable comminution. Ogilvie(1904) noted the angular nature of supraglacial debris. Souchez(1966) observed frost-shattering of supraglacial debris in Antarctica. He argued that an emerging rock fragment near the ice surface absorbs heat during the day melting a narrow layer of surrounding ice which percolates into cracks and fissures in the fragment. Through fluctuations about freezing point on the fragment surface frost-shattering of the fragment takes place. Small and Clark (1974) favour this process to account for the finer debris comprising medial moraines of a glacier in Switzerland. Oliver(1964) found a rounded and striated supraglacial boulder in Antarctica split apart by frost action. Sharp(1949) also noted frost-shattered supraglacial debris.

Many workers have used the evidence of such observations to argue in favour of a supraglacial origin for Pleistocene deposits. Drake(1971), for example, used the angularity and equidimensional nature of pebbles amongst other evidence to suggest a supraglacial origin for a deposit. Stewart and MacClintock(1971) used the angularity of boulders as an indication of an ablation origin.

In fluvioglacial meltwater streams crushing is not effective and the dominant process acting on rock fragments is abrasion. Few studies have been undertaken to investigate the effect of fluvioglacial transport on the shape and roundness of erratic fragments with distance from the source. Matisto(1961) noted a rapid rounding of bedrock material in an esker in south-west Finland. Gregory and Cullingford(1974) have observed a rapid increase in roundness of sandstone and limestone pebbles within 4km of the source. Hellaakoski(1931) found a considerable rounding of Rapakivi granite stones over short distance of transport in an esker at Laitila, Finland. King and Buckley(1968) measured shape and roundness for stones from different glacial environments. Fluvioglacial deposits(eskers and kames) consisted of more rounded stones than moraines. Between stones of the eskers and kames a statistical difference of the mean roundness values was found. The stones in kames with a lower mean roundness underwent very short transport, yet still showed a higher mean roundness than stones in the moraines. Esker stones, although showing greater roundness than stones in kames, had not travelled much farther. It was concluded that rounding in fast-flowing, heavily laden meltwater streams must be very effective to produce such a marked degree of rounding in such a short distance. Mean values of size, sphericity and flatness, however, failed to differentiate between the three glacial environments. This supports the view that fracturing of stones is largely absent in meltwater streams and that abrasion is the major process.

From source to point of deposition an erratic can undergo processes acting in a combination of the four generalised glacial environments outlined above. Price(1969) identified rock fragments in till as being derived from reworked fluvioglacial material. In the supraglacial environment angularity may be characteristic of fragments on active ice, but meltwater streams flowing on stagnant ice may lead to rounding (Sharp,1949). The Rapakivi granite fragments in the esker at Laitila have undergone processes acting in the subglacial and fluvioglacial environments since the drift acted as the source for the esker material (Hellaakoski,1931).

Bergesen(1973) has attempted to identify the roundness characteristics of stones undergoing a varied transport history. Using four visual classes of roundness, he has identified four roundness types for pebbles in glacial deposits in the Gudbrandsdal area, Norway (Fig.2.8). He distinguishes between "single-phased" and "multi-phased" roundness. For example, roundness type Aa shows single-phased roundness since it has only been transported directly by the ice. The pebbles are characteristically subrounded with less than 10% rounded pebbles. On the other hand, type Ba, which also represents pebbles sampled from till, has a greater percentage of rounded pebbles. Bergesen argues that this has resulted from fluvioglacial pebbles being incorporated and redeposited with the till. This type represents pebbles with multi-phased roundness. Types Ab and Bb represent material sampled from fluvioglacial deposits. Ab has a lower percentage of rounded and well rounded material than Bb. Bergesen suggests that this is due to an englacial or supraglacial transporting mode for the former compared to the subglacial or subaerial

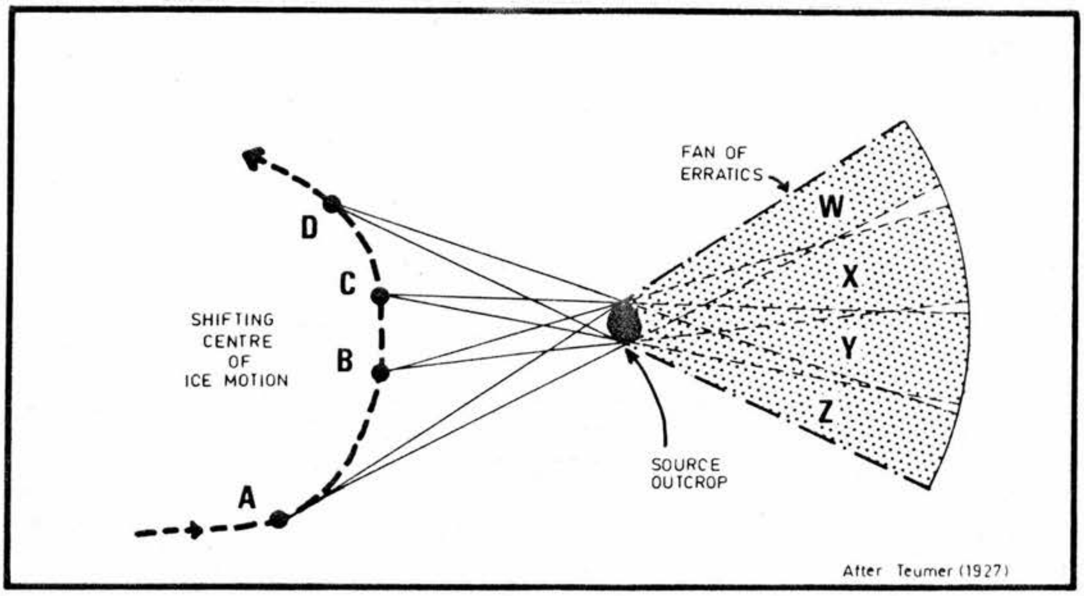


Figure 2.7

Formation of a fan of erratics resulting from a shift in the centre of ice motion.

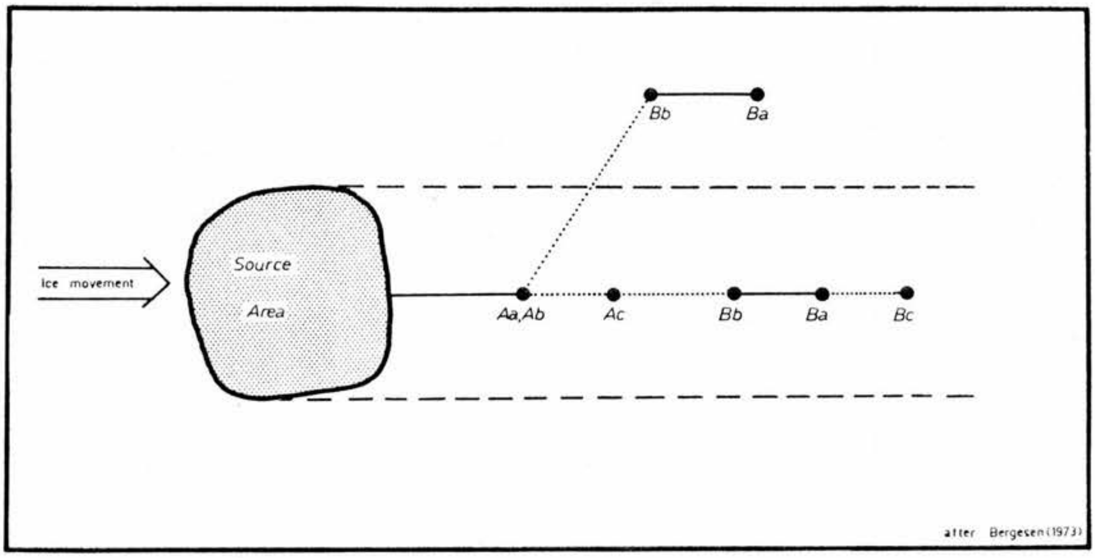


Figure 2.8

Classification of roundness types of erratics according to Bergesen(1973).

meltwater origin for the latter. Types Ac and Bc represent the roundness of pebbles derived from glacial deposits that have undergone further rounding in subaerial streams.

In this chapter the literature concerning aspects of glacial erratics has been discussed. Consideration has been given to the rôle of erratics in the development of the Glacial Theory, the upward transport and distribution of erratics, the various theories put forward to explain the formation of erratics trains and the effects of glacial and fluvioglacial transport on erratics. Before detailing the analysis carried out for the pilot study and for the distribution of essexite fragments in till in chapter 4, an introduction to the Lennoxtown essexite outcrops and their surrounding area in terms of the geology, geomorphology and inferred directions of ice movement will be dealt with in chapter 3.

CHAPTER 3

BACKGROUND TO THE RESEARCH

The first step in carrying out a detailed investigation of an erratics train is to choose an outcrop of rock from which to trace erratics. This decision should not only depend on the attributes of the outcrop itself but also on the nature of the terrain where the distribution of the erratics is to be determined.

In the present analysis, five major requirements were considered essential, and all of them had to be fulfilled by the source rock and its surrounding area before it was regarded as suitable. Firstly, the source rock had to be distinctive both on freshly broken and on weathered surfaces, especially the latter since the majority of erratic fragments from glacial deposits would be expected to show at least some signs of superficial weathering. Any rock that could not be identified in the hand specimen was rejected as unsuitable. Secondly, there had to be no similar outcrops in the vicinity of the chosen outcrop, or fragments likely to have been transported there by ice, since this would lead to confusion with erratics from the chosen source rock. Thirdly, there had to be minimal variation in the mineral composition and geological structure over the source rock outcrop. This was considered important not only because it aided positive identification of erratics but also because such variation might lead to differences in the durability and initial shapes of erratic fragments on being removed from the bedrock by glacier ice. The fourth requirement was that the outcrop should be of modest areal extent, which would allow the distance of transport of individual erratics to be determined with little error. Fifthly, the area down-ice of the outcrop had to be suitable for determining the distribution pattern of the erratic fragments.

It might seem that these five requirements would leave little room for choice. However the nature of the geology of Central and Southern Scotland in particular, with many small igneous intrusions, meant that several outcrops were ultimately regarded as suitable. From a list of possible outcrops, the Lennoxtown essexite, located some 10km north-east of Glasgow, was selected since it best fitted these requirements.

In terms of distinctiveness the Lennoxtown essexite is especially suitable. Firstly it is easily distinguished from other rocks in the area both on fresh and weathered surfaces (MacGregor & MacGregor,1948). Secondly the Lennoxtown essexite in fact consists of two adjacent outcrops that are distinguishable from one another in the hand specimen. There are other outcrops of essexite in Scotland (Clough <u>et al</u>.,1911; Scott,1915; MacGregor & MacGregor,1948) but in view of the known directions of ice movement it is unlikely that erratics from these sources could have been transported by glacier ice into the area down-ice of the Lennoxtown outcrops. Both Lennoxtown essexite outcrops are uniform in terms of mineral composition and geological structure with only a narrow zone of chilling (c. 1cm wide; MacDonald,pers. comm.) at the point of contact with the surrounding bedrock. The essexite outcrops are also both of small areal extent, only covering a combined total area of slightly less than $0.05km^2$, this figure being based on the most recently available information (MacDonald,1973; Fig.3.1). The Lennoxtown essexite outcrops also fulfil the requirement of a suitable down-ice area since they are in a position from which it is possible to trace the erratics uninterrupted for a considerable distance in the direction of ice movement. The area is free from large tracts of urban development or any other major obstacle obscuring the glacial deposits. Streams incised into the till lying on the lower slopes of the Campsies have cut a number of sections. Many sand and gravel quarries, both abandoned and in current use, meant that the effect of fluvioglacial transport on erratics could be studied. The abundance of essexite fragments on the foreshore of the modern beaches along northern and southern shores of the Firth of Forth meant that the effect of beach processes on erratic fragments could also be investigated.

The essexite outcrops

Essexite derives its name from Essex County, Massachusetts where Sears(1891) described a distinctive rock resembling a porphyritic diabase and proposed this term for it. One of the original distinguishing criteria was a lack of olivine. Rosenbusch(1896), however, with more detailed study, incorporated local varieties that included olivine (Clough et al.,1911). Brögger (1894) described so-called essexites from Norway, but these appear to be similar to what others would term olivine-gabbros (Hatch et al.,1961). Essexite in Scotland was first mentioned by Allport when he described the Lennoxtown lower outcrop as a "very beautiful porphyritic dolerite... coarsely crystalline in texture, with large disseminated crystals of augite" (Allport,1874,p.559). Young(1874,1895) also made reference to the "Campsie augite". Lacroix(1900) described a similar rock near Crawfordjohn in Lanarkshire but refered to it as "an olivine teschenite passing in texture to tephrite" (Clough et al.,1911). Scott(1915), however, assigned this rock to the essexite group. Since this time the Lennoxtown essexite has attracted attention from geologists (apart from the work on the erratics by Peach(1909)) owing to its rarity (e.g. Tyrrell,1923; McCallien,1938; Bassett,1958). However it was not until recently that the Lennoxtown essexite was recognised as comprising two intrusions, rather than one dyke-like mass with varying characteristics (Clough et al.,1911).

The lower outcrop ranges from about 120m to 180m in altitude and measures some 200m by 190m in size. It has been interpreted as being in the form of a plug due to its association with a magnetic anomaly (MacDonald,1973). Microscopic analysis reveals that it consists of a porphyritic microgabbro or dolerite with euhedral, purple, titanaugite phenocrysts set in a groundmass of augite, olivine and plagioclase with lesser amounts of red-brown biotite, apatite, analcite and titaniferous magnetite (MacGregor & MacGregor,1948; Harker,1960; MacDonald & Whyte,1969). The presence of orthoclase and nepheline as rarer constituents distinguish essexites from other olivine-gabbros (Hatch et al., 1961). In the hand specimen the well-shaped phenocrysts of titanaugite immediately attract the attention, and stand out from the paler groundmass on weathered surfaces (MacDonald,1973). This pale colour on weathered surfaces appears to be a characteristic feature of analcite-bearing rocks (Tyrrell,1923; MacDonald,pers. comm.). However the titanaugites"remain prominent and more or less unaltered" (Peach,1909,p.26). The lower outcrop also possesses a pronounced set of joints, the most prominent being only a few centimetres apart (MacDonald,1973). Measurement of these joints on the outcrop revealed an average distance of 7cm between such joints (Plate 1).

The extreme altitudes to which the upper essexite outcrop extends are from 210m to 290m and it measures 120m by at least 300m, the latter figure being minimal due to the eastern end being obscured by a landslide (Fig.3.1). Four major characteristics distinguish this outcrop from the lower one. Firstly the outcrop appears to have the form of an inclined sheet (MacDonald & Whyte, 1969). Secondly the titanaugites are not as large as in the porphyritic variety, the whole rock presenting a more even-grained appearance. Thirdly it is a little richer in olivine at the expense of augite, and fourthly

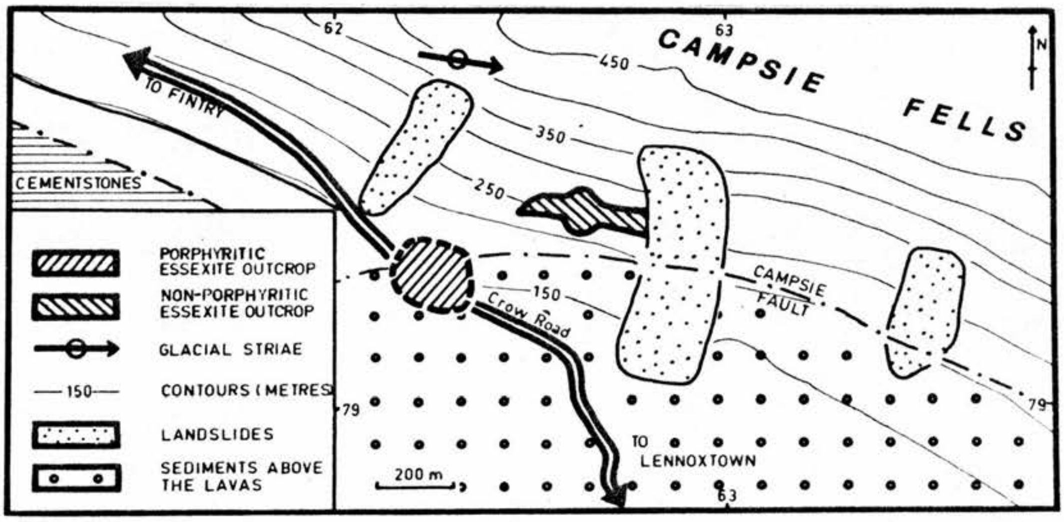


Figure 3.1

Lennoxtown essexite outcrops, after MacDonald(1973).

the joints are noticeably more widely spaced. Measurements taken across a number of parallel joints produced an average figure of 17cm (Plate 2).

Petrographically the two outcrops are similar to the Late-Carboniferous theralites. They are therefore probably more closely connected with that phase of activity than, as previously believed, with the Dinantian vulcanism (Clough et al.,1911), which gave rise to the Clyde Plateau Lavas into which the essexite outcrops have been intruded (MacDonald & Whyte,1969).

The fieldwork area

Peach(1909) mapped the extent of the Lennoxtown essexite boulder train as a narrow cone-shaped area with the apex positioned on the outcrops, situated about 1.5km north of Lennoxtown, and the two sides extending eastwards into the Forth estuary (Fig.3.2). As one of the main objectives of the present study was to attempt an accurate determination of the lateral extent of the erratics train, the fieldwork area extended considerably farther north and south than the cone of boulders shown in Fig.3.2. It was also considered necessary to determine whether there had been any movement of the boulders in a direction other than eastwards away from the outcrops, despite confident statements elsewhere to the contrary (Peach,1909; McCallien,1938). Gregory(1926) claimed to have found an essexite boulder on a building site in Glasgow to the south-west, but as no other record

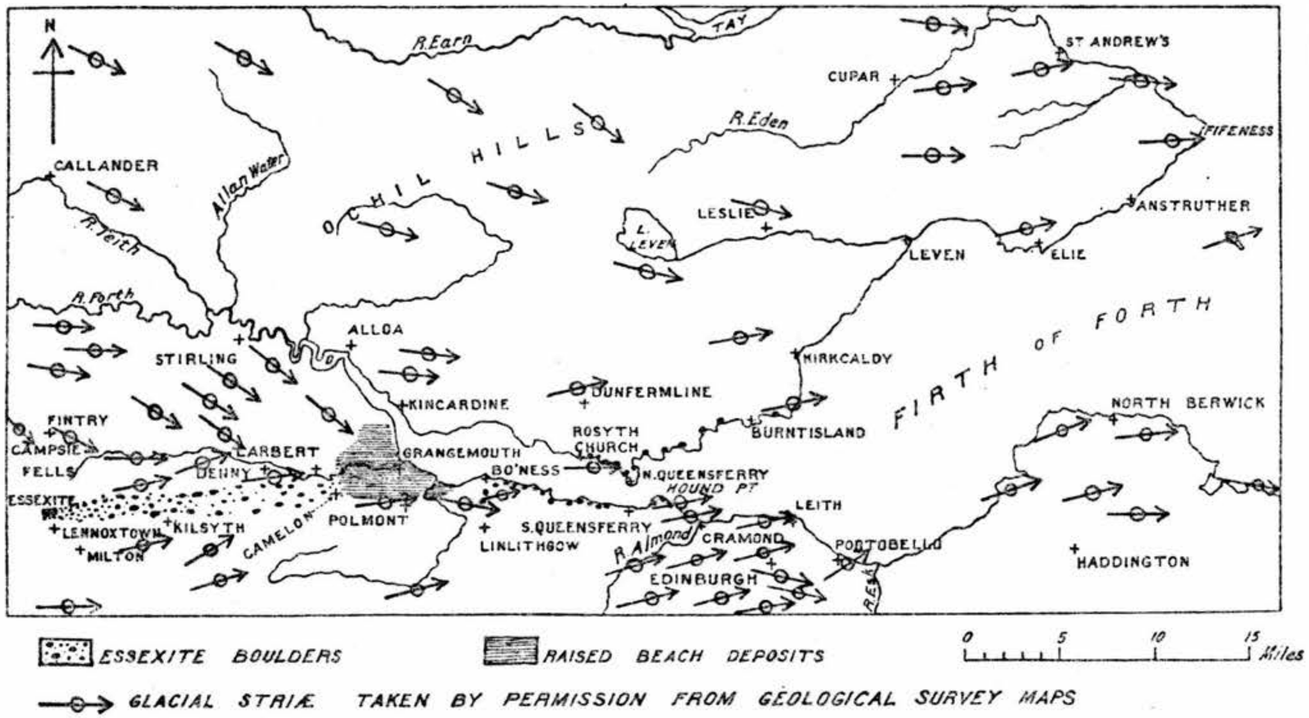


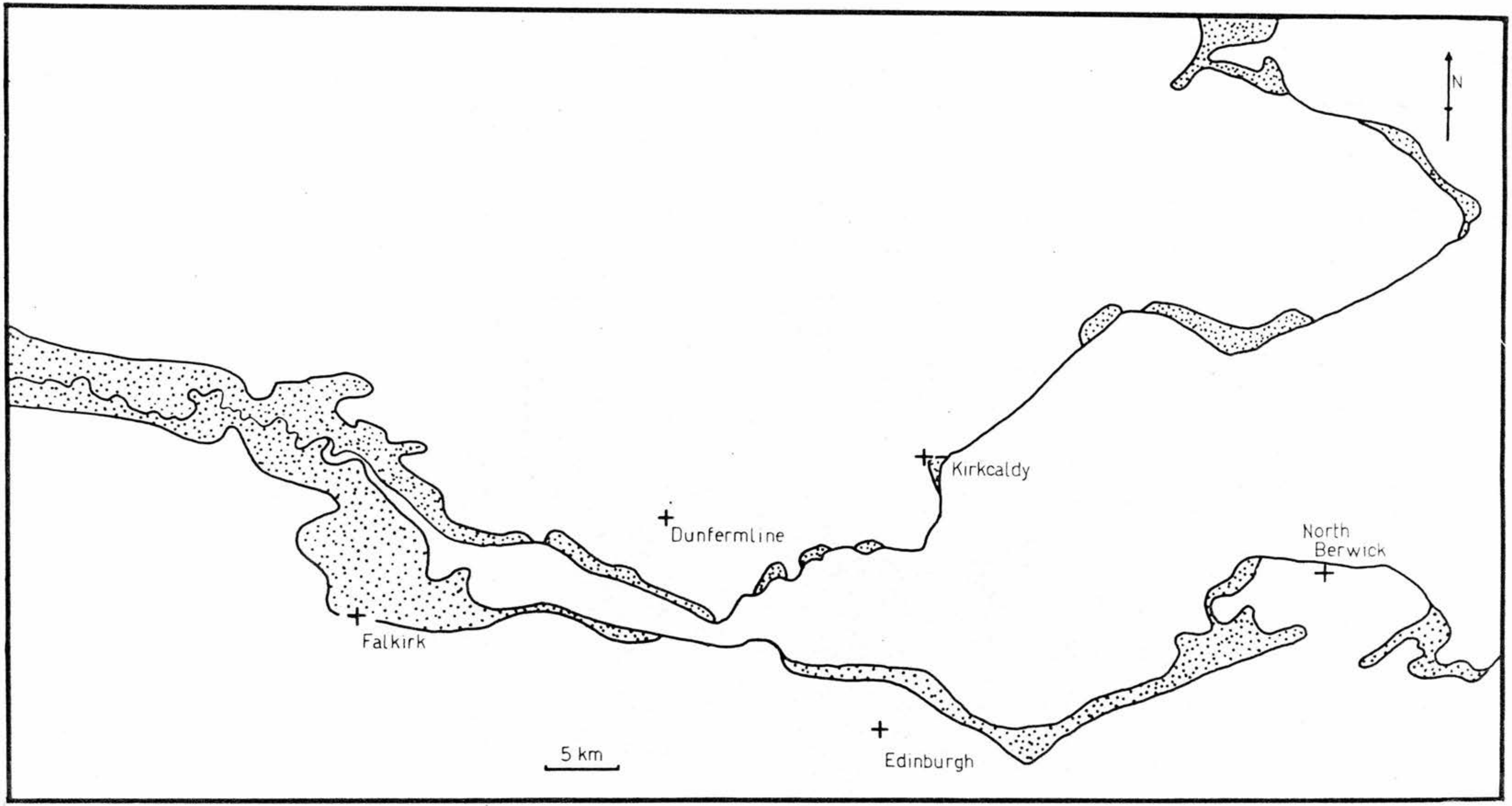
Figure 3.2

Map of the Lennoxtown essexite boulder train by Peach(1909).

of this find exists, it must be regarded as very dubious.

The large expanse of raised beach and outwash deposits between Larbert and Grangemouth interrupts the material in which the erratics can be traced (Fig.3.3). It also marks the approximate easterly point in the train at which erratic fragments are so diluted in the till that they become very difficult to trace. This expanse of raised beach and outwash material splits the erratics train into two discrete parts; the area from Larbert to Ballagan Burn (west of the essexite outcrops), which will be referred to as the Main Study Area, and the remaining part of the train, from Grangemouth into the Forth estuary, which will be called the Secondary Study Area (Fig.3.4). The former area is distinguished from the latter in terms of the amount and type of field-work carried out. In the Main Study Area investigation inbo the distribution patterns of essexite erratics, measurement of the size and morphometric properties of essexite fragments, heavy mineral analysis of till samples, till-particle orientations and the mapping of the ice-moulded landforms were carried out. In the Secondary Study Area, on the other hand, efforts were concentrated on the study of the morphometric properties of essexite stones found on the beaches of the Forth, as only a limited number of sections in till and fluvioglacial deposits were available.

Geology and relief



<u>Figure 3.3</u>

Distribution of raised beach material in the Main and Secondary Study Areas.

Both Study Areas are situated in the Central Lowlands of Scotland, which consist of a tectonic trough some 80km wide. This region is bounded by the Highland Fault to the north, and the tough greywackes, shales and slates of the Southern Uplands to the south, the intervening broad syncline being much faulted and folded (Ogilvie,1937; George,1960,1965). In the Central Lowlands there is a close correspondence between hills and igneous or volcanic outcrops, with the low ground inbetween being usually associated with sedimentary strata (Hutton,1795; Geikie,1865; Sissons,1967a).

The Campsie Fells dominate the Main Study Area geologically and topographically. (The term Campsie Fells is used here to represent the expanse of high ground comprising the Strathblane and Kilsyth Hills, Cairnoch Hill, Gargunnock and Touch Hills.) They constitute a high, undulating eastward-sloping plateau, rising in many places to more than 450m (578m at Earl's Seat and 570m at Meikle Bin) and form the north-eastern arm of the horse-shoe shaped Clyde Plateau Lavas which overlook Glasgow from the north, west and south (Fig.3.4). The Clyde Plateau Lavas comprise the Gargunnock, Kilpatrick, Beith, Renfrew Hills and Campsie Fells and consist of a series of lavas with associated vents and intrusions of Calciferous Sandstone Age (Young,1860; Bassett,1958; MacDonald,1965; Francis,1965a).

Strathblane, a deep trough, separates the Kilpatrick Hills and Campsie Fells. The floor of this trough does not exceed a height of 90m, whereas the

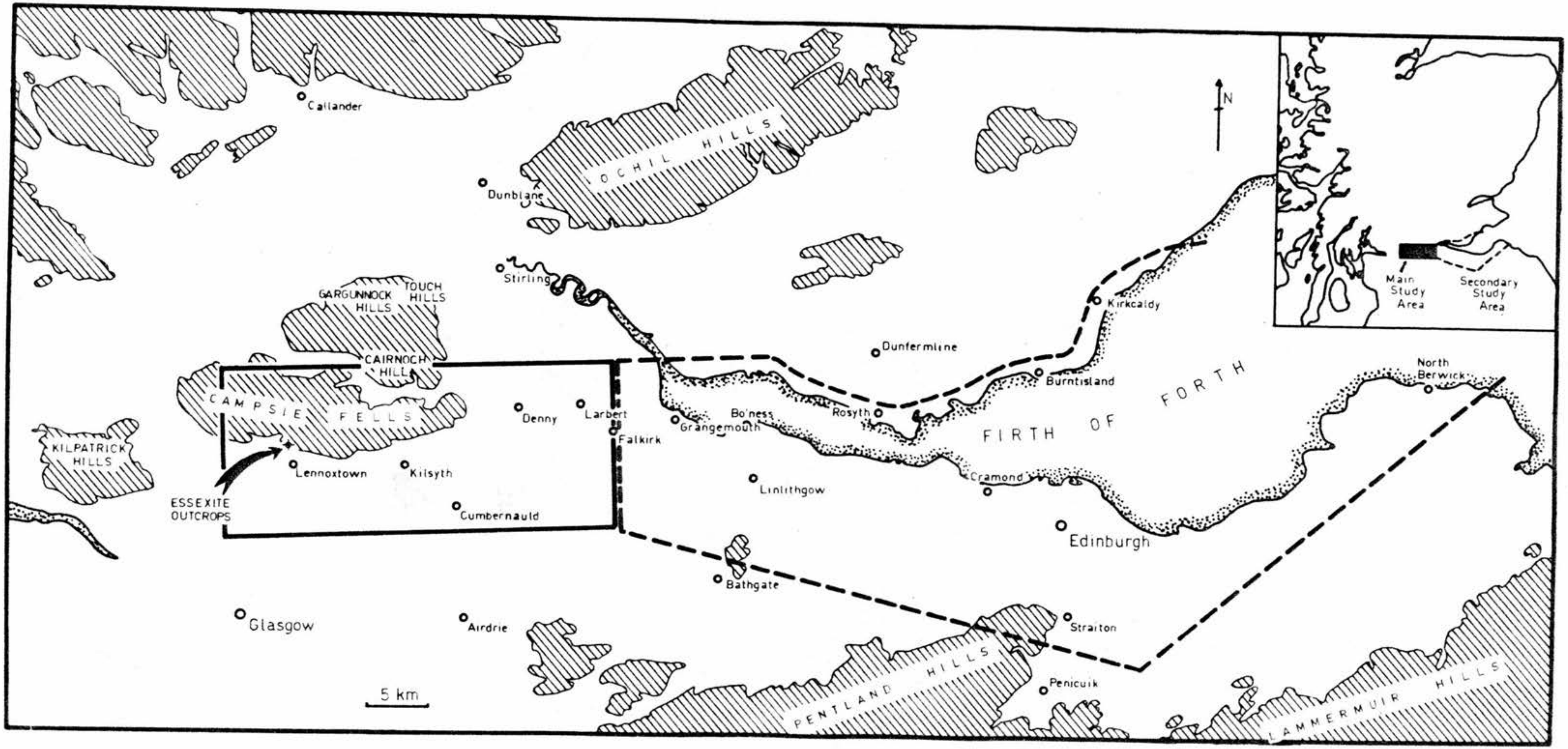


Figure 3.4

Extent of the Main and Secondary Study Areas.

surrounding hill masses rise to more than 500m. A similar, though less dramatic feature, cuts the Campsie Fells in two, separating the Gargunnock Hills, Touch Hills and Cairnoch Hill from the main mass to the south. The Carron and Endrick rivers drain this valley from a mid-point and flow to the east and west respectively.

Old Red Sandstone crops out to the north of the Campsies as far as the metamorphic rocks of the Highland edge. It is pierced by a large number of small vents, suggesting a considerable extension of the Clyde Plateau Lavas in this direction at some time in the past (Whyte & MacDonald,1975). The southern edge of the Campsie Lavas forms a steep, southward-facing scarp coinciding with the Campsie Fault, which has a downthrow of about 900m to the south (MacDonald,1973).

From this scarp southwards the ground falls some 400m to the floor of the valley in which the Kelvin and Bonny Water flow respectively west and east. This narrow valley provides a connecting trough of low ground between the Forth and Clyde estuaries (Fig.3.6). At the eastern end of the Campsies the descent of 350m from the lavas to the broader valley of the Carron is less abrupt. Southwards of the Kelvin-Bonny Water valley and east of the Carron the ground rises gently to a low, undulating topography underlain chiefly by Carboniferous sediments. The highest point on these sediments occurs where the Millstone Grit forms the underlying bedrock, reaching about 175m a few kilometres south of Bonnybridge. The Millstone Grit forms a band of rock stretching from south-east of Kilsyth to the north-eastern corner of the Main Study Area (Fig.3.5). Parallel to this band of rock on the western side, are a number of upstanding outcrops of quartz-dolerite of which Bar Hill (155m) and Croy Hill (147m) south of Kilsyth are two examples. These quartz-dolerite outcrops form parts of a particularly thick sill that underlies a large area of the Central Lowlands (Francis, 1965b).

The Secondary Study Area differs from the Main Study Area in that it has no single large tract of high ground corresponding to resistant igneous rocks. However, between the bounding hill ranges of the Ochils to the north and the Pentlands to the south are a number of locally thick outcrops of igneous rock (both intrusive and extrusive) that stand up from the surrounding, more easily eroded Carboniferous sediments (Burke,1969a).

The effects of glaciation

It is known that at the time of maximum glaciation the whole of Central Scotland was covered by ice. Along the Highland edge in Perthshire striae have been found at 945m, and erratics and striae have been found on the summits of the Ochils (720m), the Lomond Hills of Fife (420m) and the Pentlands (580m) as well as the Campsies (Sissons,1965; Fig.3.4). So clear is the legacy of the ice sheets in the Central Lowlands that they have often been quoted as an example of an area showing

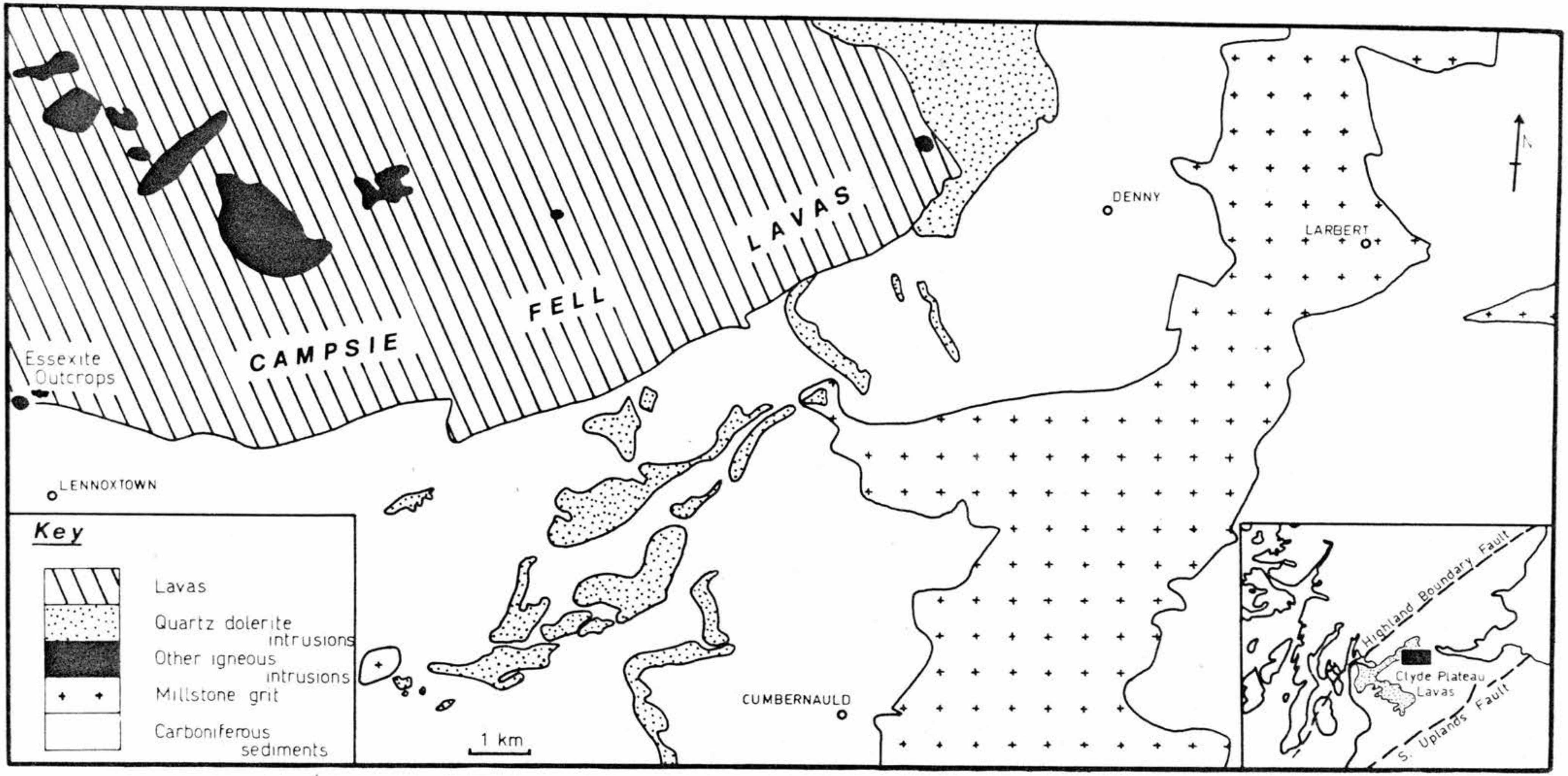
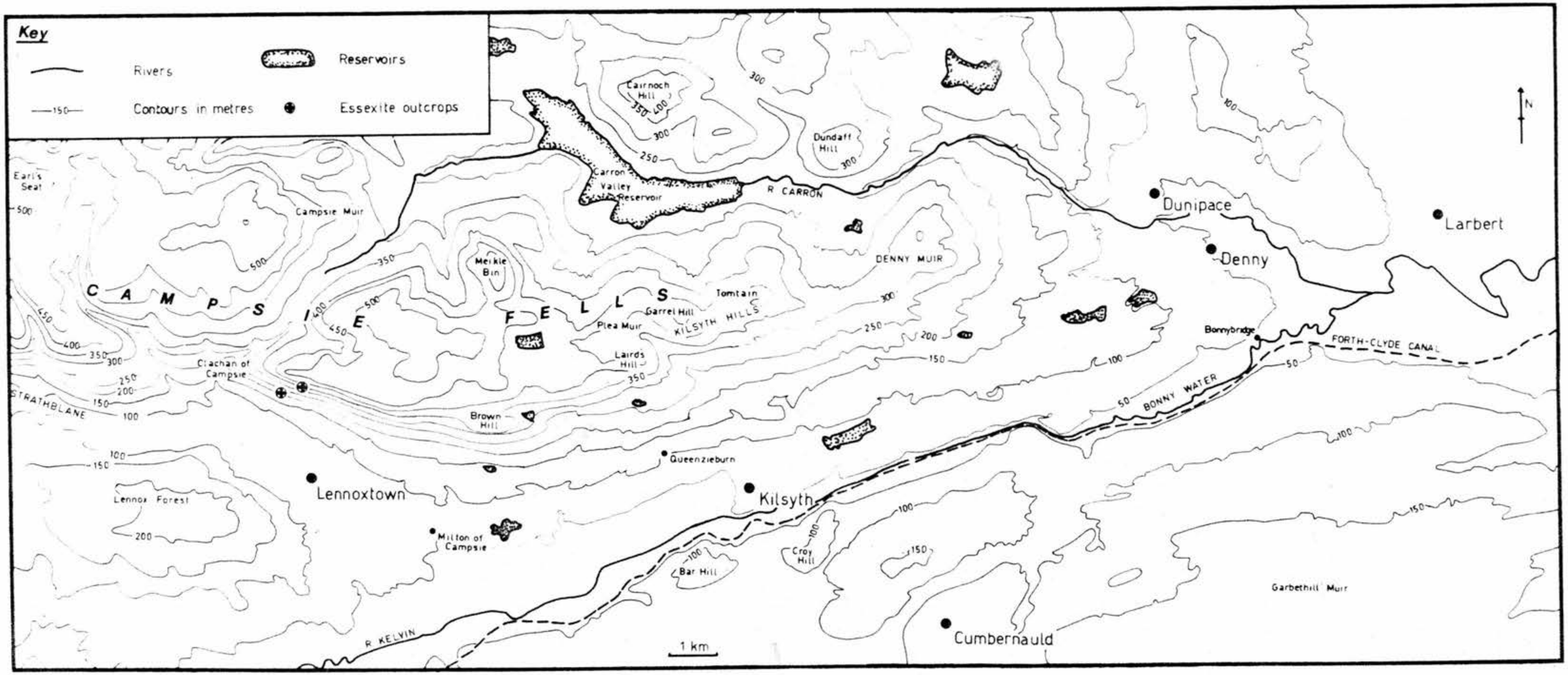


Figure 3.5

Bedrock geology of the Main Study Area.



<u>Figure 3.6</u>

Location of places in the Main Study Area mentioned in the text.

clear evidence of both glacial erosion and deposition. Such evidence is well demonstrated in the Main and Secondary Study Areas.

In terms of glacial erosion, the most easily recognisable features are the "isolated masses of igneous rock" which "project through the sheet of drumlinized drift" (Wooldridge & Morgan,1937,p.390). These igneous rock masses, being of a more resistant nature than the surrounding softer sediments, have withstood glacial erosion better and often show the classic "crag-and-tail" form. The eastward moving ice has tended to cause a steepening of the western slopes in these features contrasting with the eastern slopes which are usually less steep, being protected in the lee of the resistant rock masses (Chambers,1852; Geikie,1865). Dispite their former greater extent, the Campsie Fells, together with the series of outcrops of quartz-dolerite in the Main Study Area already mentioned, have also been better able to withstand the erosive forces of glaciation than the surrounding sediments (Linton,1962).

In the Main Study Area two major breaches of preglacial watersheds have resulted from selective glacial erosion (Linton,1963). These are Strathblane and the broader valley in which the Endrick and Carron flow. The gently curving course of the trough-shaped Strathblane reflects the changing direction of the ice stream that occupied it. The ice here was forced round between the Kilpatrick Hills and Campsie Fells to turn in an easterly direction after joining the eastward moving ice on the southern side of the volcanic hills (Sissons,1967a; Fig.3.7).

One striking feature resulting from glacial erosion in both Study Areas is hidden from view. This is the channel cut in bedrock extending from west of Larbert into the Firth of Forth, which has been buried by subsequent glacial and fluvioglacial deposition (Bennie,1871). Although previously considered to represent erosion by former Carron and Forth rivers (Croll,1868; Cadell,1883, 1886,1913; George,1965), recent borehole evidence (Sissons, 1969) suggests that the feature is a closed rock basin, as is a similar feature just to the north (Soons,1960). The supposition that the trench is in the form of a basin suggests that it has been excavated at least in part by ice. This is further supported by the trend of the buried rock surface which closely parallels that of ice-moulded features in the till immediately to the south (Sissons, 1969). The same feature has been traced using borehole evidence along the Kelvin-Bonny Water valley into the estuary of the Clyde (Clough et al.,1911; Ross,1927).

Some of the results of glacial erosion have been masked by deposits laid down during the later stages of glaciation. The till and associated boulders mantling all but the highest and steepest parts of the hills, however, bear witness to the considerable removal of rocks and debris by ice (Bell,1871; Bennie,1871; Hinxman et al., 1907; Cadell,1913; Fig.3.8). In areas of low relief the till, in places attaining thicknesses of over 30m, generally reaches depths of 3 to 6m (Burke,1969a). Over much of the lower ground of both Study Areas, where the till is relatively thick, the topography has been moulded by ice into drumlins which are elongated in the direction of ice movement (Clough et al.,1911; Elder,1935; Rose & Letzer, 1975).

It is generally accepted that these deposits and others resulting from ice wastage are the result of the last ice sheets to occupy the Central Lowlands and in the last decade or so discussion relating to the existence of re-advances of the ice sheets during the last glaciation has taken place. Sissons(1967a,1967b) maintained that there were three re-advances, the Aberdeen-Lammermuir, Perth and Loch Lomond. They were thought to represent interruptions in the decay of the last ice sheet, each respectively covering a progressively smaller area of Scotland. Neither the limits of the Aberdeen-Lammermuir nor Loch Lomond Re-advance encroach on the Study Areas. However the limit of the Perth Re-advance does impinge upon the eastern end of the Main Study Area.

Simpson(1933) first postulated the idea of a Perth Re-advance and cited evidence for it in the Perth area. Sissons(1963,1964) extended the limit to the south around the southern face of the Ochils to Tillicoultry, then southwards to just west of Larbert and beyond in a meandering line towards Airdrie. In the absence of moraines in the Main Study Area, the re-advance was delimited mainly on the basis of "the extensive development of outwash gravels and sands over thick deposits of clays and silts" (Sissons,1963,p.152). The re-advance was tentatively dated at about 13,000 - 13,500 B.P. (Sissons,1967b). McLellan(1969) modified the proposed limit in Central Lanarkshire to the south of the Main Study Area. However, doubt was cast on the validity of the Perth Re-advance by the discovery of a woolly rhinoceros bone from fluvioglacial deposits beneath till at Bishopbriggs near Glasgow which gave a radiocarbon date of 27,550 (+1370, -1680) (Rolfe,1966). A radiocarbon date of 13700 (+1300, -1700) for a mammoth tusk from stratified deposits beneath about 10m of till at Kilmaurs in Ayrshire appeared to support the idea of a re-advance, but a reindeer antler from the same locality and a similar stratigraphic position gave an age of over 40,000 (Sissons, 1974). Francis et al.(1970) failed to find evidence of a re-advance in the Stirling district, and Paterson(1974) questioned the interpretation that Simpson(1933) placed on a critical section.

Current opinion is that the Perth and Aberdeen-Lammermuir Re-advances must be rejected, but the Loch Lomond Re-advance seems well established (Sissons,1972, 1974).

Sections in the Glasgow and Dumbartonshire areas just to the south and west of the Main Study Area, often reveal two differently coloured till deposits (Jardine & Moisley,1967; Jardine,1969). The lower one, which appears to be widespread across the Glasgow area, is "a tough, grey, entirely unstratified, stony clay, weathering into a lighter and more earthy material towards the surface" (Clough et al.,1925,p.223) and is accepted as being a lodgement till of the last major ice sheet (Jardine,1973). Overlying the grey till, north of a line drawn between Maryhill and Yoker, a red till has been found. The origin of this till has been the subject of some controversy. The colour difference appears to be simply due to a greater number of soft red sandstone fragments in the red than the grey till (Clough et al.,1925). Jardine(1968) argued that since the red till rests either on the grey till (which then shows only slight surface weathering), or on sands and gravels, it represents a re-advance of the ice sheets. He has suggested that the re-advance occurred between c. 12,300 and 11,950. However this interpretation does not agree with radiocarbon dates subsequently obtained.

Sissons(1968) considered that the red till represented an ablation deposit laid down by the same ice that gave rise to the grey till. This interpretation was based on the fact that the red till is associated with innumerable beds of sand, gravel and mud, and that it appears to be less compacted than the grey till. Recent work by J. Menzies(pers. comm.) also contradicts the idea of a re-advance in the area, and suggests that the red and grey tills are variations of the same deposit. In neither of the Study Areas, however, has more than one till been found, although Sissons(1969) mentioned a possible ablation deposit in the Grangemouth area and Thompson (1968) invoked a similar process of formation for deposits in the Campsie Fells.

Fluvioglacial deposits associated with ice wastage are common as sheets and kames in both Study Areas. In the Main Study Area these deposits are generally confined to the lower slopes adjacent to the Kelvin, Bonny Water and Carron Rivers(Fig.3.8). In the Secondary Study Area fluvioglacial deposits are widespread between Falkirk and east of Linlithgow (Wilson & Crampton,1908). On the higher slopes of the Campsie Fells the effect of meltwater activity has been erosional rather than depositional. Thus meltwater channels, running mainly eastwards, are present over much of the south and east facing slopes of the Campsies (Hinxman et al.,1907; Milne,1963; Sissons,1963).

Along the slopes of both sides of the Forth estuary are traces of raised shorelines which denote former high sea levels during late and post glacial times (Sissons,1974, and references therein). They are generally limited in extent, except for an area of raised beach and outwash material from Larbert to Grangemouth (Fig.3.3) which mask the underlying till and fluvioglacial deposits.

Glacier ice movements

A considerable body of information has been accumulated concerning the direction of ice flow across the Central Lowlands of Scotland as a result of more than 150 years of enthusiastic work. Since the glacial geomorphologists of the last century working in this area were at the forefront of ideas on their subject, the general directions of movement have been well known for more

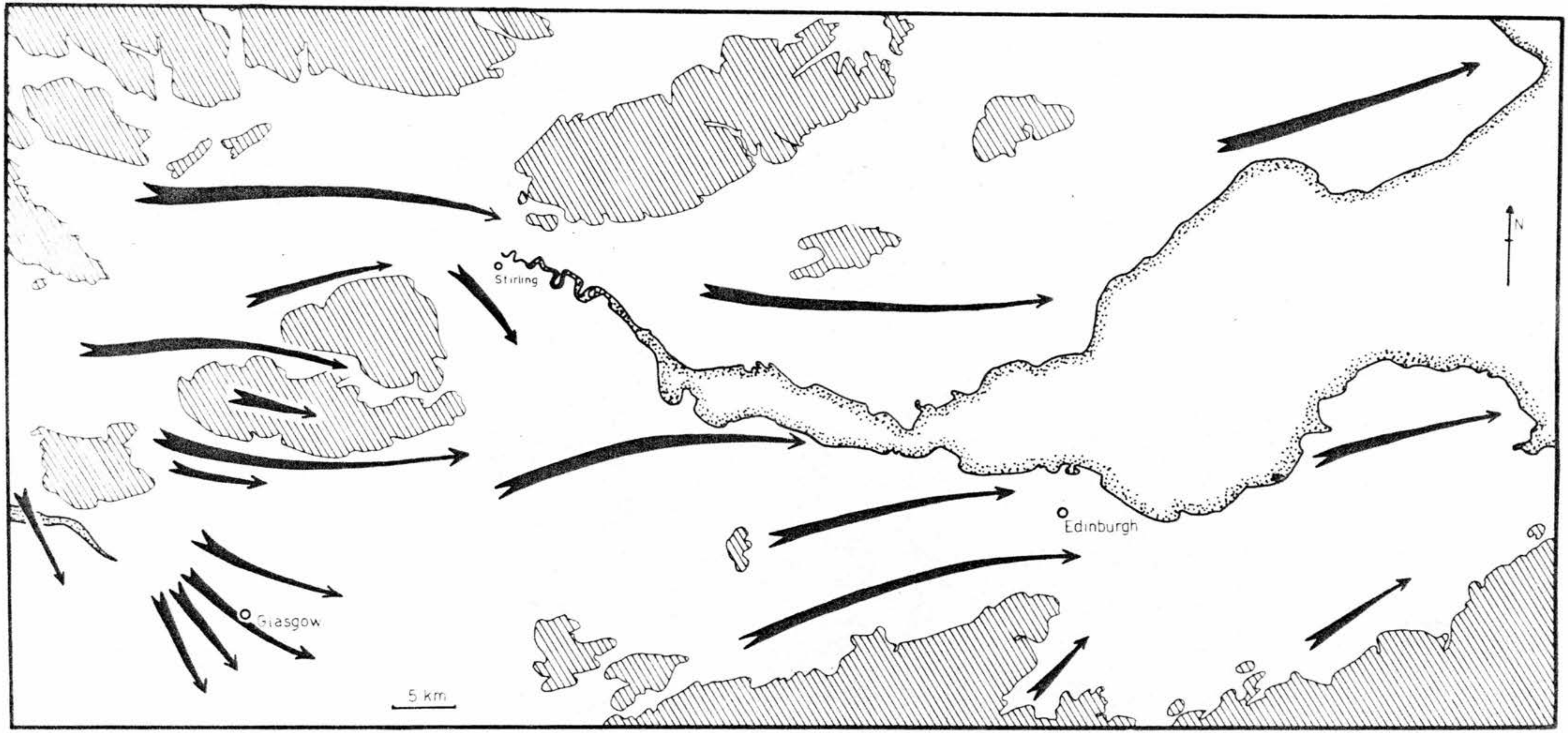


Figure 3.7

Ice movement directions in the Main Study Area after Sissons(1967) and Burke(1969a).

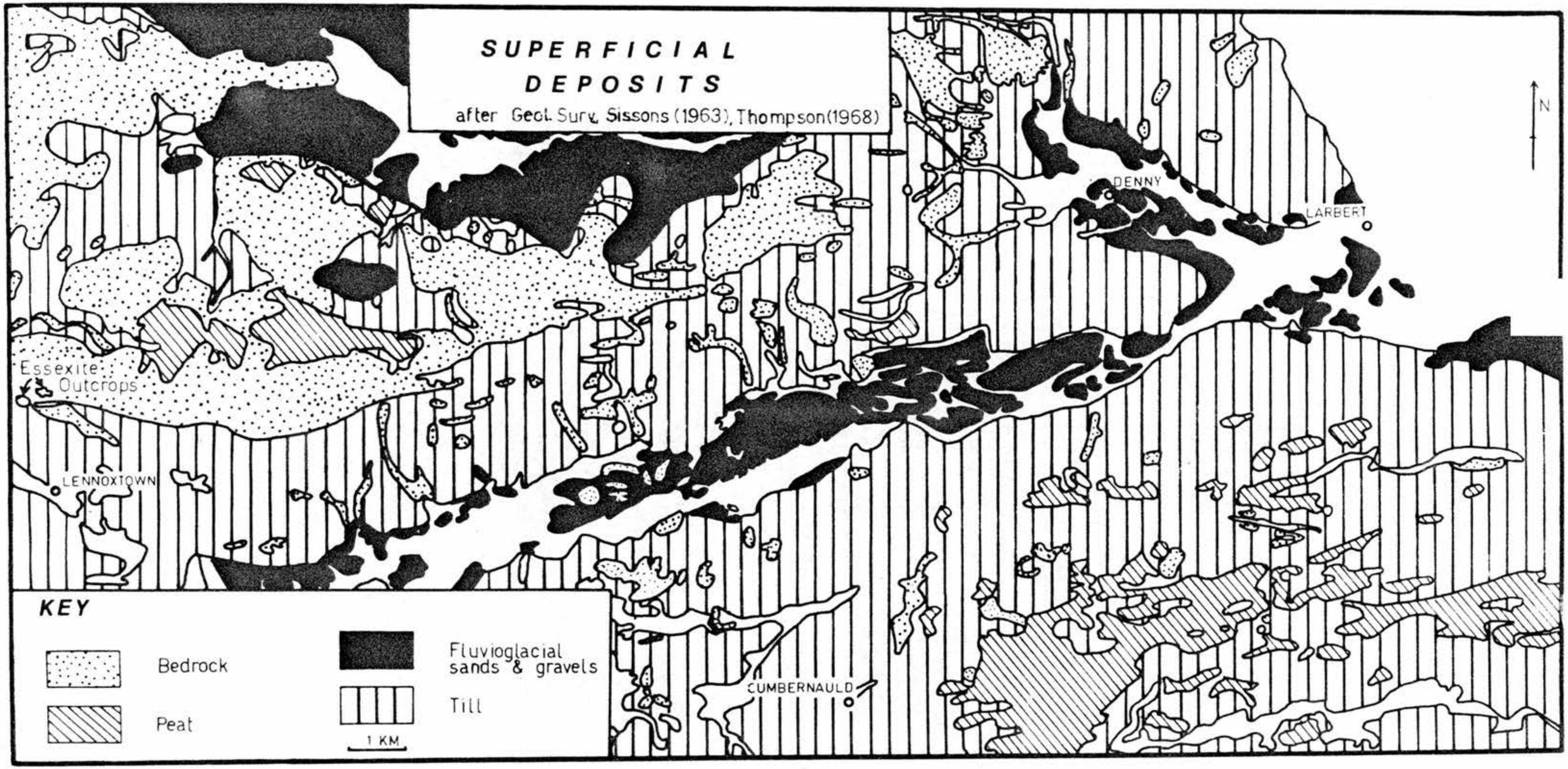


Figure 3.8

Glacial and fluvioglacial deposits in the Main Study Area.

than 100 years.

As long ago as 1814 Hall, writing "on the revolutions of the Earth's surface", noted that there was a west-east alignment of landforms in the Edinburgh district. He noticed that many of the igneous masses in the area such as Corstorphine Hill, Castle Rock, Craigleith and Calton Hill all possessed a similar form. They had steep west faces and gently sloping east faces. Hall called this type of landform a "craig-and-tail", and the term remains in use today. He also noted that the rocks were often scratched, and he measured the direction of the striae at a number of points around Corstorphine Hill. Using the evidence of the striae and the craig-and-tail landforms he concluded that a great flood had come from a direction ten degrees south of west.

Imrie(1814) found signs of moulding and scratching of the rocks in the Campsie Fells. He observed that the general alignment of these features suggested an origin to the west, and that large blocks of rock, themselves scratched, were sometimes scattered over the surface of the ground. He also noted the far-travelled nature of rock fragments in the till and correctly suggested a source. "Among the water worn stones imbedded in the clay, I seldom found specimens of the native rocks of the district; those which I examined, consisted mostly of rocks generally deemed of the oldest formations such as quartz, porphyries, granites etc.; the native beds of which, are far distant to the north and west of that part of the country" (Imrie,1814,p.35). Like Hall he assigned these phenomena to a torrent or debâcle.

Following Agassiz' visit to Scotland in 1840 many remained unconvinced but the increased vigour of the converted led to many more observations of glacial phenomena being made. Striations were noted by a number of workers e.g. Buckland(1840), Milne(1840), Maclaren(1849), Chambers(1853,1857) as well as instances of ice moulding by Chambers(1853).

By the time Geikie(1863) wrote his paper "on the phenomena of the glacial drift of Scotland" the west-east movement by some agency in the Forth Valley had become a well established fact. "No one can have passed through the district from south to north without observing that the region is deeply furrowed in an east and west direction. Long smooth-backed ridges follow each other in endless succession, and on these we can trace every gradation of eminence, until we reach the true typical form of crag-and-tail" (Geikie,1863,p.32). Geikie also noted that the colour of the till was largely a reflection of the underlying rocks. Where red till overlay coal measures in the Stirling district it suggested that this till contained material from the Old Red Sandstone cropping out to the west. Rock fragments in the till also indicated this west-east movement. "In the boulder clay of Stirling and Linlithgow, fragments of clay-slate and mica-schist may here and there be seen. These rocks may have come from the district of the Trossachs" (Geikie,1863,p.43).

Reference was also made to other glacial evidence.

Miller(1850) noticed that not only were striations on boulders preferentially aligned along the long axes of the latter, but also that the boulders themselves were pointing in the same west-east direction as the striae on the neighbouring bedrock. Miller jnr.(1884) found pavements of boulders at Portobello, near Edinburgh, grooved in an east-north-east direction.

Because of the varied nature of the geology of the Central Lowlands, erratics proved to be extremely powerful indicators of the direction of ice movement, since many could be assigned to a particular source area. One erratic had an entire paper devoted to it (Forbes,1829). Numerous examples of transported boulders were reported by the Scottish Boulder Committee. For example, a boulder of conglomerate from Callander was found at Leith Walk in Edinburgh. In the Stirling district the boulder clay was found to contain boulders of Old Red Sandstone, conglomerate, schistose grit and other rocks from the Highland border (Dinham,1927). In Leith Docks were found boulders of marcasite that had originated in thin strata of coal in the Kilsyth area (Young,1868).

Even after Geikie's paper icebergs were still cited as the agency responsible, but none disputed the general west-east movement of a powerful force. From this time until the end of the nineteenth century the movements of individual ice streams were revealed as more detailed work was carried out. Bell(1874) noted that the glaciation of the Forth and Clyde valley was from west to east, but also considered the possibility of ice streams forming as the ice sheets began to waste. He recognised two main streams in an area north of Glasgow; one to the south of the Kilpatrick Hills and another that moved "along the Strathblane valley, gradually spreading out over the neighbouring ground" (Bell,1874,p.305).

Present day detailed knowledge of ice movements in both Study Areas stems from the work of the Geological Survey who surveyed the region in the early years of the present century. Considering first the Main Study Area, it is accepted that ice fanned out in an east to south-east direction in the Glasgow area (Bell,1871; Clough et al.,1911; Elder,1935; Jardine,1973; Price,1975). This has been inferred largely from the evidence of drumlins which extend eastwards from Glasgow, where the trend of the long axes runs in an easterly direction to Kilsyth and Falkirk, where it becomes east--north-east (Sissons,1964). This was noted by the workers of the Geological Survey some 70 years ago (Crampton & Hinxman,1906; Peach et al.,1905; Clough et al.,1906). They also mapped the striae which matched the direction shown by the drumlin long axes.

Striae over the Campsies themselves indicate a general direction of ice movement from the west and north-west (Fig.3.7). Confirmation of this movement is given by the many instances of Highland erratics found in this area, and on a smaller scale by the discovery of a fragment of trachyte on the Campsies north of Kilsyth that had originated from Meikle Bin to the west (Thompson,1968) (Fig.3.6). An ice stream moved eastwards along the Carron-Endrick valley and another flowed round to the north of the Gargunnock and Touch Hills. The general movement of ice across the Campsies from the north-west is also indicated by the eastern alignment of meltwater features on the Campsie Fells.(Sissons,1963). Since their direction is mainly governed by the ice slope, it follows that the ice flowed in this direction. In the region of Stirling the ice fanned out, moving south-east towards Falkirk and east across Fife (Francis <u>et al</u>., 1970). The former movement near the eastern part of the Main Study Area is shown by the long axes of drumlins and striae in the Plean-Larbert area pointing south-east (Fig.3.2; Hinxman <u>et al</u>.,1907; Dinham,1927; Milne,1963; Sissons,1964; Sissons & Smith,1965).

Ice moved along the southern face of the Campsies as shown by striae, ice-moulded features along the Kelvin-Bonny Water valley and the train of essexite boulders mapped by Peach (1909). This was a continuation of a large ice stream from Glasgow and Strathblane. This mass of ice moved in an east-north-east direction, and met ice moving south-east from Stirling in the Denny area. (Milne-Home,1871; Hinxman <u>et al</u>.,1907; Fig.3.7).

East of Grangemouth in the Secondary Study Area these two streams of ice merged to flow almost due east. A number of new methods and additional mapping of traditional indicators of ice movement (i.e. striae and erratics) have broadly substantiated the views of nineteenth century workers. Cadell(1913) found a due west-east alignment of striae in the Bo'ness area that paralleled ice-moulded landforms in the vicinity. Farther east along the Forth Valley there appears to be an increasing northerly component in the direction of ice movement as shown by striae and the orientation of the long axes of ice-moulded landforms (Fig.3.7).

Burke(1969a) carried out a quantitative analysis of the relief orientation of the Forth Valley. By measuring contour directions in a unit area and deriving a mean direction for each area by vector analysis, he produced a map of relief orientation for the Forth Valley (Fig.3.9). This shows a remarkable correspondence with the evidence of erratics and striae in the area, suggesting that the moulding has been largely the work of ice. Fig.3.9 clearly shows the confluence of two ice streams near Falkirk which then moved eastwards towards Edinburgh. A mean direction of E 10°N was obtained for all the contour directions analysed.

The west-east corrugation of the landscape by ice appears to have diverted the trend of the valleys tributary to the Forth since, "instead of running due north to the sea, as one might expect, the side valleys run persistently in an easterly or north-easterly direction" (Burke,1969a,p.58). This does not appear to be a result of structural control, since the structures trend roughly north-south.

Whilst the consideration of ice movements has so far been confined to ice issuing from the Highlands, the Southern Uplands also acted as an independent source and should therefore be discussed. Evidence for the incursion

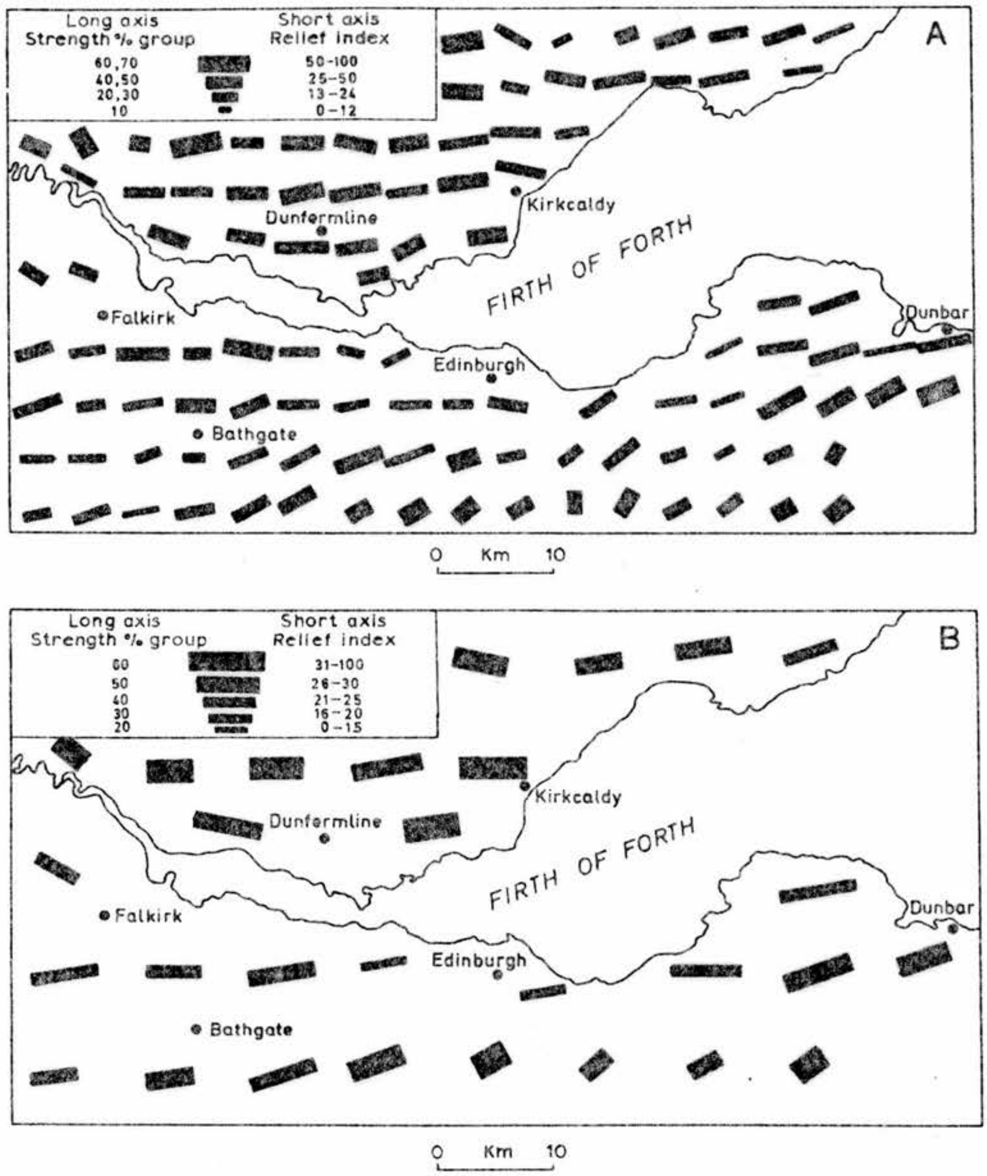


Figure 3.9

Maps of relief orientation by Burke(1969a) according to A) 25 km^2 areas and B) 100 km^2 areas.

of Southern Uplands ice into the Main Study Area has not been found, though chert from sand underlying till in the Airdrie district appears to have had an origin to the south (Clough et al.,1909). McLellan(1969) found evidence for ice from both a Highlands and Southern Uplands source in Central Lanarkshire. The confluence of Highland and Southern Uplands ice therefore appears to have taken place some way to the south of the Main Study Area, though ice from the latter source must have been instrumental in diverting the flow of Highland ice eastwards from the Glasgow area.

Similarly in the Secondary Study Area no incursion of Southern Uplands ice took place, although it no doubt influenced the direction of Highland ice. "Southern Uplands ice would have been able to restrict Highland ice to low ground, even though it was deflected eastwards by the more massive Highland outflow when both were at their maximum" (Kirby,1966,p.29). The influence of Southern Uplands ice is best seen in the anticlockwise diversion of ice movment in the Forth Valley east of Edinburgh as shown by the striae and ice-moulded landforms (Kirby,1969; Fig.3.7).

CHAPTER 4

DISPERSION OF ERRATIC FRAGMENTS IN TILL

> "Field measurements in geology are usually approximate and depend in large part on the accidental exposures that one finds" (Krumbein,1937,p.578).

Two approaches have become established for quantitatively determining the proportion of a rock type in any till. They are stone counting and estimation of the percentage weight of the rock type. By repeated sampling at a number of sites a distribution pattern can be built up of the dispersion of rock fragments in a specific till.

Stone counting is the quicker of the two methods, although it is more often used for deriving the relative proportions of different rock types than the proportion of one particular lithology. Stone counting has been extensively employed in till studies for many years (e.g. Craig,1874; Krumbein,1933; Holmes,1952; Järnefors,1952; Anderson,1955,1957; Dreimanis & Terasmae,1958; Beaumont, 1971; Szabo _et al._,1975). It requires the collection of many samples of stones from till. Where possible the lithology of each stone is identified, and the percentage of each rock type or group of rock types is calculated.

Although this method has the advantage of being relatively rapid compared to other techniques used in the analysis of till, it also has a number of drawbacks. Firstly, there is no agreement as to the number of stones that constitutes a representative sample. For example, Arneman and Wright(1959) considered 100 stones sufficient while Holmes(1952) counted up to 800 stones at a single site. Similarly the size of material used in stone counting varies from researcher to researcher. Size has been selected on the basis of convenience (e.g. Holmes,1952) and in relation to the variety of rock types present in a single size grade (e.g. Anderson,1957), but sometimes it appears to have been ignored altogether (e.g. Kirby,1968). The selection of any particular size grade is almost bound to exclude or misrepresent the proportion of one or a number of rock types within a till. This is due to the fact that for any rock type in a till there will tend to be one or more preferential size grades into which the fragments will fall (Dreimanis & Vagners,1965,1969,1971; Krüger,1974). For each rock type the preferential size grade pattern will differ and the selection of any one size grade for stone counting will never produce a truly representative sample. Finally the percentage count of a rock type with a relatively distant origin, might locally appear to fluctuate considerably. Yet in many cases it is not the amount of distant but the amount of local rock material that is fluctuating, according to the proximity of the source outcrop and its propensity to produce rock fragments of the size grade that is counted.

In an attempt to overcome the last two problems, some workers have identified and counted fragments in a number of size grades (e.g. Järnefors,1952; Gillberg, 1965,1967,1968a,1968b; Willman,Glass & Frye,1966; Beaumont,1971). Not only is this method more time consuming than counting stones in only one size grade, but also the problem remains of the fluctuation in amounts of stones of distant origin according to the proximity of a local, prolific source of till stones.

A second approach to the quantitative determination of a rock type in till has been developed in an attempt to avoid the problem associated with stone counting. A number of variations have been tried, but they are all similar in that some measure of the absolute quantity of erratic material has been derived. In Scandinavia absolute methods per unit volume and per unit weight have been used since the last century (Lundqvist, 1935). In recent years in North America a number of investigations have been made involving the percentage weight content of a particular rock type in a till (e.g. Dreimanis & Vagners,1965,1969,1971; Harrison,1960; Gravenor,1957; Horberg & Potter,1955). This approach avoids the problems associated with stone counting, except for the size of sample from which to calculate the amount of erratic material and the fluctuation in the amount of material with a distant origin due to large influxes of local bedrock material. The effect of these influxes, however, is greatly reduced using percentage weight methods since the whole particle size range is under consideration and a large influx of local material will tend to predominate in only one particle size.

There are two major drawbacks to the percentage weight method. Firstly, the method is restricted to rock types where the whole size range of material can be extracted from the till. This constraint usually confines the analysis to rock types such as limestone that can be chemically separated from the finer fraction. Secondly, any absolute method, whether by weight or by volume of till, is extremely time consuming and often involved (Lundqvist,1935).

Rather than confront the problems associated with stone counting it was decided that the percentage weights of erratic material within various size grades would be calculated.

The pilot study

An opportunity to test the viability of this method presented itself early in the first year of study when a trench running in a south-west to north-east direction close to a distinctive rock outcrop was excavated near Edinburgh. A pilot study in a research programme such as this one is unusual due to the constraints of time. However its usefulness in some contexts must not be overlooked. As the pilot study involved a different rock outcrop from the main study it was hoped that the most suitable techniques would emerge prior to analysis on the Lennoxtown essexite erratics train.

The rock outcrop concerned was the Dalmahoy sill, situated about 14km south-west of Edinburgh. The rocks of the sill form a succession of intrusions of tholeiites, basalts and dolerite, and comprise " a single suite quite distinct from the quartz dolerites and teschenites of the Edinburgh district" (Campbell & Lunn,1927,p.489). The intrusions crop out c. 1km west of Balerno. They are associated with the shallow synclinal fold known as the Dalmahoy syncline and are situated between the north-eastern flank of the Pentland Hills and the Murieston Fault. The thickness of the rocks amounts to some 45m and they encompass the Ravelrig, Kaimes and Dalmahoy hills, the latter two forming a crag-and-tail feature.

The sill consists of a number of differently classified rocks that vary mainly in terms of texture so that positive identification is not difficult. Furthermore the nature of the weathered surface of the rock means that washed Dalmahoy fragments from till down to a size of 2mm can be identified by eye without the necessity of breaking each fragment to expose a fresh surface. This results from the weathering within the rock of the mineral fayalite which becomes partly replaced by chlorophaeite. A series of white flecks is formed which contrast with the reddish-brown colour of the remaining weathered surface (Campbell & Lunn,1927; Smith,1962).

A gas-pipeline trench was excavated during the winter of 1973 into the basal till and bedrock in the vicinity of Dalmahoy sill. The line of the trench, running westwards towards the outcrop was diverted to the south-west in order to avoid the main upstanding part of the outcrop at Dalmahoy Hill. It ran over the outcrop at Ravelrig Hill, where the ground surface is not as steep or rugged as on Dalmahoy Hill, before changing direction to an almost east-west alignment beyond Ravelrig Hill (Fig.4.1). The general direction of ice movement in this area is towards a point slightly north of east (Fig.3.7). Glacial striae in the vicinity of the outcrop however, suggest a more northerly component in ice movement direction (Fig.4.1). Thus the line of the trench offered an excellent opportunity to collect basal till samples for determination of the dispersion of material with distance from the Dalmahoy sill along the general direction of ice movement.

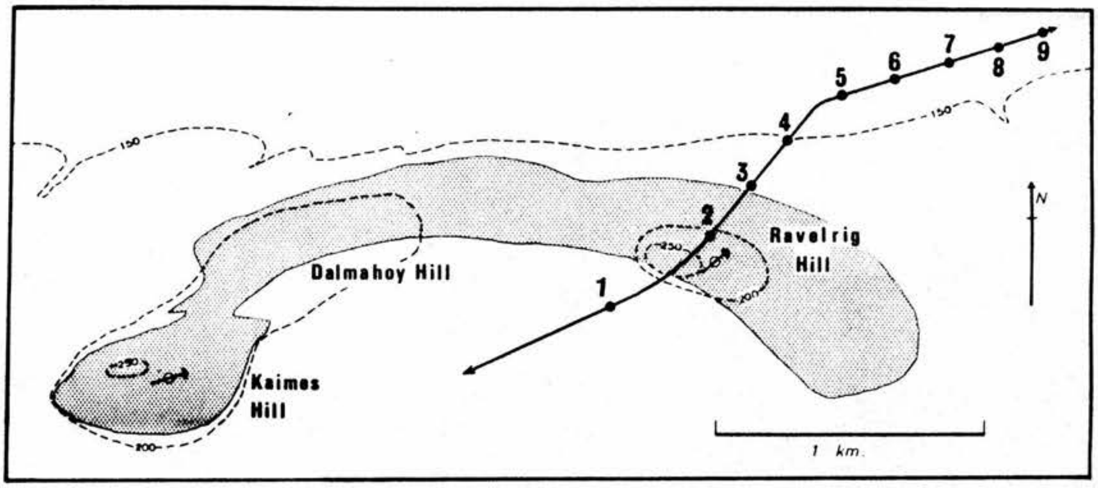
The distance over which samples could be taken eastwards of the Dalmahoy sill was limited because the eastern part of the trench had been filled in and returned to farmland before the pilot study began. Although the section of trench sampled had already been partly filled in, much of the excavated till still remained as spoil heaps alongside.

These spoil heaps were considered to be representative of the till in the section of the trench immediately adjacent to them. The infilled trench made it impossible to measure the variation in the amount of Dalmahoy material vertically in the till. Samples of about 20kg each were taken <u>c</u>. 100m apart, seven to the east of the outcrop, one on the outcrop at Ravelrig Hill and another west of Ravelrig Hill (Fig.4.1). The last was collected in order to determine whether any Dalmahoy material had been carried westwards of the outcrops.

In the laboratory the nine samples were first air-dried. As the material began to dry out, the lumps of till were broken up by hand to aid later analysis. Once dry, the till samples were placed in separate steel drums perforated with apertures of 2mm size. Each drum was placed on motor-driven rollers and allowed to rotate until the majority of the fine fraction of the till had passed through the apertures in the drum. The fine fraction was then collected. Any particle matter still adhering to till stones was washed through a 2mm aperture sieve, collected, dried and weighed with the finer material that had passed through the apertures in the drum.

The coarse fraction retained in the steel drum and on the 2mm sieve was placed on the largest aperture sieve of a nest of sieves of aperture sizes 51, 16, 8, 5 and 2mm. This nest of sieves was placed in a "Rotap" sieve shaker and allowed to vibrate for ten minutes. The material retained on each sieve was then weighed separately. Each of these graded portions was then scrutinised under a strong light and any fragments identified as Dalmahoy material were placed on one side. After processing the whole of each sample, the total amount of identified and extracted Dalmahoy erratic material over 2mm was weighed.

When the size grades of all nine samples had been examined in the same manner, the weight of the



The Position of the Sample Points

KEY

Extent of Dalmahoy sill

Course of trench

1 Sample points

--200-- Contours (metres)

Glacial striae

Figure 4.1

Dalmahoy material as a percentage of each size grade, of the entire coarse fraction in each dried till sample, was calculated.

The results of the analysis are shown in Fig.4.2. The intervals between the sample points were not equal with respect to distance from the Dalmahoy sill, and the trench followed a sinuous path in this area. In order to obtain a more representative assessment of dispersion of Dalmahoy fragments with distance from the outcrop in the direction of ice movement, a base line was drawn adjacent to the nine sample points aligned in the assumed mean direction of ice movement. The sample points, which are shown in Fig.4.2, were projected by perpendiculars on to this line.

Fig.4.2 indicates that the percentage weight of the fragments identified as Dalmahoy sill material tends to decrease with distance from the outcrop. In Figs 4.2A and 4.2B the upper line linked by open circles represents the percentage weight of Dalmahoy material within the coarse fraction of the till samples between 2mm and 16mm, and 2mm and 51mm respectively. The upper line in Fig.4.2C shows the weight of all the Dalmahoy material at each sample point as a percentage of the whole till coarse fraction above 2mm. The lower lines in Figs 4.2A, B and C show the same weights of Dalmahoy material expressed as percentages of the entire dried till samples below 16mm, 51mm and for the whole till sample respectively.

The graphs indicate that the Dalmahoy percentage in the coarse fraction of the till sample provides the more sensitive reflection of the fall in the amount of Dalmahoy material with distance from the outcrop. Had it been possible to identify fragments of Dalmahoy material below 2mm in size, then the lower line might have been of greater analytical value.

The upper lines in Figs 4.2A, B and C show considerable variation. Fig. 4.2A indicates the most consistent trend in the dilution of Dalmahoy material with distance from the outcrop, despite a slight deviation at sample point 8. With increasing size of material in Figs 4.2B and C however, the trend, though still reflecting a characteristic decrease, does show greater variability from one sample to another. This raises the question of determining the necessary size of a till sample to be sure of including a representative amount of material up to a particular size. Earlier it was stated that the nine samples were of the order of 20kg when moist. The weights of the samples when air dry ranged from 16.3kg to 23.0kg. With reference to the recommendations of the British Standards (1377) represented by a graph in Fig. 4.3, it can be seen that using the sieve sizes of the present study, the maximum size of material giving a representative amount in the sample is 16mm. Figs 4.2B and C include material above this size limit, and this very probably explains the greater variability in the trend of the percentage weights of Dalmahoy material. These graphs illustrate the effect of including fragments of rock

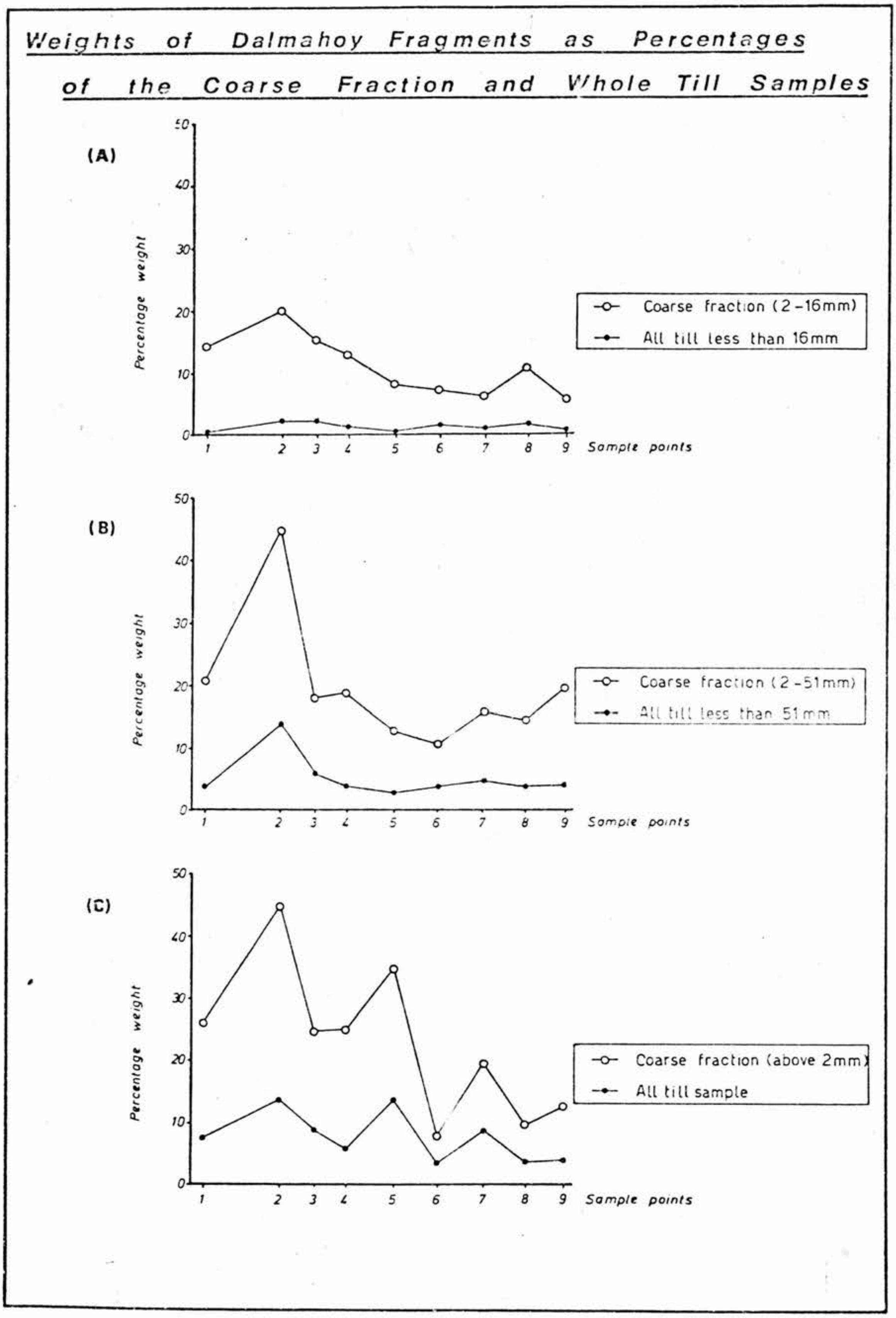

Weights of Dalmahoy Fragments as Percentages of the Coarse Fraction and Whole Till Samples
(A)
Percentage weight
0
10
20
30
40
50
1 2 3 4 5 6 7 8 9 Sample points
Coarse fraction (2-16mm)
All till less than 16mm
(B)
Percentage weight
0
10
20
30
40
50
1 2 3 4 5 6 7 8 9 Sample points
Coarse fraction (2-51mm)
All till less than 51mm
(C)
Percentage weight
0
10
20
30
40
50
1 2 3 4 5 6 7 8 9 Sample points
Coarse fraction (above 2mm)
All till sample

Figure 4.2

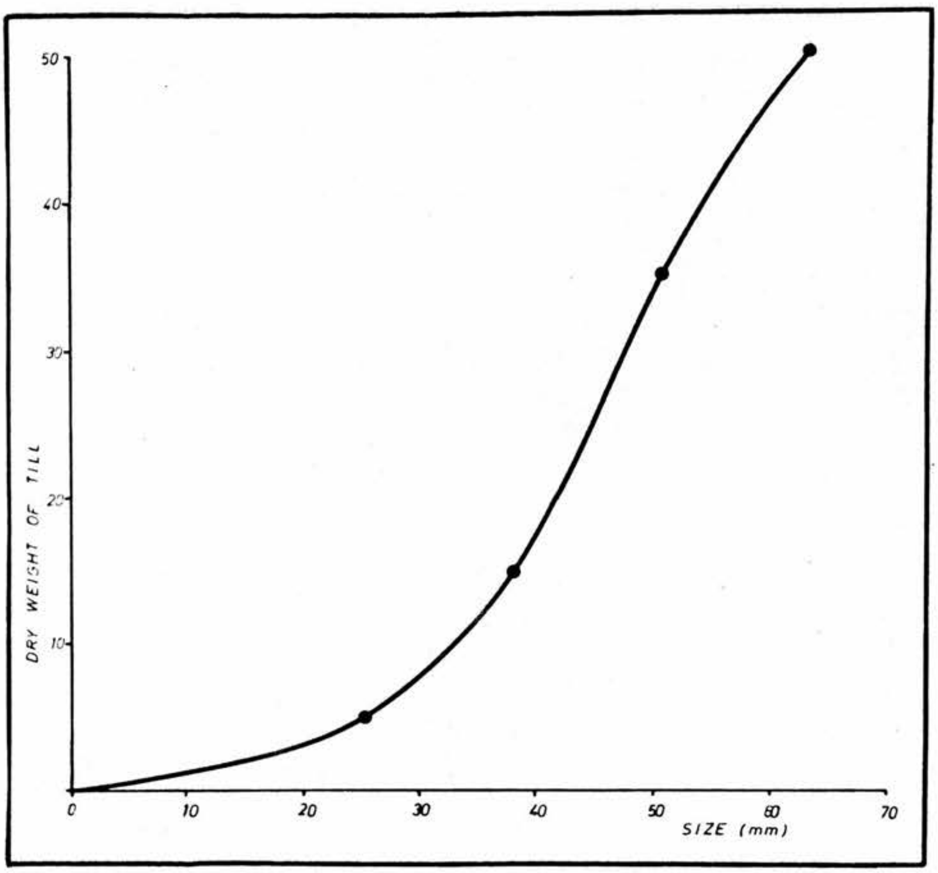


Figure 4.3

Graph showing the relationship between dry weight of till and the maximum size of particles present in representative proportions according to B.S. 1377.

in the analysis that are outside the size limits of a representative sample of material. The presence or absence of a single, large fragment of Dalmahoy material dramatically affects the resulting percentage weight of that material.

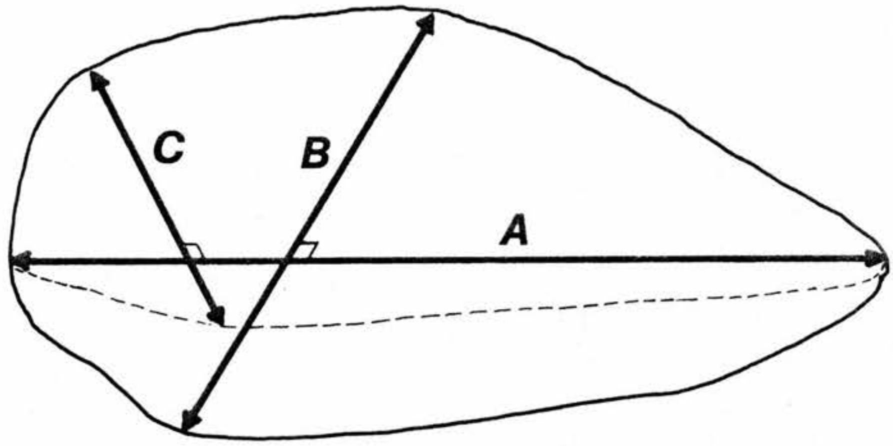
Many studies of the dispersion of rock fragments in till have show that the sphericity, shape and roundness of the fragments undergo a change with distance from the bedrock outcrop (see chapter 2). In order to discover whether these indices and degree of weathering change in fragments of Dalmahoy sill material with distance from the outcrop, all Dalmahoy fragments retained on the 8mm and 16mm aperture sieves for each sample were subjected to a number of measurements. These two size grades yielded 845 Dalmahoy fragments in all, providing sample sizes ranging from 49 for sample 9 to 166 for sample 2. For each fragment indices of sphericity, shape,roundness and weathering were derived.

Sphericity

To calculate this parameter the long, intermediate and short axes of each fragment are measured. These axes were first defined by Krumbein (1941a) using the notations a, b and c respectively for them. In order to measure these three, the maximum projection plane of the pebble must be found. If the pebble is placed on a flat surface, then it will normally rest with this plane exposed. The b-axis is defined as the shortest axis across the maximum projection plane with the a-axis normal to it. If the pebble is turned until the minimum projection plane is revealed then this defines the c-axis (Fig.4.4). The angular definition of the a-axis of a rhombohedral-shaped pebble can lead to confusion (Fig.4.5). If one looks for the "longest" axis then a_1 should be measured. In the present study however, the alternative interpretation has been adopted, and a_2 and b_2 define the a and b axes respectively (Andrews,1971). It will be noticed from Fig. 4.4, which shows the three axes for one pebble, that although all they are mutually orthogonal they need not necessarily intersect at any one point (Krumbein,1941a).

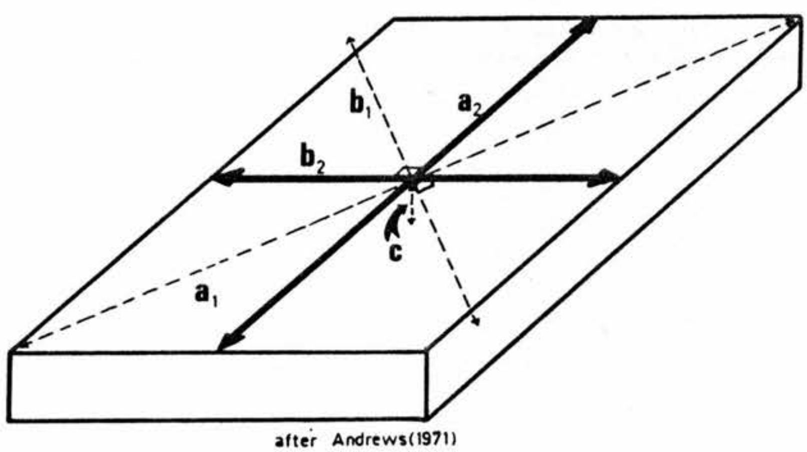
The axes were measured by placing each pebble of Dalmahoy material on a piece of centimetre graph paper. Two ratios were then determined. The first is the ratio of the intermediate to the long axis (b/a), and the second is the ratio of the short to the intermediate axis (c/b). Using a chart similar to that shown in Fig. 4.6 the point of intersection of these two values was determined. The value for sphericity can then be read off by estimating the value of the point of intersection according to the set of mathematically derived curves. The resulting sphericity value can be determined accurately to the nearest two-hundredths unit (Krumbein, 1941a). Even greater accuracy can be achieved for sphericity using the formula

$$\text{intercept sphericity } (\Psi) = \sqrt[3]{\frac{bc}{a^2}}$$



Measurements required to obtain pebble shape and sphericity

Figure 4.4



Definition of axes on rhombohedral-shaped pebbles

Figure 4.5

For the present study the graphical method for determining sphericity was considered sufficiently accurate,as the extra precision obtained using the formula did not warrant the greater time involved.

Fig.4.8B shows the mean sphericity of the Dalmahoy fragments for each sample. Little change in sphericity occurs with distance from the outcrop. The only deviation from an almost horizontal line is for sample 3,where there is a fall in the mean sphericity compared to the remaining samples. Sample 3 was collected just east of the Ravelrig Hill part of the Dalmahoy outcrop, and contained a significant number of fresh, angular, asymmetrical fragments of Dalmahoy material. Although sample 2 was taken from till resting on the Dalmahoy sill it did not show a similar decline in the mean sphericity, but recorded a value comparable to the remaining seven samples. The fact that no apparent change in sphericity is shown in Dalmahoy fragments from the outcrop to sample 9 cannot be regarded as unusual. Other work that has indicated a change in the sphericity of rock fragments with distance from their outcrop has considered distances of tens of kilometres rather than hundreds of metres (e.g. Dreimanis,1956; Holmes,1960; Drake,1972).

<u>Shape</u>

Zingg(1935) developed a classification of pebble shapes based on the same b/a and c/b ratios that Krumbein (1941a) used for calculating sphericity. A chart similar to that used for deriving sphericity is shown in Fig.4,7. The two ratios are joined at the 2/3 value by perpendicular lines that divide the chart into four shape classes referred to as spheres, discs, blades and rods. In a similar manner to that used for determining sphericity, the intersection of the two ratios b/a and c/b for each pebble is located on the chart. The position of this point in one of the four divisions indicates the shape class of the pebble. The names given to the four shape classes are only intended to indicate the general form to which the pebble approximates. For example, pebbles classed as spheres on the Zingg chart need not necessarily be spherical. These four classes can also be expressed in tabular form (Table 4.1). This is the preferred method of deriving the shape class of a pebble if no graphical plot of the results is required.

Table 4.1 Zingg classification of particle shape

b/a	c/b	shape
$>2/3$	$<2/3$	discs
$>2/3$	$>2/3$	spheres
$<2/3$	$<2/3$	blades
$<2/3$	$>2/3$	rods

The percentages of Dalmahoy fragments classified as spheres, discs, blades and rods are shown in Fig.4.8A. In all the histograms the percentages of discs and spheres are high while blades and rods tend to record low percent-

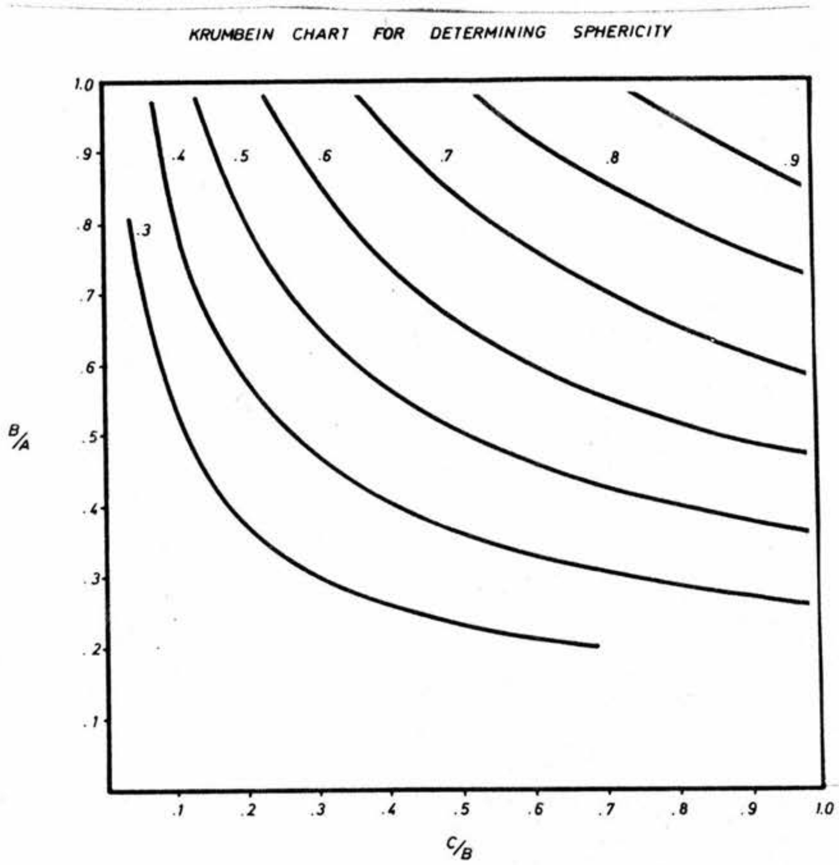


Figure 4.6

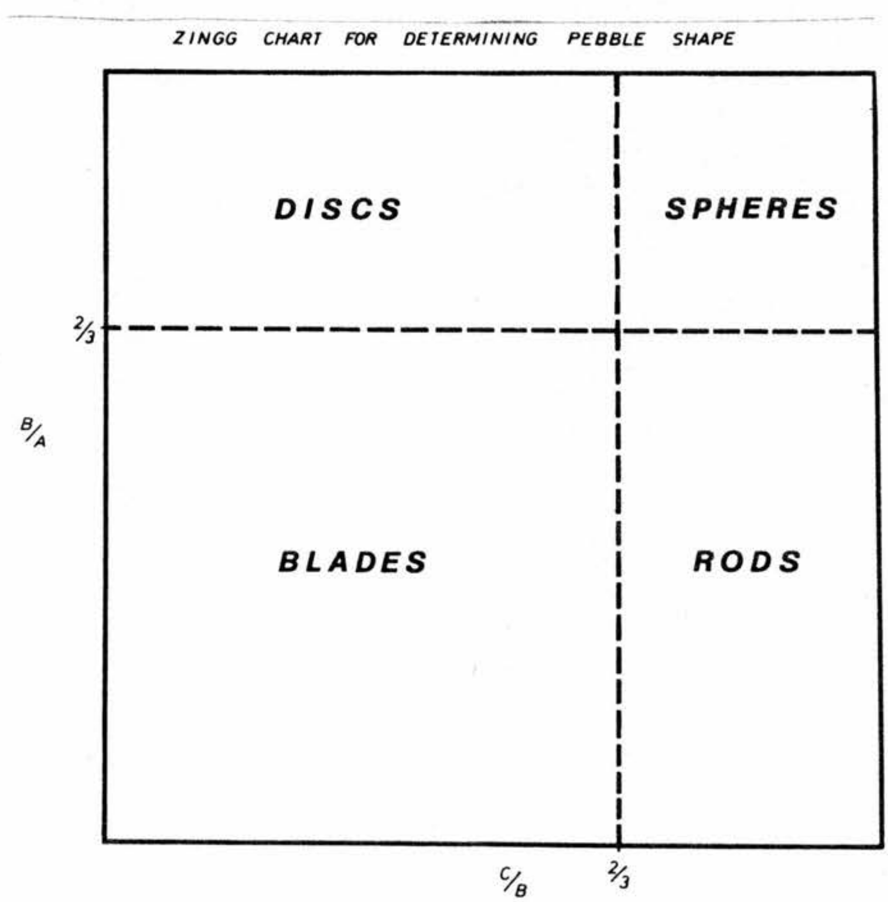
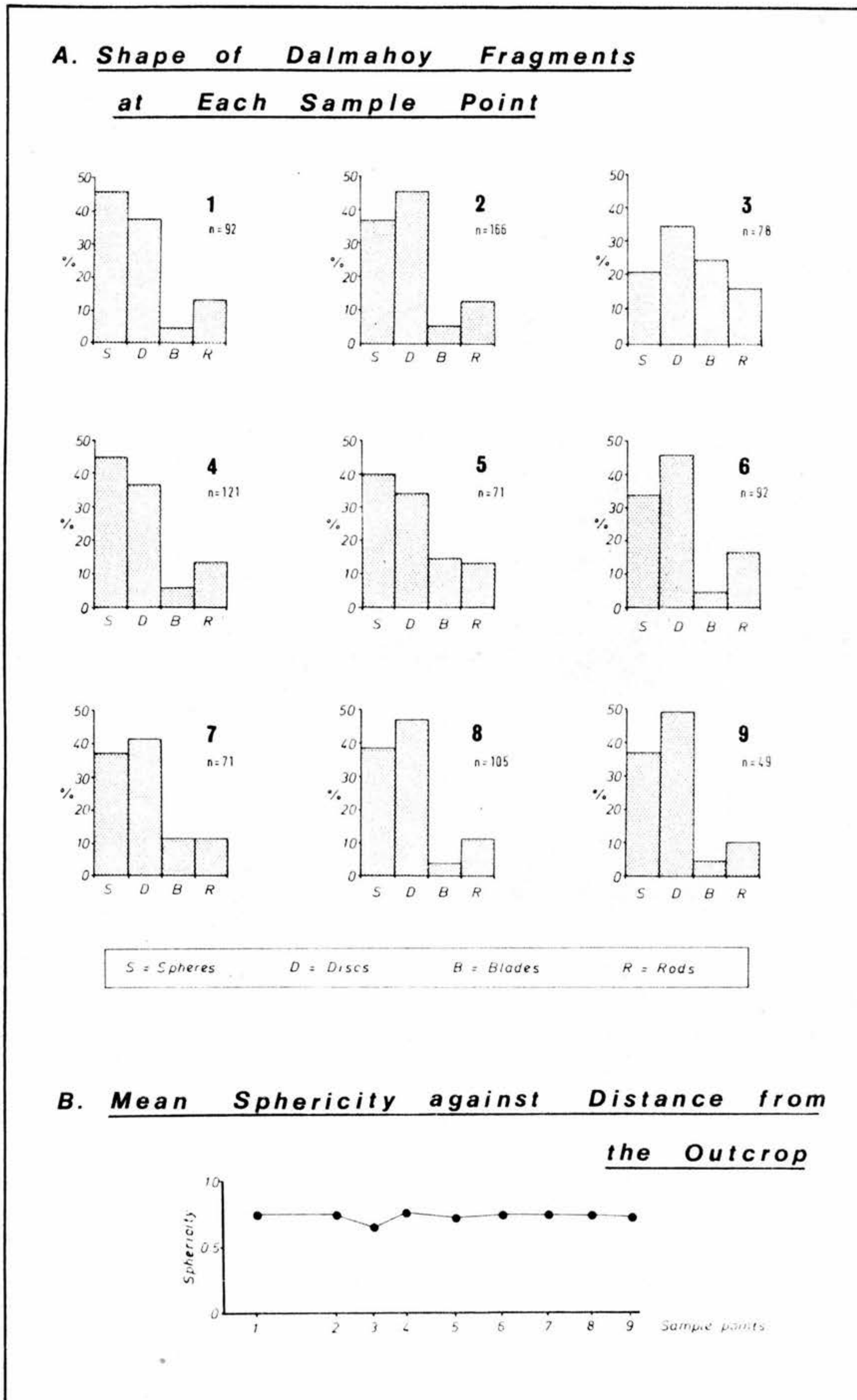


Figure 4.7



A. Shape of Dalmahoy Fragments at Each Sample Point
1
n = 92
2
n = 166
3
n = 78
4
n = 121
5
n = 71
6
n = 92
7
n = 71
8
n = 105
9
n = 49
%
S D B R
S = Spheres
D = Discs
B = Blades
R = Rods
B. Mean Sphericity against Distance from the Outcrop
Sphericity
Sample points

Figure 4.8

ages. Drake(1972) considered changes in till-particle morphology with distance from the source outcrop. He found that blades and rods of various rock types were reduced in numbers with distance from their outcrops compared to spheres and discs. He suggested that crushing and abrasion in a subglacial environment were dominant factors controlling the shape of pebbles. Spheres were least susceptible to crushing and were actually produced by abrasion. They therefore have the most durable shapes. On the other hand blades and rods were most susceptible to crushing owing to their elongate shape. Discs, though not as durable as spheres, were less susceptible to crushing than blades and rods and could actually be produced by the breaking up of these two.

Fig.4.9 shows the combined percentage of blades and rods for each sample point. From sample 3 to 9 there is a tendency for this percentage to fall with distance away from the outcrop. Once again sample 3 stands out from the other samples and shows a higher percentage of blades and rods. This reflects the fresh, unweathered appearance of the Dalmahoy fragments in this sample.

Samples 1 and 2 show low values for the combined percentage of blades and rods, suggesting a greater similarity to the samples some way to the east of the outcrop rather than to sample 3, which is the nearest.

Roundness

The third parameter was measured on the 845

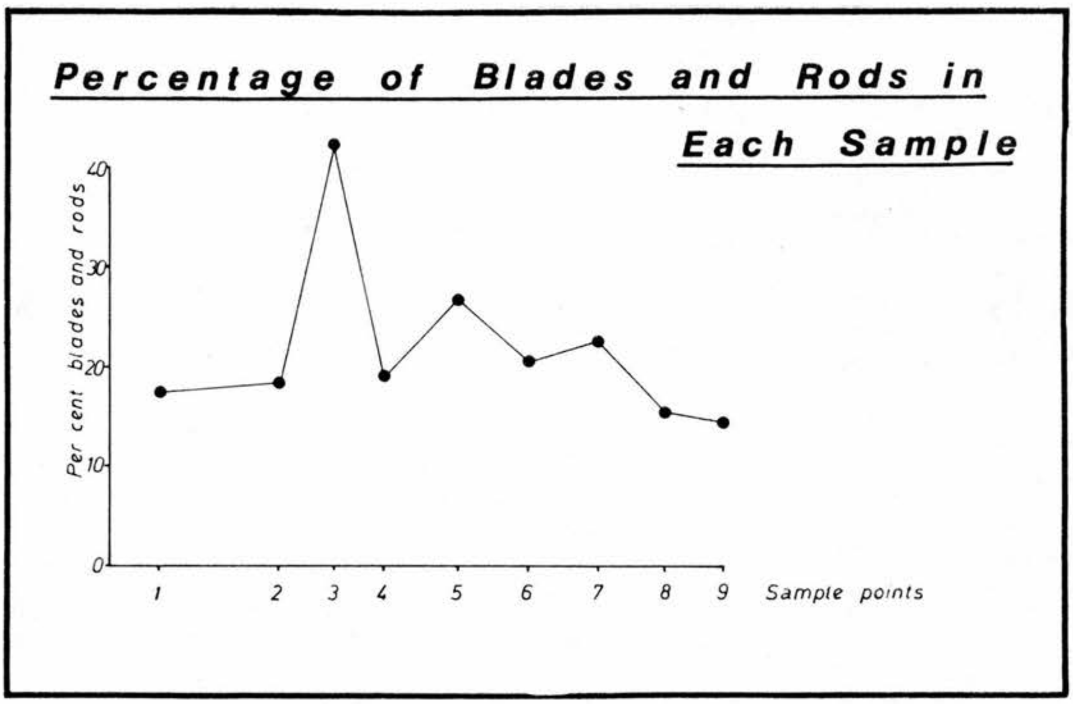
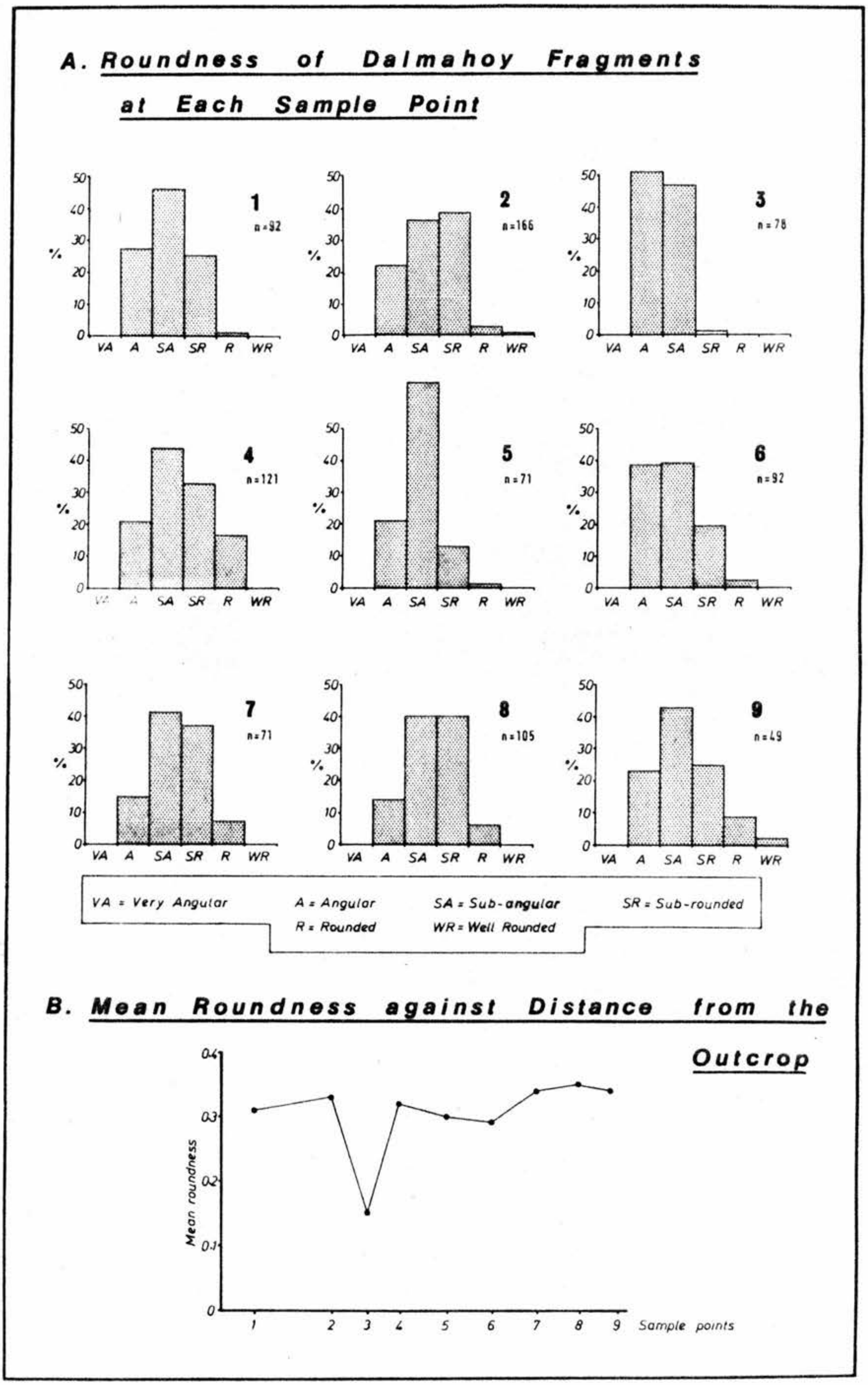

Percentage of Blades and Rods in Each Sample
Per cent blades and rods
0
10
20
30
40
1
2
3
4
5
6
7
8
9
Sample points

Figure 4.9

fragments using a visual chart developed by Powers(1953). Each fragment was compared with a set of photographs of clay models representing varying degrees of roundness, and then allotted to one of six numerically defined classes. The six classes are defined descriptively as very angular, angular, sub-angular, sub-rounded, rounded and well rounded. The histograms of the percentages for each class in all the samples are shown in Fig.4.10A. None of the pebbles has been classified as very angular and only one pebble from sample 9 has been assigned to the well rounded class. The most distinctive histogram is that of sample 3 where all but one of the Dalmahoy fragments considered have been designated as angular or sub-angular. This suggests that the fragments in this sample have been little affected by abrasion and therefore represent freshly-quarried material. Fig.4.10B shows mean roundness for each sample. Sample 3 stands out as recording a lower mean roundness than the remaining samples. From sample 3 to 9 there does appear to be a tendency for the roundness of the Dalmahoy fragments to increase. Drake(1972) found that pebble roundness increased from a low value near the source to a medium value after a short distance. Beyond this, roundness tended to remain approximately the same up to 30km away. He considered that this reflected the fact that the "pebbles go through many cycles of change each mile or so" (Drake,1972,p.2160) as a result of crushing and abrasion in the subglacial environment. The increase in the roundness of Dalmahoy fragments with distance from the outcrop could well reflect the initial



A. Roundness of Dalmahoy Fragments at Each Sample Point
1
n=92
2
n=166
3
n=78
4
n=121
5
n=71
6
n=92
7
n=71
8
n=105
9
n=49
%
VA A SA SR R WR
VA = Very Angular
A = Angular
SA = Sub-angular
SR = Sub-rounded
R = Rounded
WR = Well Rounded
B. Mean Roundness against Distance from the Outcrop
Mean roundness
Sample points

Figure 4.10

stage of rapid rounding of freshly entrained bedrock fragments. Samples 1 and 2 show more similarities to the results of samples 4, 5 and 6 than sample 3 which is the nearest to them.

Weathering index

This index allows comparisons to be made of the extent of weathering in the 845 Dalmahoy fragments. Three subjective classes were chosen; "fresh", "weathered" and "rotten". A similar scale has been used by Drake(1971) in considering "weatherability" of till clasts but he referred to his three classes as "hard", "soft" and "rotten". Drake found that for 29 lithologies the pebbles classified as rotten and soft tended to die out with increasing distance from their source. He suggested that this was a result of such pebbles being less able to withstand the crushing and abrasion in the subglacial environment than the pebbles that had been classed as hard.

In the present study a fragment was classed as fresh if the external surface showed little or no weathering. Because the weathered surface of the Dalmahoy material is so distinctive compared to a freshly broken surface, this class was easy to distinguish. A pebble was weathered if it possessed the familiar appearance of the weathered rock i.e. white flecks superimposed on a reddish-brown background. Finally the term rotten was applied to any pebble that could be crushed between the finger and thumb or with a light tap from a hammer.

Table 4.2 Percentages of Dalmahoy fragments classified as fresh, weathered or rotten

weathering index	1	2	3	4	5	6	7	8	9
fresh	-	8.4	35.6	-	-	20.6	-	-	-
weathered	92.4	83.2	64.4	91.7	94.4	75.0	93.1	86.0	83.0
rotten	7.6	8.4	-	8.3	5.6	4.4	6.9	14.0	17.0

The results of the analysis are given in Table 4.2. Only two samples include pebbles in all three classes. These are samples 2 and 6. The pebbles analysed in sample 3 are classed as fresh and weathered only, whilst the remaining samples record pebbles in only the weathered and rotten classes.

Once more sample 3 stands out from the remaining samples by having the highest percentage of fresh fragments (35.6%) and no fragments classed as rotten. With all the indices this sample has constantly shown significantly different results from the other samples. It would seem therefore that the Dalmahoy fragments in this sample represent either freshly entrained material quarried by glacial action from the bedrock or, more likely, material removed during excavation of the pipeline trench.

Summary

The main object of carrying out this pilot study was to test the techniques involved in analysing the dispersion of bedrock material in till. As sampling of the till was possible over only a short distance in the direction of ice movement, the data were not expected to reveal results of major importance to the understanding of subglacial processes. Nevertheless the analysis did indicate many features that are characteristic of the dispersion of rock fragments in till and the effect of glacial processes on these fragments. There are two main conclusions.

(1) Fragments of material identified as originating from the Dalmahoy sill become less frequent in till in the direction of ice movement with increasing distance from the outcrop. This has been shown to be quite marked even over the short distance of c. 1.5km between the outcrop and the most distant sample.

(2) The mean values of sphericity and roundness show no particular trend towards increasing with distance from the outcrop. Shape indices, however, reflect the processes of crushing and abrasion on the Dalmahoy fragments in the subglacial environment. The blade- and rod-shaped fragments decrease in frequency with increasing distance from the outcrop.

The dispersion of essexite fragments in till

Having demonstrated the dilution of till particles with distance from the Dalmahoy outcrop by means of a variant of the percentage weight method, attention was given to the problem of carrying out a similar but more extensive study of the dispersion of essexite material in till. In the light of the experience gained from the pilot study, a number of techniques had to be modified and others rejected entirely.

For analysing the dispersion of essexite erratics the arbitrary imperial sieve sizes of the pilot study were discarded in favour of a set of standard metric sieve sizes. The aperture sizes of the sieves were 2, 4, 8 and 16mm. The geometric increase of the sieve sizes is based on a particle size scale introduced by Wentworth(1922b).

The size of sample collected at each site in the pilot study was considered too large for easy handling in the field and laboratory. There was a restriction on the number of samples that could be taken in the field each day due to their cumulative weight, and many of the processes undertaken during laboratory analysis had to be performed twice or even three times for each sample. Since a sample of till weighing 3kg would provide a representative amount of material up to 16mm in size according to the British Standards recommendation (Fig.4.3), it was decided that this particle size would be the upper limit for detailed analysis. Field samples weighing more than 3kg were taken to allow for the subsequent loss in weight when the samples were dried and to allow for the weight of fragments larger than 16mm in the samples. Dry weights of the till samples ranged from 3.7kg to 7.8kg. The smaller size of the main study samples meant that in the field they were far easier to transport, and in the laboratory analysis was much quicker. For example, oven-drying of the samples was made possible.

During mechanical separation of coarse and fine fractions of till in the pilot study, many of the more fragile rock fragments were broken up together with the dry lumps of till. In order to separate the two fractions in the study of essexite dispersion, the oven-dried samples were first weighed and washed through a 2mm aperture sieve. The coarse fraction was dried, placed on the largest aperture sieve of a nest of sieves of sizes 2, 4, 8 and 16mm and allowed to vibrate in a "Rotap" sieve shaker for ten minutes. The material retained on all but the 16mm sieve was weighed, and the essexite material extracted and weighed in a similar manner to that employed in the pilot study. When the essexite material was being extracted no attempt was made to distinguish between the porphyritic and non-porphyritic varieties of essexite. For the purposes of this analysis therefore the two outcrops have been treated as a single source. The fine fraction (<2mm) of each sample was retained for later heavy mineral analysis.

The extraction of the essexite material from the coarse fraction of the till samples proved to be easier than with the Dalmahoy material. This was a result of the groundmass of the essexite material which weathers to a white colour, contrasting with the greys and browns of the majority of the other rock fragments in the till samples. Only in the case of the material retained on the 2mm sieve was identification difficult. Many essexite fragments at this size consisted solely of purple titanaugite phenocrysts.

The location of the 23 sites where 28 till samples were collected are shown in Fig.4.11. All the samples are within a radius of 6km from the two essexite outcrops. They were collected mostly from convenient sections exposed in the till by streams issuing from the Campsie Fells. The remaining samples were taken from sections provided by limestone quarrying or other human activity. The distribution of sample sites is irregular. This is a result partly of the distribution of the streams that provided the majority of the sections, and partly of a desire to record the detailed variation in the amount of essexite across the train. Thus samples 4, 5, 6, 8, 9, 10, 11, 12, 13 and 22 form a string of closely spaced sites at right angles to the direction of spread of the essexite material.

The results of the analysis are shown in Table 4.3. The highest percentage of essexite material within the coarse fraction (2-16mm) in all the samples analysed is 1.8% for sample 1, which is the sample located closest to the essexite outcrops. Other samples also record a very low percentage weight of essexite material despite the fact that many are located in an area of the erratics train containing a considerable number of essexite boulders, many of which have been incorporated in the dry stone walls (see chapter 5). In many samples no essexite fragments were identified. Several of these samples were located in the peripheral areas of the erratics train

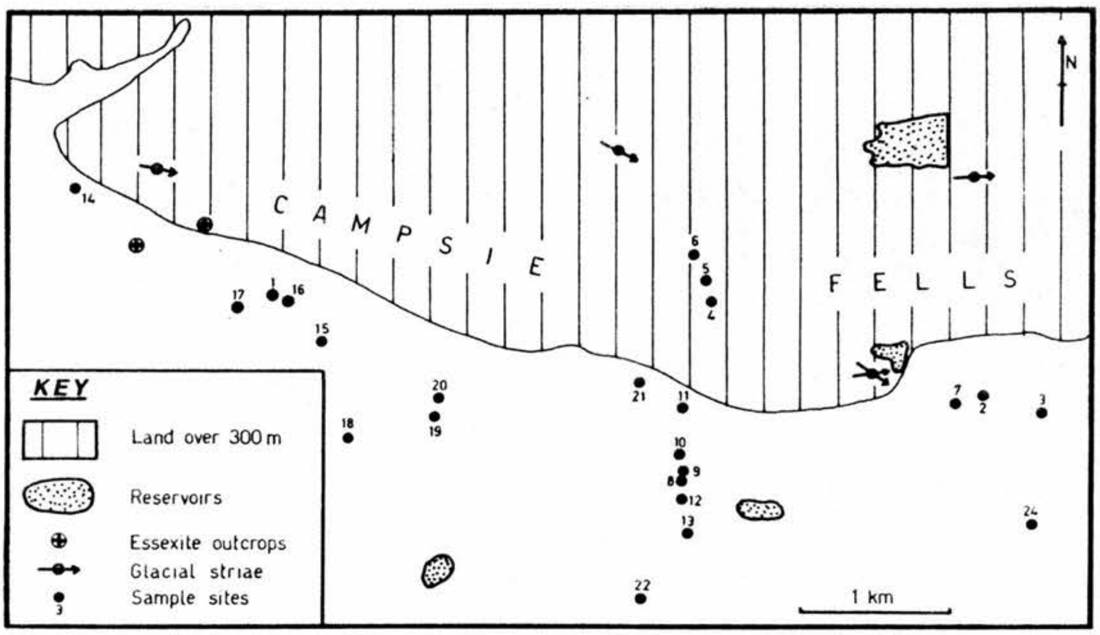


Figure 4.11

Location of sample sites in the vicinity of the essexite outcrops.

Table 4.3 Results of the analysis of the amount of essexite material in till

Sample	Dry wt. of sample (gm)	Total wt. material (2-16mm)(gm)	wt. essexite (2-16mm)(gm)	% wt. essexite (2-16mm)	sample depth (cm)
1	6859.9	2804.5	51.2	1.80	60
2	7299.7	3288.8	0.3	0.01	90
3	6100.8	1703.1	0.5	0.03	90
4	3644.8	1781.5	0.4	0.02	60
5	3703.0	1450.5	0.2	0.01	70
6	5123.7	2863.9	-	-	80
7	5626.7	767.9	0.5	0.06	90
8	4481.1	602.9	-	-	80
9	4911.9	617.3	0.2	0.03	70
10	4468.6	504.3	-	-	110
11	4730.2	1466.5	0.1	0.01	80
12a	5238.2	1966.0	-	-	30
12b	3548.5	301.2	-	-	90
12c	3960.0	652.4	-	-	130
12d	4925.8	1257.2	-	-	190
12e	5013.8	1165.8	1.2	0.10	220
13a	4463.8	647.4	-	-	120
13b	4730.1	788.3	-	-	180
14	3658.0	1203.2	-	-	60
15	6728.8	1692.2	10.3	0.60	60
16	7074.5	3083.7	7.3	0.24	60
17	7806.8	2887.4	5.3	0.18	80
18	5208.6	1824.6	0.1	0.01	60
19	6225.8	845.2	0.2	0.02	80
20	6550.0	1703.0	-	-	80
21	6751.8	1790.2	-	-	80
22	5486.5	346.6	-	-	60
24	5506.2	792.6	-	-	60

(see chapters 5 & 7). However other samples containing no identifiable fragments of essexite are situated close to the major axis of the train.

The till overlying bedrock to the east of the essexite outcrops is generally rather thin, rarely approaching a metre in depth. Thus the majority of the samples used for this analysis were taken from exposures less than a metre beneath the surface. However it was possible at site 12 to sample a section that was over 2m in depth before bedrock was encountered. It was hoped that, by collecting five samples spaced c. 40cm apart vertically over the exposed face of the section, variation in the amount of essexite vertically within the till could also be assessed. In all five samples, only one fragment of essexite was found and this was located in the deepest sample collected (12e). Similarly at site 13 two samples were taken vertically from the exposed section of till. Not as much till was exposed here as at site 12 and no essexite erratic material was found in the coarse fractions of either sample.

The low amount of essexite recorded in the samples is problematical and requires further consideration. It contrasts markedly with the appreciable amounts of Dalmahoy material at corresponding distances from its source.

This lack of essexite within the 28 samples analysed made it clear that further sampling along similar lines was unlikely to further the investigation. If samples of till from the centre of the erratics train and close to the outcrop yielded no identifiable fragments of essexite, then it was unlikely that the periphery of the train could be delimited with any degree of accuracy. Thus following the collection of a sample from site 24 it was decided that future samples would only be analysed for their heavy mineral content. This meant that the sample size could be further reduced.

The small quantity of identifiable essexite fragments within the till immediately down-ice of the outcrops poses problems. In order to resolve this question one must consider those factors that affect the amount of a particular rock type within till. As has already been mentioned in chapter 2, Anderson(1955,1957) listed these factors under the four headings of provenance, lithology, glacial processes and dilution. ~~The~~

Considering firstly the provenance of the essexite outcrops, the surface area of the two sources is, as chapter 3 has shown, very small. The topographic positions of both outcrops are not prominent in the landscape, but parts of a continuous scarp slope. There is therefore a difference here between the Dalmahoy outcrop and the two essexite outcrops, since the former is more prominent in the landscape and of greater areal extent than the latter. Thus it might be inferred that the lack of essexite material compared to Dalmahoy material is a result of its smaller outcrop area and insignificant topographic position. However this does not account for the low percentage weights of essexite material in samples so close to, and down-ice of the outcrops. Furthermore the number of essexite boulders in the dry stone walls near these samples makes it clear that the outcrops have been subjected to considerable glacial erosion.

If one considers the effect that the lithology of essexite might have had on the amount of material in the till, then there are several features that might have caused the anomaly of low amounts of essexite in the till compared with relatively high amounts of Dalmahoy material in the pilot study. One can disregard a difference in the durability of Dalmahoy material and essexite as being responsible for the differing amounts in the till since both are tough, intrusive igneous rocks. However other features of the essexite rock masses could well be important. The jointing characteristics outlined in chapter 3 in conjunction with the inherent strength of both types (see chapter 6) have possibly caused the bedrock to be quarried easily by ice along the joints. The influence that bedrock jointing has on the size of the same material found in the till is well known (Charlesworth,1924; Holmes, 1952; Elson,1961; Krüger,1974; Gry,1974). Subsequent comminution of essexite fragments during glacial transport might have tended to produce larger fragments. Holmes found that "larger stones generally broke into two pieces instead of many" (Holmes,1960,p.1651). Beaumont (1967) considered that coarse grained igneous material is generally resistant to erosion and breaks down into sizes greater than 10cm in diameter. Below this size he thought that the rock fragments would tend to break down into individual mineral grains. Thus it could be that the multi-modal size distribution (see p.29) of essexite comprises modes in the mineral grain size and a mode in the cobble and boulder size. This is one explanation that might account for the paucity of essexite material in the samples.

The effects that glacial processes might have had on the amount of essexite material are many and varied. If the mode of transport is considered alone, then the apparent paradox of a large number of essexite boulders in the dry stone walls compared to the small percentage of pebble-size material in the till might be resolved. It may be that the essexite material now in the dry stone walls and in the till have been transported in different ways by the ice sheets. In this case the essexite material within the till would have been dragged intermittently beneath the ice or carried near its base, while the cobbles and boulders now in the walls might have been transported englacially. One would have to envisage a situation in which most of the glacially-quarried material from the outcrops was carried up into the ice.

Dilution through the continuous incorporation of other rock fragments, as mentioned earlier in this chapter, can have a great effect on the amount of erratic material found in a till sample. However its potential as an explanation for the small amount of essexite material seems limited, since there remains the problem of a paradoxically large number of essexite boulders in the walls. The possibility of a large number of small fragments being produced by the erosion of other outcrops in the vicinity causing an apparently low value of essexite material can be discounted since the coarse fraction of all the samples was notable for the variety of its rock types.

Another possible explanation for the small amount of essexite material in the till arises from the effect of postglacial processes on pebble-size fragments of essexite. It has already been mentioned in chapter 3 that the groundmass of both essexite rocks weathers to a pale colour on exposed surfaces. In particles of 2 to 16mm in size the thickness of this weathering "rind" forms much of the particle itself. Consequently some of the small essexite particles were found to be extremely fragile and could be crumbled between finger and thumb. This susceptibility to weathering might have caused many essexite particles to rot completely. This view is supported by the fact that the majority of samples was collected from oxidised (and therfore weathered) till. However one point tends to argue against this view. Even if the groundmass of many essexite particles had been weathered to fine material there still should have been a number of residual lumps of titanaugite phenocrysts, since this material is relatively resistant to erosion (see chapter 7). These titanaugite phenocrysts, though not as easily identified as fragments possessing groundmass minerals, could be relatively easily distinguished.

This issue will be considered further in chapter 9 together with evidence from chapters 5, 6, 7 and 8.

CHAPTER 5

DELIMITATION OF THE ESSEXITE ERRATICS TRAIN USING DRY STONE WALLS

> "les méthodes dont on vous parle ne sont pas tombés du ciel" (Cailleux,1961,p.143)

Over much of the Main Study Area the use of dry stone walls as field boundaries is common. The walls are scarce or absent on the high and steep parts of the Campsie Fells, on recent alluvial deposits, raised beach material and on the peat-covered areas of Millstone Grit to the north and east of Cumbernauld.

The walls range in height from about 60 to 120cm, an individual wall usually maintaining a fairly consistent height unless it has been allowed to fall into disrepair. The material in the walls, for the most part, comprises stones derived from the surface of the adjacent fields, shallow ploughing contributing to the available material (Plate 3). Where the number of loose, surface stones is small, either alternative methods of enclosing fields have been used such as hedgerows or wire, or (where rock crops out) blocks have been quarried for building the walls. The size of wall stones varies from cobbles to boulders up to a size that can be physically moved.

Although the walls are repaired from time to time with new material if necessary, they appear to have been first erected in the second half of the eighteenth century during the major time of field enclosure in Scotland. Few walls were built before this time as Roy's military maps (completed between 1747 and 1755) indicate (Skelton,1967), for dry stone walls as well as other field boundaries likely to prove an obstacle to military movement were accurately drawn on these maps. Except for a small area north of Kilsyth, field boundaries are absent on the Roy maps that cover the Main Study Area. Conversely it seems that towards the end of that century dry stone walls were commonplace in the area, as the entry for the Campsie Parish in the Statistical Account for Scotland indicates. "Our inclosures are little better than rickle dykes, built of stones gathered from the land" (Sinclair, 1795,p.342).

The majority of the dry stone walls can therefore be regarded as random samples of stones of a certain size range collected from the surface of the adjacent land. Where a wall rests on glacial deposits, the stones within it represent a random sample of glacially transported cobbles and boulders. The presence of essexite stones in the walls has already been mentioned in chapter 4. Since the essexite bedrock has never been quarried (Peach,1909), any essexite stones in the walls must have been derived from the surface of the neighbouring fields. Using this basic assumption it was planned to delimit the essexite erratics train by detailed investigation of the frequency of essexite stones in the walls. Within the limits of the train it was hoped that point values representing the amount of essexite per unit area of wall might be obtained. From these point values an isarithmic map of the decline of essexite erratic material with distance from the source could then be derived.

Other workers have regarded dry stone walls in glaciated terrain as random samples of locally-deposited glacial erratics. Peach used dry stone walls in tracing the Lennoxtown essexite boulder train, considering them as "composed of surface boulders gathered from the immediate neighbourhood" (Peach,1909,p.27). In Ireland dry stone walls have been used to trace glacial erratics from ore bodies covered by glacial deposits (Morissey & Romer, 1973). Morrissey and Romer agree with Peach in considering that the stones in the walls have not been carried far by man. The locally-derived nature of stones in the walls is well illustrated by an example of field boundaries for a small area in Dorset given by Mead(1964). Dry stone walls extend to the limit of limestone bedrock which is the only source of stones. On the Wealden clay and chalk strata the walls are superseded by hedgerows and barbed-wire fencing.

Prior to commencing fieldwork it was decided that an individual wall should fulfil the following two requirements.

(i) It had to comprise stones gathered from the adjacent land and not blocks of quarried material nor stones from one particular source. In the Main Study Area these three types of stone can be differentiated with ease. Firstly the latter two contain only one rock type whereas walls comprising loose surface stones are of varied lithology. Secondly quarried blocks are angular and often tabular whereas loose surface stones tend to be subrounded, having undergone abrasion during glacial transportation. The distinction between these types of wall meant that any form of systematic or random sampling of walls for study from maps or aerial photographs would not be possible. If field boundaries had been sampled from maps prior to fieldwork there would have been no way of knowing firstly whether they were walls, and secondly, even if they were walls, whether they were suitable for analysis. The second problem would also have applied to the use of aerial photographs.

(ii) A wall had to be in reasonable repair and of sufficient length to make analysis worthwhile. Many walls that had become grassed over were avoided as were stretches of wall shorter than c. 150m, except where such walls were the only ones available. Initially a wall almost 1km in length fulfilling these requirements and situated about 1km down-ice of the essexite outcrops was analysed to test the feasibility of the proposed method (wall A in Fig.5.1). Since the wall was both close to the outcrops and aligned almost perpendicular to the direction of ice movement, it was hoped that an analysis of it might reflect a large change in amounts of essexite over a short distance. The wall extends farther north up the scarp slope of the Campsie Fells, but this section was not analysed since it consists only of rock fragments from the underlying lavas. It was decided that a 10m length of wall should act as the basic unit of measurement for recording the presence or absence of essexite stones. For each 10m unit the height of the wall was recorded to the nearest 10cm together with a note of the presence of any essexite stones and whether they were from the porphyritic or non-porphyritic outcrop. These two types were easy to distinguish where the weathered surfaces of the essexite could be seen. In many cases the covering of lichens, mosses and other vegetation towards the base of the wall meant that close scrutiny was required to distinguish essexite stones from the other rock types. With practice, however, essexite stones could be quickly identified while walking alongside a wall (see Morrissey & Romer,1973).

Two measurements were also made on each essexite stone encountered. These were the greatest distance (d) across a stone and the width (e) perpendicular to d, both measured to the nearest 1cm. These two measurements were made on the actual portion of an essexite stone that was presented in the vertical face of the wall (Fig.5.2). Occasionally during fieldwork two parts of an essexite stone were found that had been broken during the construction of the wall. These were treated as two stones for the wall analysis. The number of such breakages however was small.

To calculate the amount of essexite represented by the essexite stones in the wall, the results from 10m sections were combined to form 100m sections. Gaps in the wall caused, for example, by gates were recorded during fieldwork and were subtracted from these 100m sections at this point. For each of these sections the area of wall (L x H) and the cumulative "areas" of essexite (d x e) were calculated (Fig.5.2). Then for both porphyritic and non-porphyritic varieties the following calculation was made.

$$E_A = \sum_{i=1}^{i=n} \frac{(d \times e)}{L \times H} \times 10^4$$ where n = the number of essexite stones

The term 10^4 was included to make all values of E_A greater than 1, except where no essexite stones were recorded. The E_A values for porphyritic and non-porphyritic essexite stones are shown opposite the central point of the section of wall they represent (Fig.5.1).

The E_A values for wall A in Fig.5.1 indicate that the method reflects changes in the amount of essexite material from a central point to a peripheral part of the erratics train. The rapid decline in E_A values over the short distance analysed supports the assumption made prior to fieldwork that wall stones have not been carried far to their location in a wall. The E_A values for the other walls shown in Fig.5.1 also indicate that the walls represent a random sample of the most readily available, loose, surface stones. This is particularly well illustrated by the wall that encroaches on the southern edge of the porphyritic essexite outcrop. Values of E_A for porphyritic stones are extremely high for the northernmost data point where loose boulders immediately downslope of the outcrop comprise a large proportion of the available

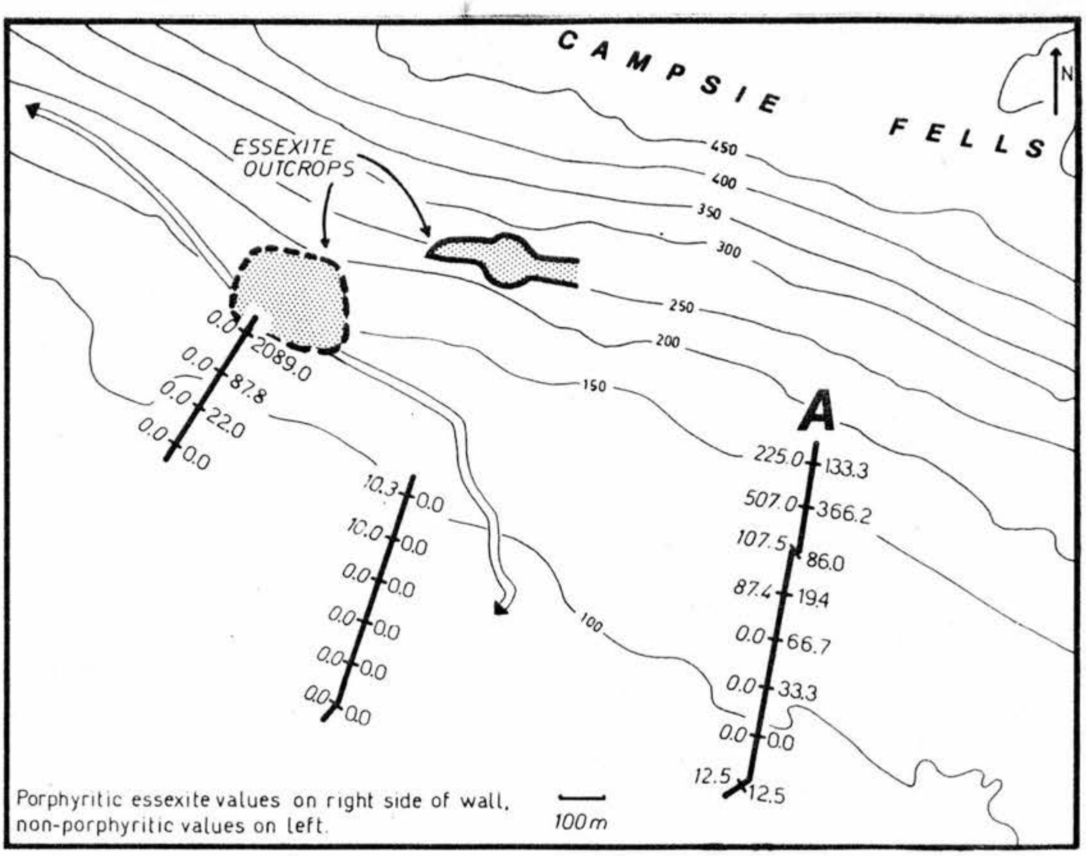


Figure 5.1

Location of dry stone walls analysed in close proximity to the essexite outcrops.

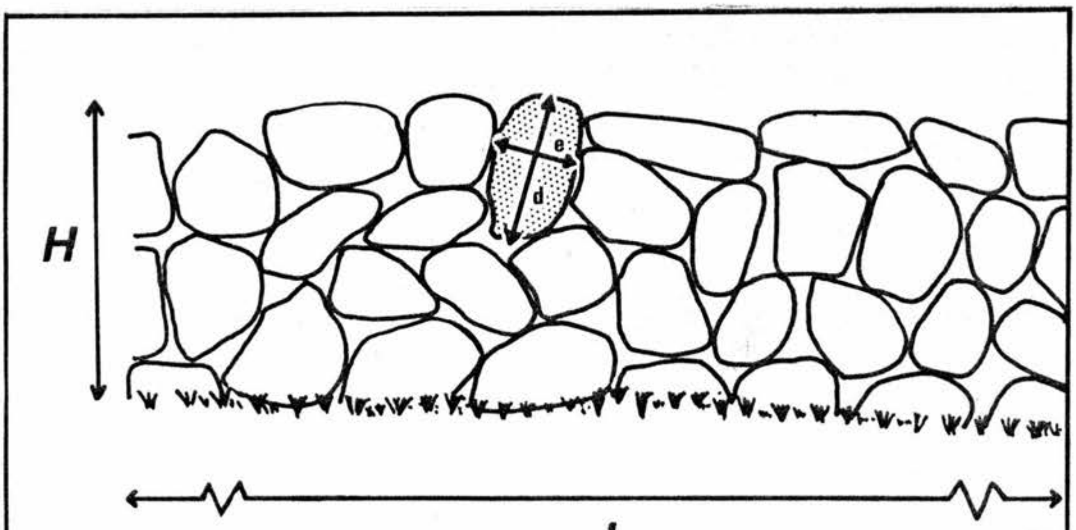


Figure 5.2

Measurements made on the dry stone walls and an essexite erratic (shaded).

wall-building material. To the south along the wall, however, E_A values decline rapidly to nil, reflecting the lower frequency of locally available essexite stones compared to stones of other rock types. Non-porphyritic E_A values for this wall are all nil. In view of the west-north-west to east-south-east movement of ice in the immediate vicinity this lack of non-porphyritic stones to the south of the outcrop is to be expected and lends support to the argument for local collection of stones for the walls.

Having demonstrated the feasibility of the method, other suitable walls were analysed in the area between a point west of the outcrops and Larbert in the east, and as far to the north and south in the Main Study Area as was necessary to establish the limits of the erratics train, or as was possible in terms of the walls available. Analysis of walls was not continued east of Larbert because of the large expanse of raised beach material. Farther to the east of these deposits in the Secondary Study Area analysis of the walls was not possible due either to their absence or to the unsuitability of those walls that were available.

Within the area investigated the distribution of analysed walls was intended to be evenly-spaced. As can be seen from Fig. 5.3 however, there are areas where analysed walls are clustered or sparse. The aggregation of walls west of Denny resulted from the desire to establish the northernmost limit of the essexite erratics train which was found to extend some 3km farther north than its position on the map produced by Peach (Fig.3.2).

The long stretch of east-west aligned walls north of Kilsyth was analysed in order to determine whether essexite stones had been transported northwards across the crest formed by Garrel Hill and Tomtain. The paucity of analysed walls along the Kelvin-Bonny Water valley reflects the absence of dry stone walls due to the lack of available stones in the underlying fluvioglacial and alluvial deposits. North and east of Cumbernauld and east of Denny there are more walls present than are shown in Fig. 5.1, but the underlying Millstone Grit bedrock has resulted in the majority of the walls comprising only stones from this source. Analysis of these walls was therefore not undertaken.

Two sections of wall were investigated to the west of the essexite outcrops to determine whether essexite stones had been carried westwards from their source. One section of wall is located c.100m west of the lower porphyritic essexite outcrop and extends some 300m up the steep slope of the Campsie Fells. No essexite stones were found in this wall. Another section of wall c.3km west of the outcrops was also analysed and provided a further confirmation of this negative result.

When all the walls shown in Fig. 5.3 had been analysed the data were prepared for interpolation by the SYMAP computer-mapping system (Muxworthy,1972). This program basically requires an input of three variables (x_i, y_i, z_i), where x_i and y_i are locational co-ordinates for a data point D_i and z_i is the corresponding data

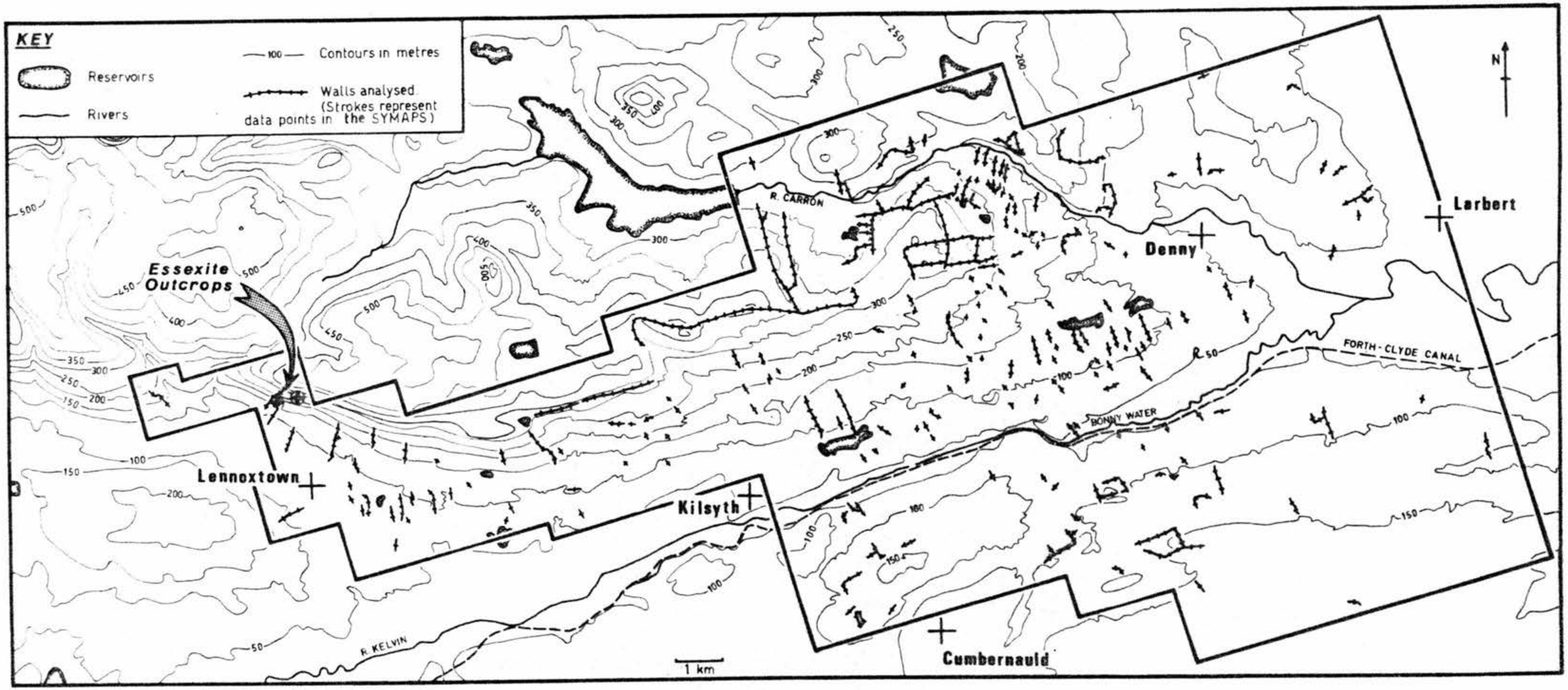


Figure 5.3

Location of the dry stone walls analysed in the Main Study Area.

value (Shepard,1968). A two-dimensional interpolation function is used to smooth the data whilst still passing through the specified points (D_i). For each location a value is calculated according to distance and direction weightings based on the neighbouring data points. The number of data points used in this interpolation varies between four and ten with an average of seven, and is dependent on the density of points within the area of the largest polygon enclosed by the data points. The interpolation function is defined at every point on a plane and the computer print-out records isopleths of the surface using print and overprint characters on a standard ten line per inch printer (Fig.5.4). Since the program will continue to interpolate values outside the smallest polygon whose closure contains all the data points, which might lead to erroneous interpretation, a border can be placed around the data points to prevent this occurring. This line is represented by a continuous line of asterisks in Fig.5.4 and by a solid line around the walls in Fig.5.3.

The SYMAP program was preferred to some form of contouring by hand for two main reasons. Firstly, the data had a wide range of values on a local scale necessitating some form of objective smoothing prior to contouring. Secondly, knowledge of glacier ice direction would have introduced operator bias towards elongating the contour lines in the supposed direction of ice transport. The SYMAP program, on the other hand, gives equal regard for all directions.

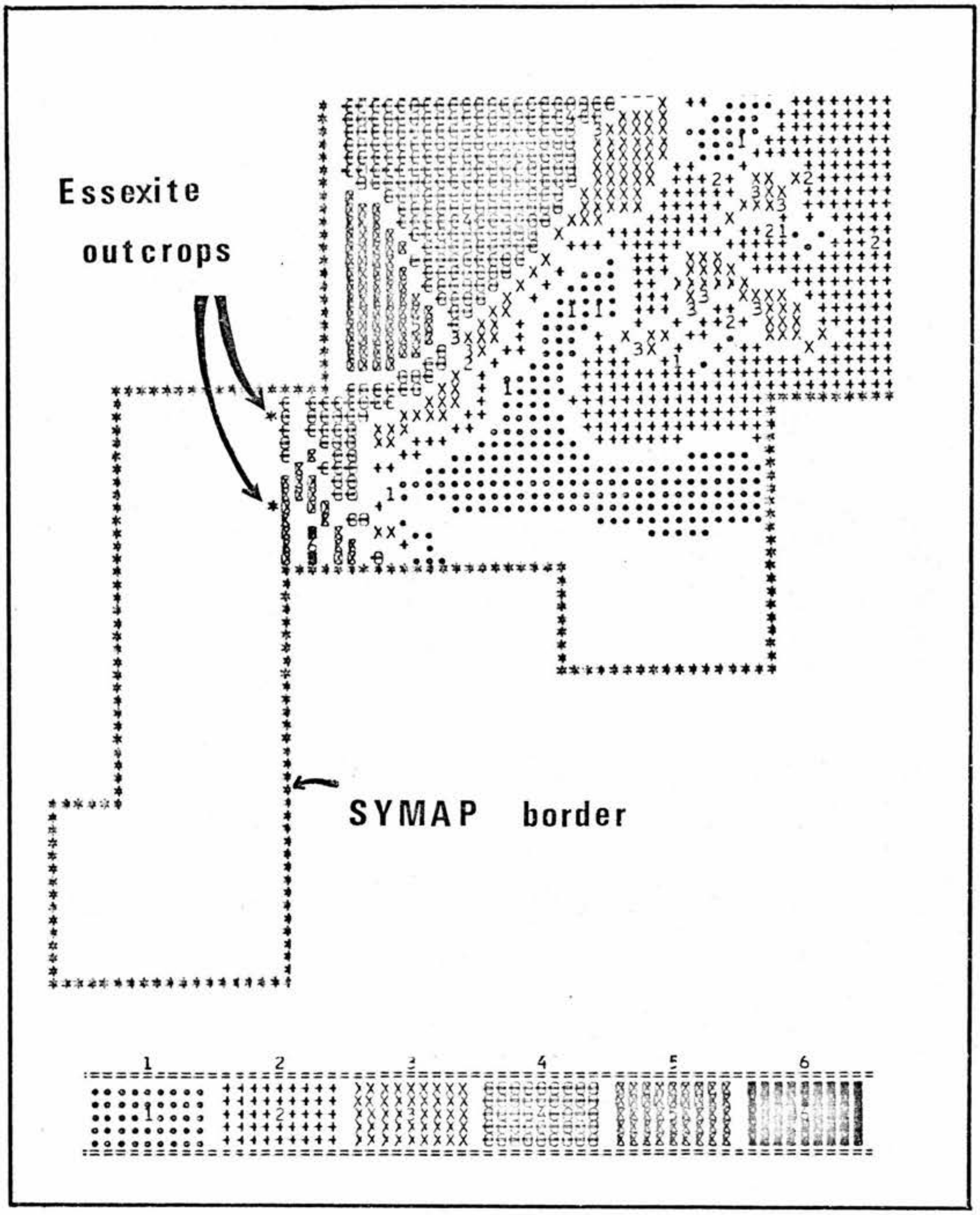


Figure 5.4

Detail of part of a SYMAP contour map. Numbers denote locations of data points and the corresponding shading level.

The z_i values for the data input were calculated in a similar manner to that described earlier for the walls shown in Fig.5.1. However, since a data point interval of 100m would have led to a superimposition of many data points in the SYMAP output at a 1:1 scale to the original 1:25,000 map, intervals of 200m were used with the following exceptions. Where analysed walls were longer than 300m but less than 400m in length, the wall was equally divided and two data points obtained. In a few cases individual stretches of wall amounted to less than 150m. For such walls one data point was derived and located in the centre of the section of wall. The 478 data points obtained for all the walls analysed are shown in Fig.5.3.

For each data point six z_i values were obtained. Three values represent calculations of E_A for (i) non-porphyritic plus porphyritic (ii) non-porphyritic and (iii) porphyritic stones. The remaining three z_i values were for the same three categories of essexite stones used for the E_A calculations but were derived from a different formula. This formula is

$$E_N = \frac{n}{(L x H)} \times 10^7$$

The term n represents the number of essexite stones in a section of wall of length L and height H. The term 10^7 was included to make all values of E_N greater than 1, as for E_A. The additional calculation of E_N was carried out since there was no precedent upon which to base the derivation of the amount of erratic material within a length of wall. Both E_A and E_N values were therefore calculated to determine which was the more suitable.

The six contour maps of E_A and E_N values are shown in Figs 5.5 to 5.10. These maps have been redrawn from the original computer output for the sake of clarity. Contour intervals based on a geometric progression were chosen for both E_A and E_N values since equal contour intervals gave rise to only one shading level beyond c.6km east of the outcrops for Figs 5.5, 5.6, 5.8 and 5.9. The lack of shading on all the maps indicates areas that have been interpolated by the SYMAP program from the data points as not having any essexite stones in the walls.

Fig.5.5 reflects the classic erratics train features described by other workers such as Shaler(1893) and Lundqvist(1935; Fig.2.4). Firstly, a major axis of high erratic values is evident. Secondly, the values decline both along the axis in the direction of ice movement and perpendicular to it. Thirdly, the train broadens from the outcrops in the direction of ice movement.

The major axis appears to follow a slightly sinuous course pointing east-south-east immediately down-ice of the outcrops, then east-north-east up to a point north of Cumbernauld where it once more turns east-south-east. The axis is not central, being closer to the northern edge of the train.

The contour map shows a marked contrast to the map by Peach(1909; Fig.3.2) in terms of the width of the train. It appears that Peach mapped only the major axis of the train in the Main Study Area whereas the train in fact extends a considerable distance farther north and south (Fig.9.1).

It is unfortunate that in some parts of the train, particularly north-east of the outcrops, the SYMAP border encroaches on the erratics train. This was unavoidable owing to the lack of walls on the higher peat-covered areas of the Campsie Fells. Similarly the southern periphery of the train could not be delimited due to the lack of suitable walls: hence the continuation of shading up to the SYMAP border.

The shapes of individual shaded areas in Fig.5.5 and the remaining contour maps are not significant in themselves being largely controlled by the spacing as well as the values of the neighbouring data points. The whole interpolated surface should therefore be considered rather than concentrating on the significance of small areas.

The standard interpolation procedure has been interrupted in one instance. Immediately to the north-west of the outcrops an impermeable "barrier" to interpolation was set up to prevent a value gradient being interpreted between the high values of data points east and south-east of the outcrops and nil value data points to the west and north-west (Fig.5.4). Without the barrier, the contour map would have indicated the presence of essexite stones west and north-west of the outcrops, which is incorrect. A barrier was placed in the same position for the other contour maps (Figs 5.6 - 5.10).

A comparison of the six contour maps reveals a number of similarities. Firstly, the maps of E_A values show few differences from the corresponding maps of E_N values, except that areas of shading of the latter are usually slightly larger. Both calculations therefore appear to be more or less equally representative of the amount of essexite present. Secondly, the porphyritic and non-porphyritic contour maps (Figs 5.6 & 5.7) indicate a similar direction of glacier ice transport. Although the map for porphyritic essexite has few areas of shading beyond c.6km from the outcrop there appears to be a clustering of such shaded areas towards the point where the major axis is present in the non-porphyritic map. Thirdly, both types of essexite stones show a rapid decline in E_A and E_N values away from the outcrop until a lower shading level is reached, when the values decline more slowly.

The contour maps for the two essexite types also show one important contrast. This is the difference shown by the rapid decline in the amount of porphyritic essexite stones with distance from the source compared to the non-porphyritic stones which are represented by an uninterrupted shaded area for some 20km from the outcrop. This contrast is attributed to the action of glacial crushing during transport. A difference in the spacing of parallel joints of the two essexite types has already been described in chapter 3. In chapter 2 the importance of bedrock jointing in controlling the size and shape of glacially transported debris was noted in terms of the observations of other workers. Gry(1974), for instance,

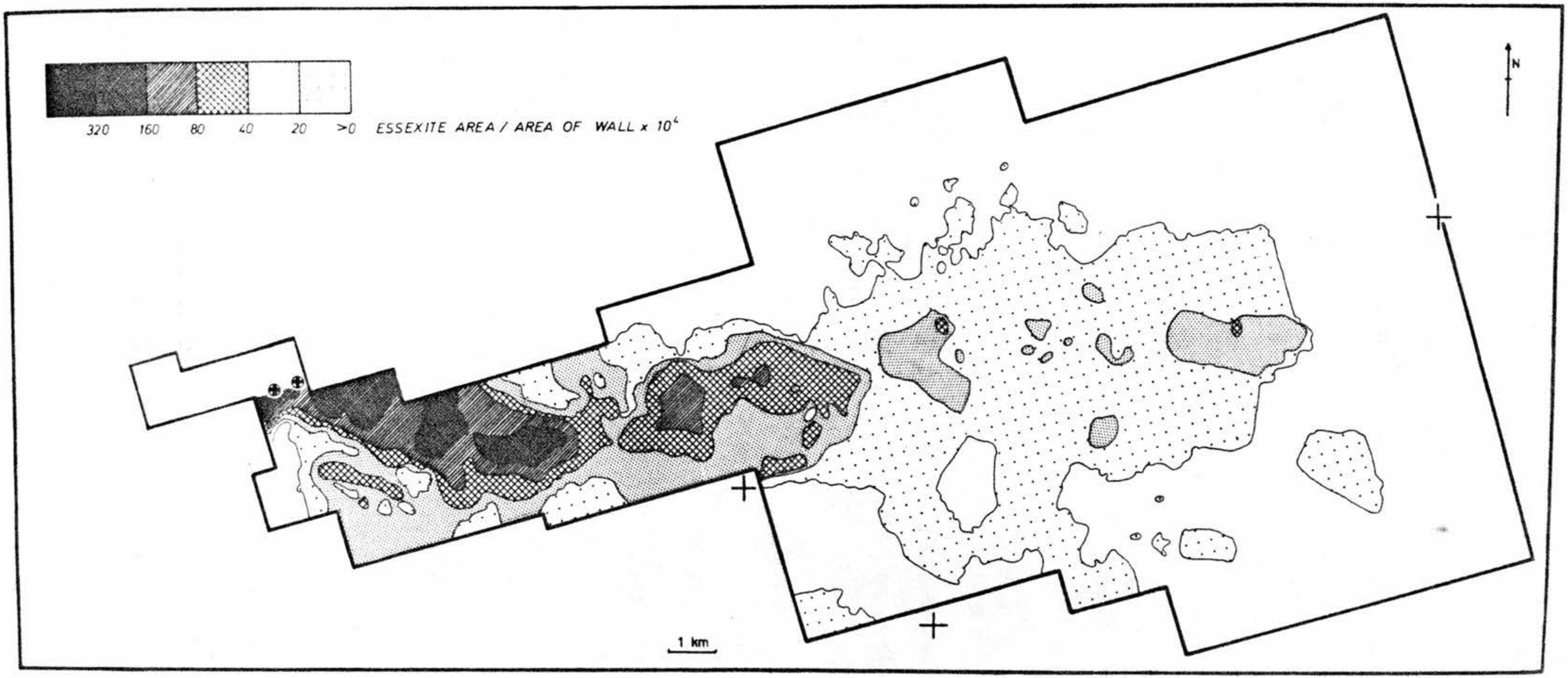


Figure 5.5

SYMAP of non-porphyritic + porphyritic (E_A) values.

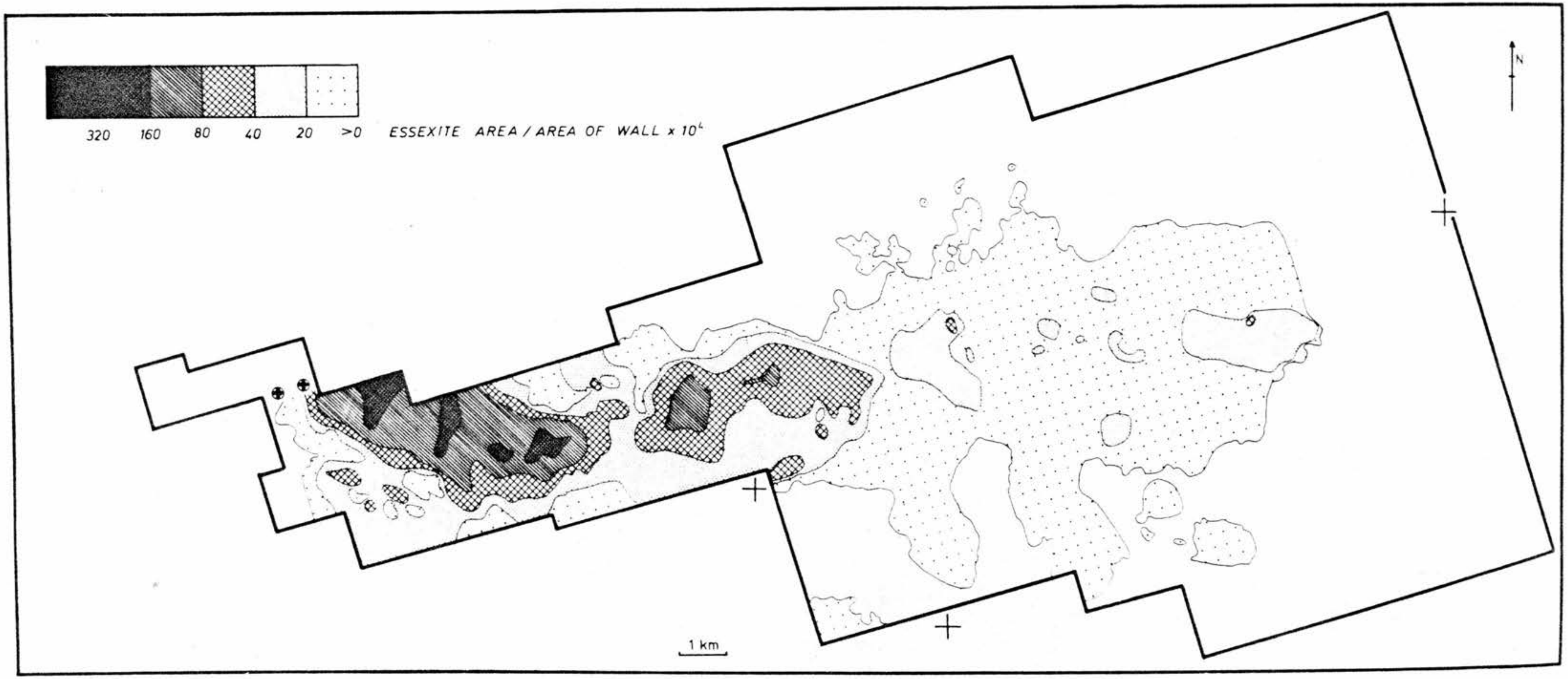


Figure 5.6

SYMAP of non-porphyritic (E_A) values.

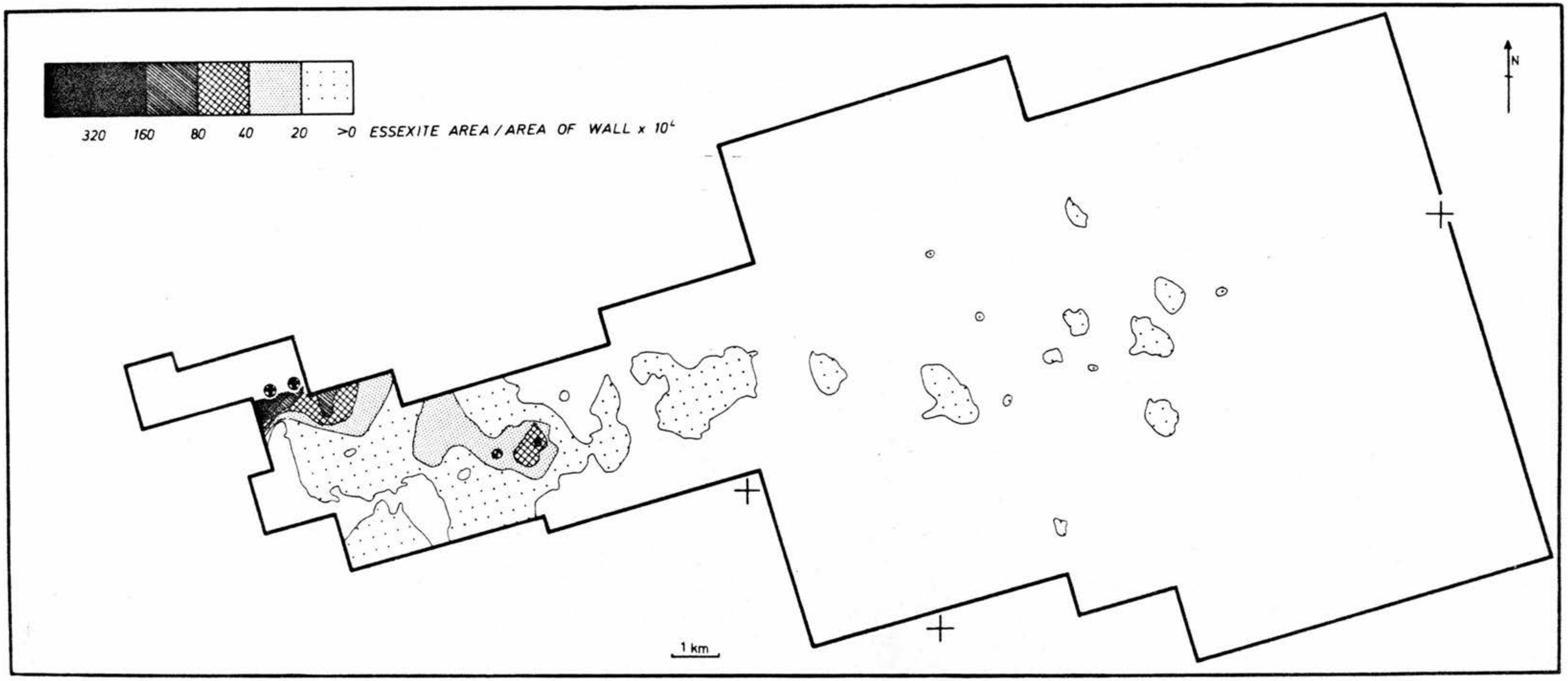
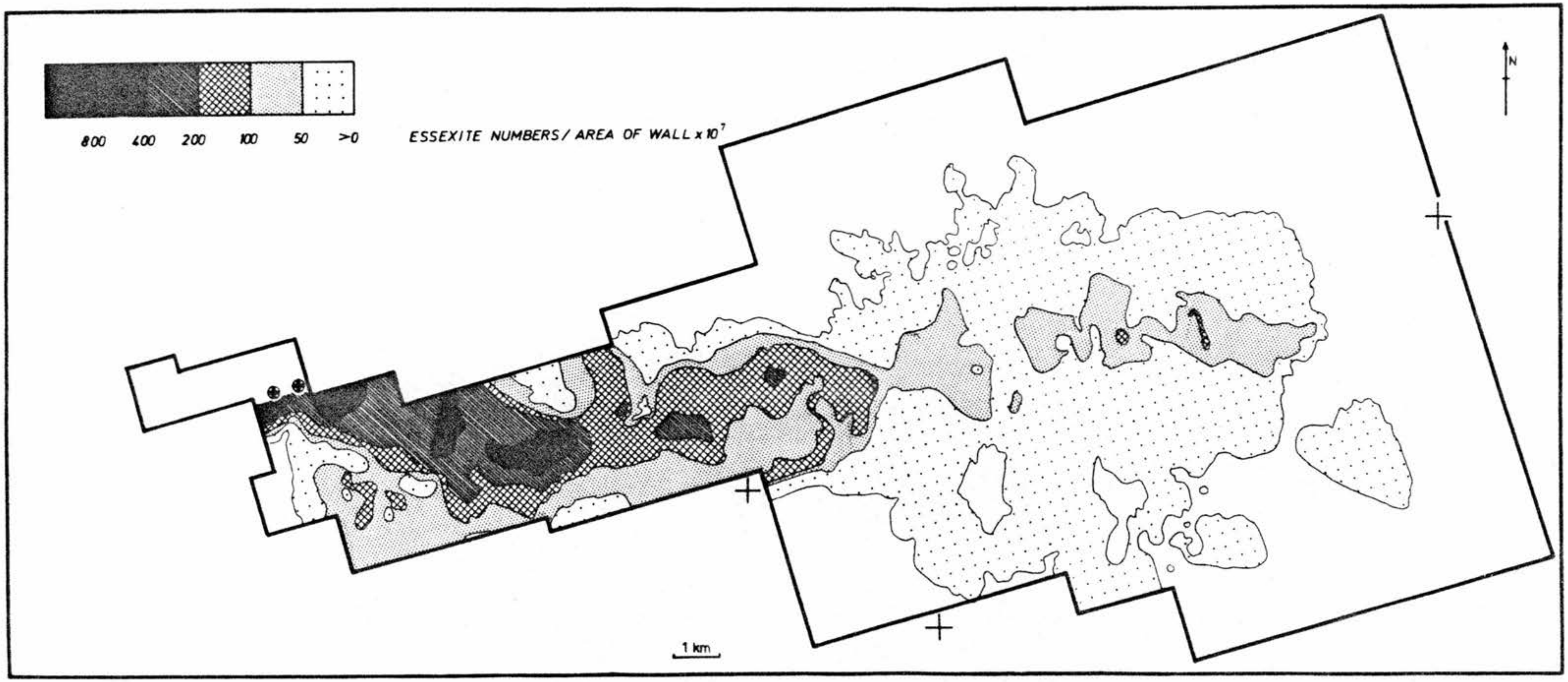


Figure 5.7

SYMAP of porphyritic (E_A) values.



<u>Figure 5.8</u>

SYMAP of non-porphyritic + porphyritic (E_N) values.

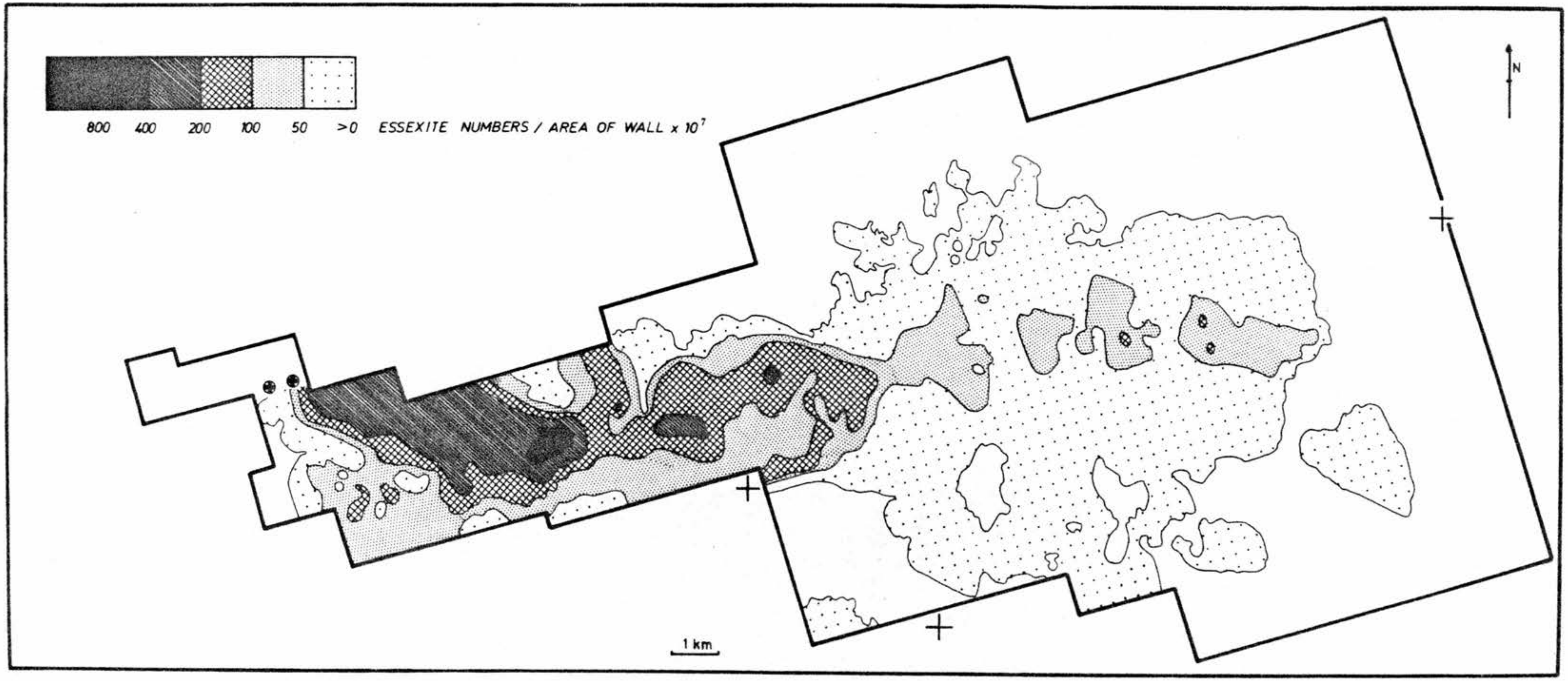


Figure 5.9

SYMAP of non-porphyritic (E_N) values.

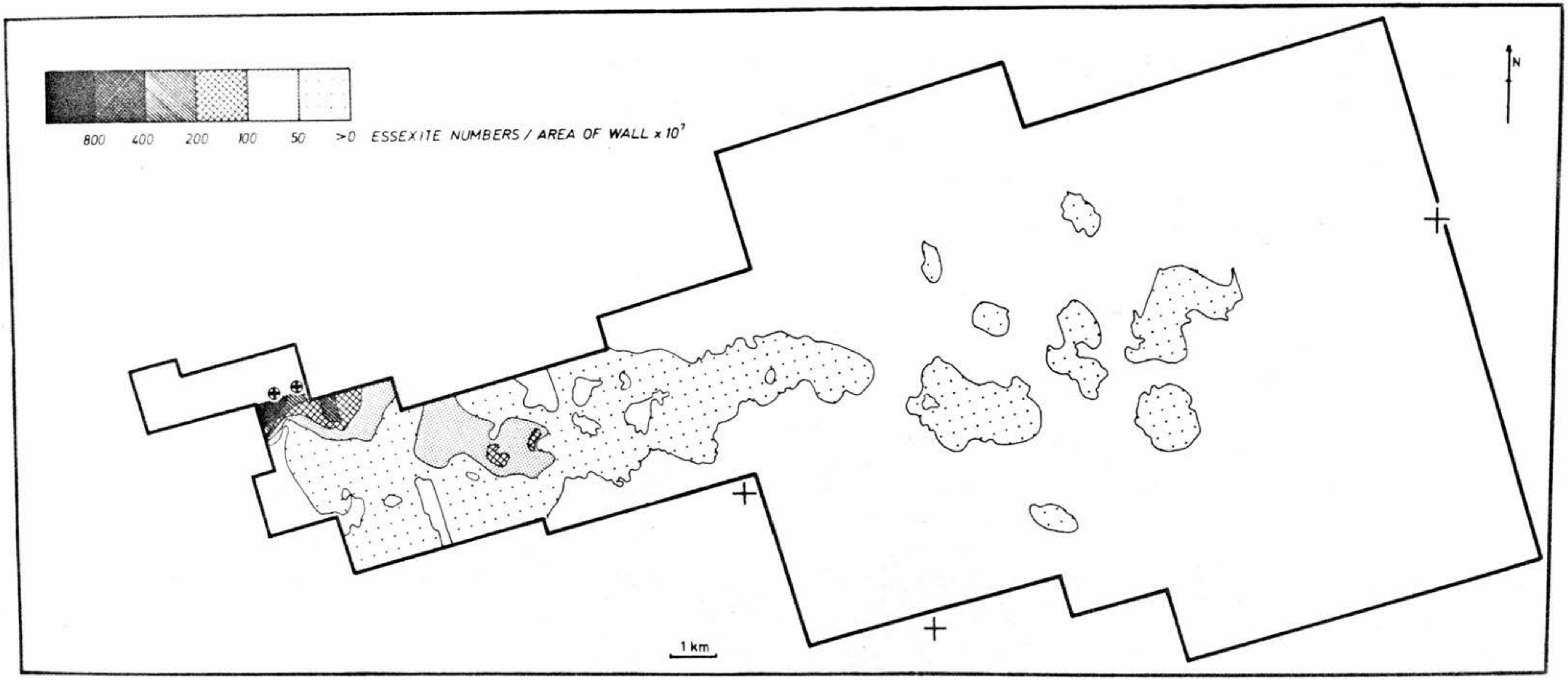


Figure 5.10

SYMAP of porphyritic (E_N) values.

has investigated the grain size distribution of some erratics in Denmark. He concludes that material was incorporated into the ice and rapidly crushed down to a size determined by the jointing of the rocks. This appears to apply to the two essexite types and would explain the rapid disappearance of porphyritic stones in the walls down-ice of the outcrop. The closely spaced jointing would cause them to become broken down into stones too small to warrant clearing them from the land and including them in the walls. The boulder-sized, joint-controlled blocks of the non-porphyritic variety, on the other hand, would still be of sufficient size to be selected for wall-building.

The data input for the SYMAP computer program is also suitable for generating SYMVU three-dimensional graphic displays of the absolute data point values (Muxworthy,1972). The surface representing data values can be viewed from any azimuth direction or elevation. Certain viewpoints lead to areas of the surface being hidden behind intervening areas of high value. Nevertheless the resulting diagrams give excellent over-views of the data. Figs 5.11 - 5.16 show SYMVU perspective views of the same data point values that were used in the interpolation of the SYMAP contour maps. They are all viewed from the eastern end of the SYMAP border with the outcrops at the far end of the display. The rapid decline in the amount of porphyritic essexite (Fig.5.13) with distance from the source is apparent as is the decline perpendicular to the major axis of the train. Figs 5.17 - 5.22

show the same six surfaces viewed from base-level perpendicular to the elongated side of the area enclosed in the SYMAP border. This viewpoint illustrates the contrast in the rates of decline of non-porphyritic and porphyritic stones to the best advantage. If curves were drawn to pass as closely as possible through the peaks in Figs 5.21 and 5.22 they would resemble the form of the negative exponential decay curve derived by Krumbein (1937) for the Mount Ascutney boulder train (Fig.2.1a).

The SYMVU drawings are, however, not entirely suitable for this purpose due to the effect of perspective as well as inaccuracies introduced by the plotting machinery. In order, therefore, to determine whether the negative exponential function was a close approximation to the decline in the amount of essexite with distance from the source, values for points representing this decline were obtained from the original data. Values of E_N, rather than E_A, were considered preferable for the calculation of these points since the diagrams of Krumbein (Fig.2.1a), Dreimanis(Fig.2.1b) and similar graphs by Gillberg(1965,1967,1968a) and Dionne(1973) have considered numbers of erratics. All the data point E_N values were allotted to ten equal-width bands with a common centre on the essexite outcrops, the limits of the bands varying in radius from 2 to 20km. The highest value occuring within each band was selected . The resulting ten values of E_N for porphyritic stones are shown in Fig.5.23 and those for non-porphyritic stones in Fig. 5.24. The highest values were chosen as opposed

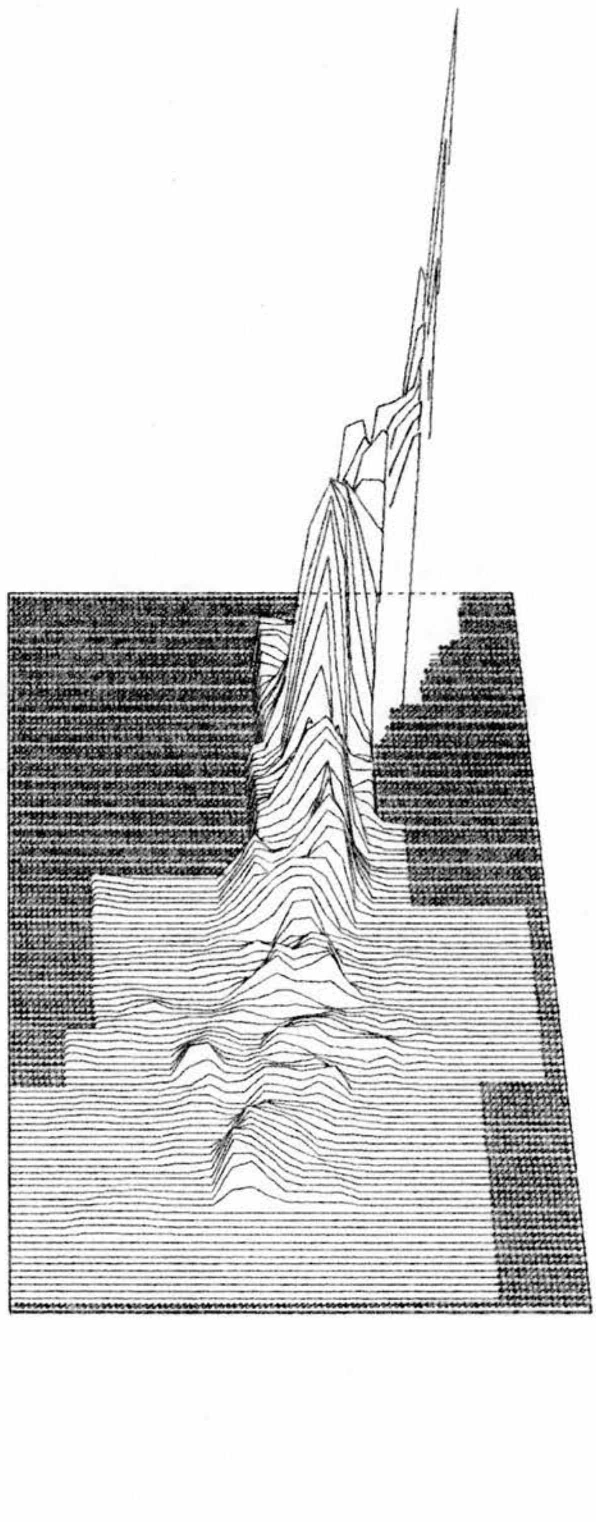


Figure 5.11

SYMVU of non-porphyritic + porphyritic (E_A) values viewed from the east-north-east.

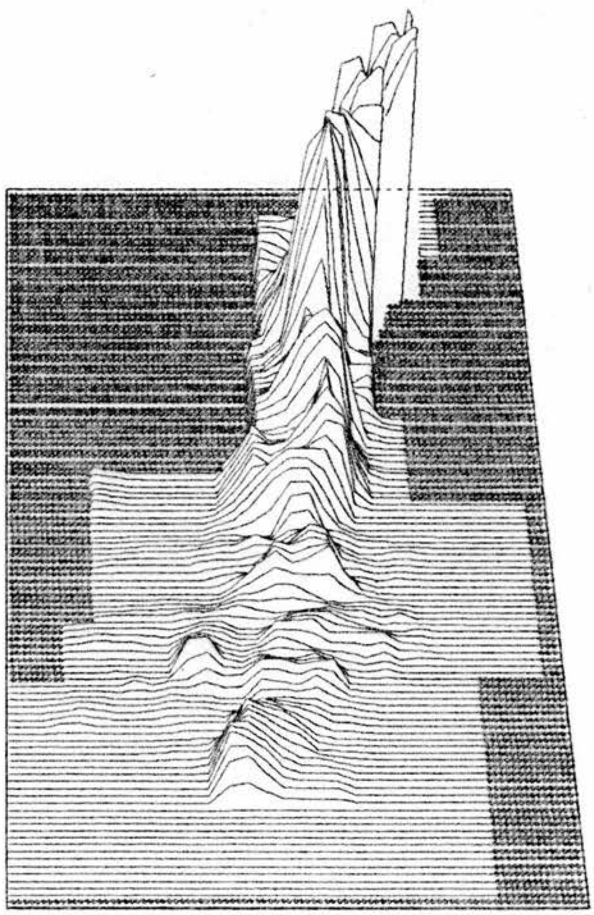


Figure 5.12

SYMVU of non-porphyritic (E_A) values viewed from the east-north-east.

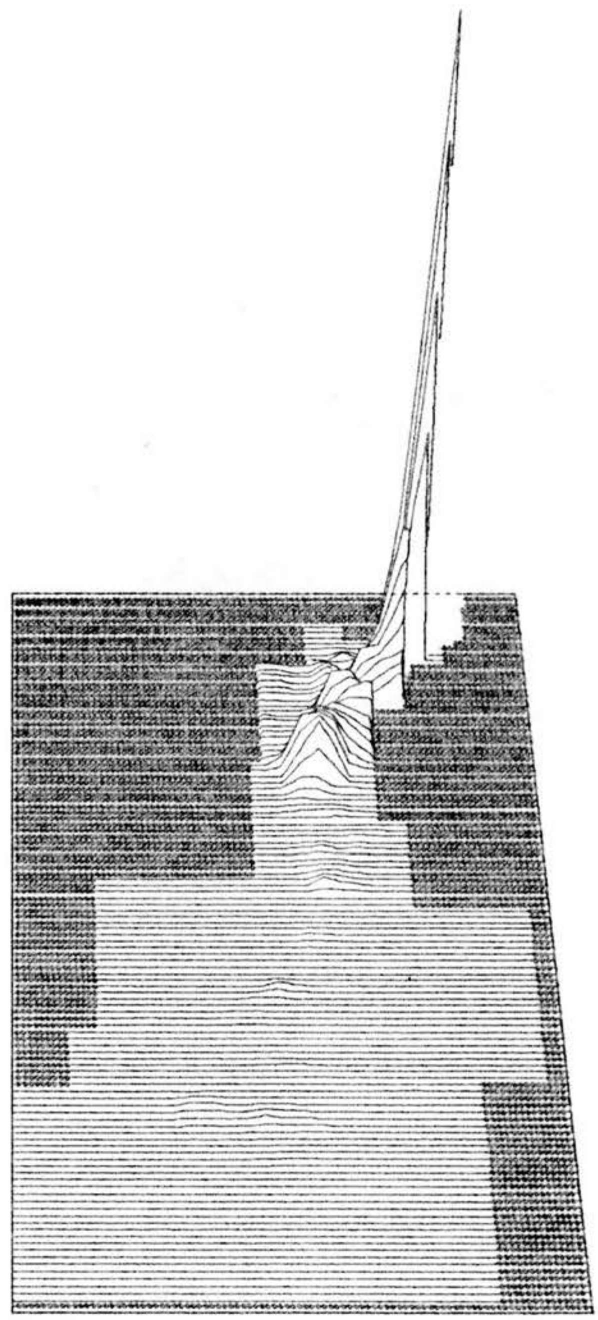


Figure 5.13

SYMVU of porphyritic (E_A) values viewed from the east-north-east.

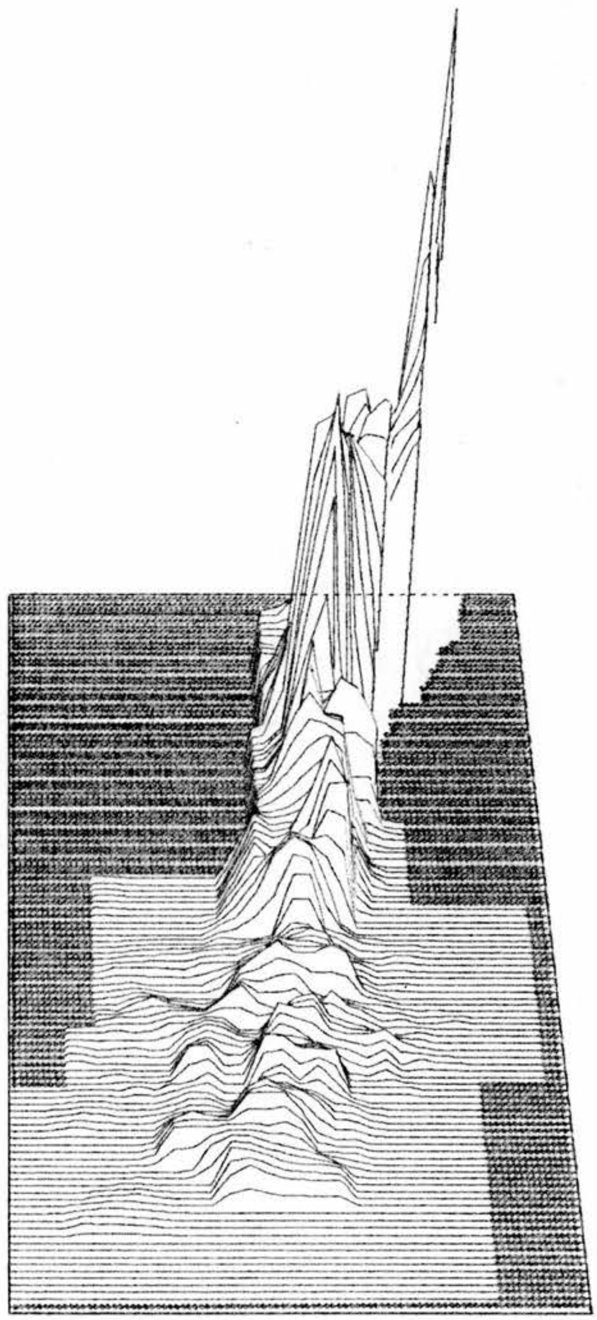


Figure 5.14

SYMVU of non-porphyritic + porphyritic (E_N) values viewed from the east-north-east.

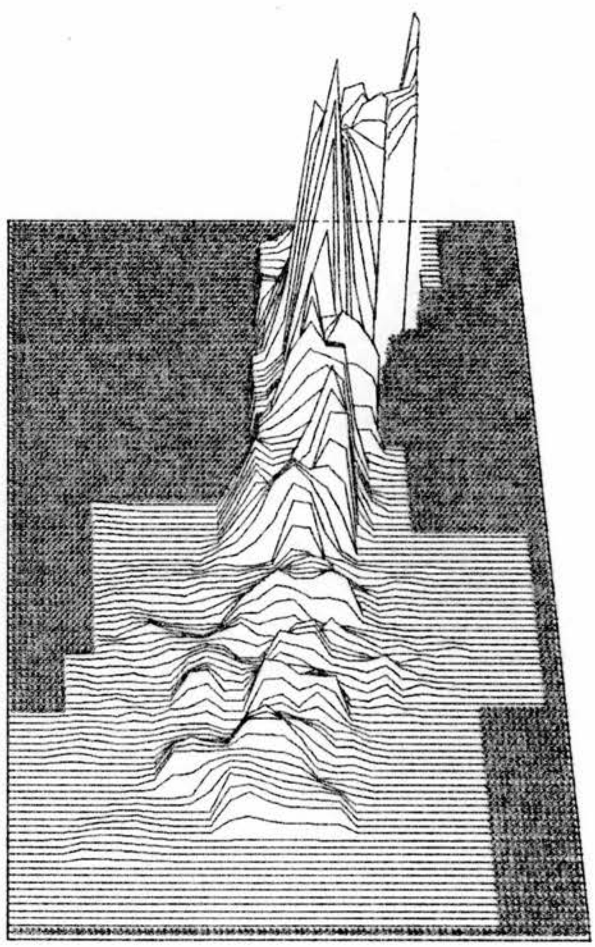


Figure 5.15

SYMVU of non-porphyritic (E_N) values viewed from the east-north-east.

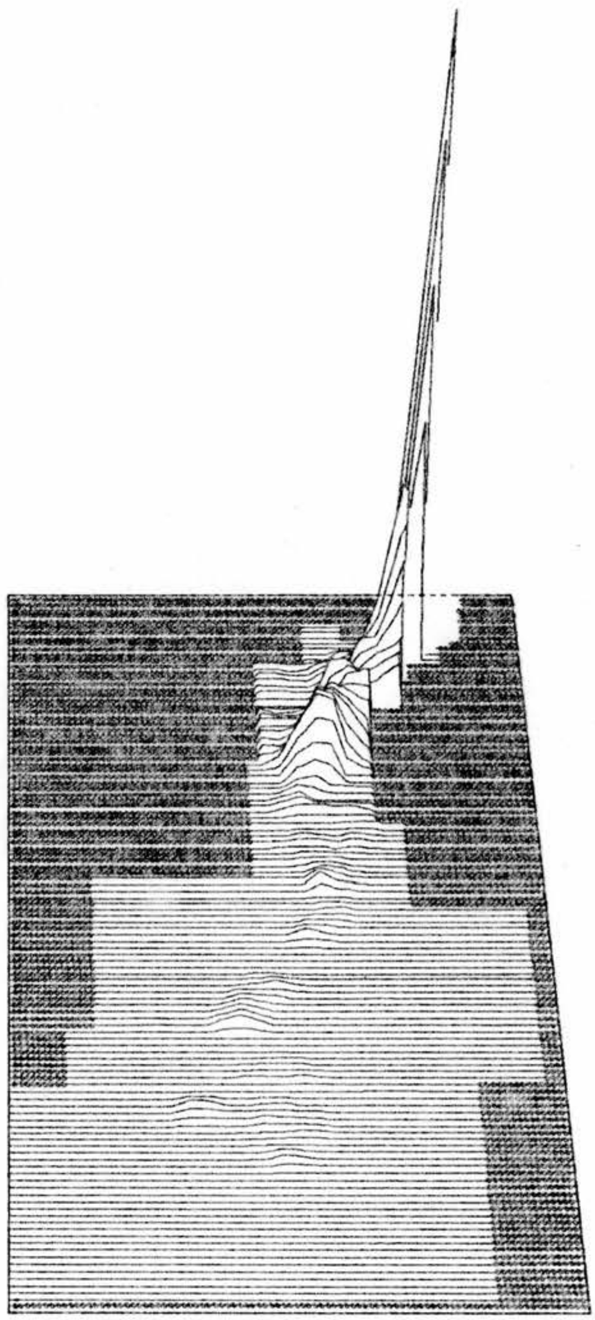


Figure 5.16

SYMVU of porphyritic (E_N) values viewed from the east-north-east.

Figure 5.17

SYMVU of non-porphyritic + porphyritic (E_A) values viewed from the south-south-east.

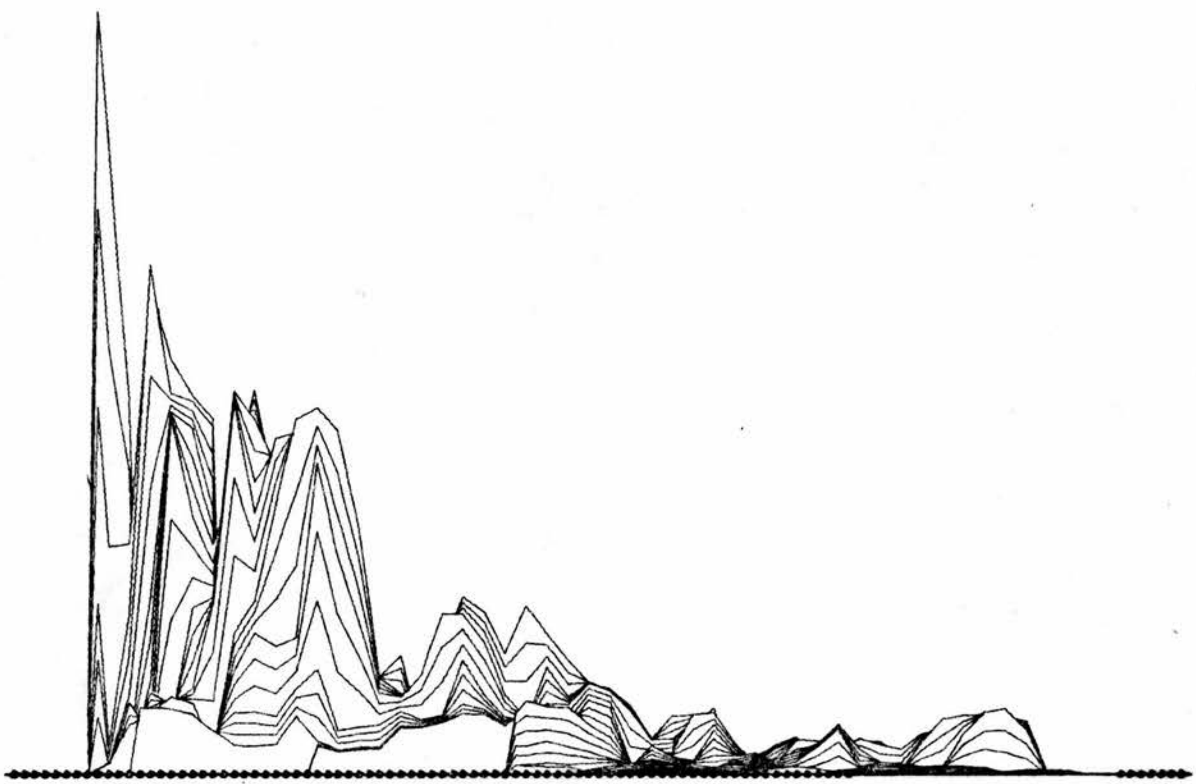


Figure 5.18

SYMVU of non-porphyritic (E_A) values viewed from the south-south-east.

Figure 5.19

SYMVU of porphyritic (E_4) values viewed from the south-south-east.

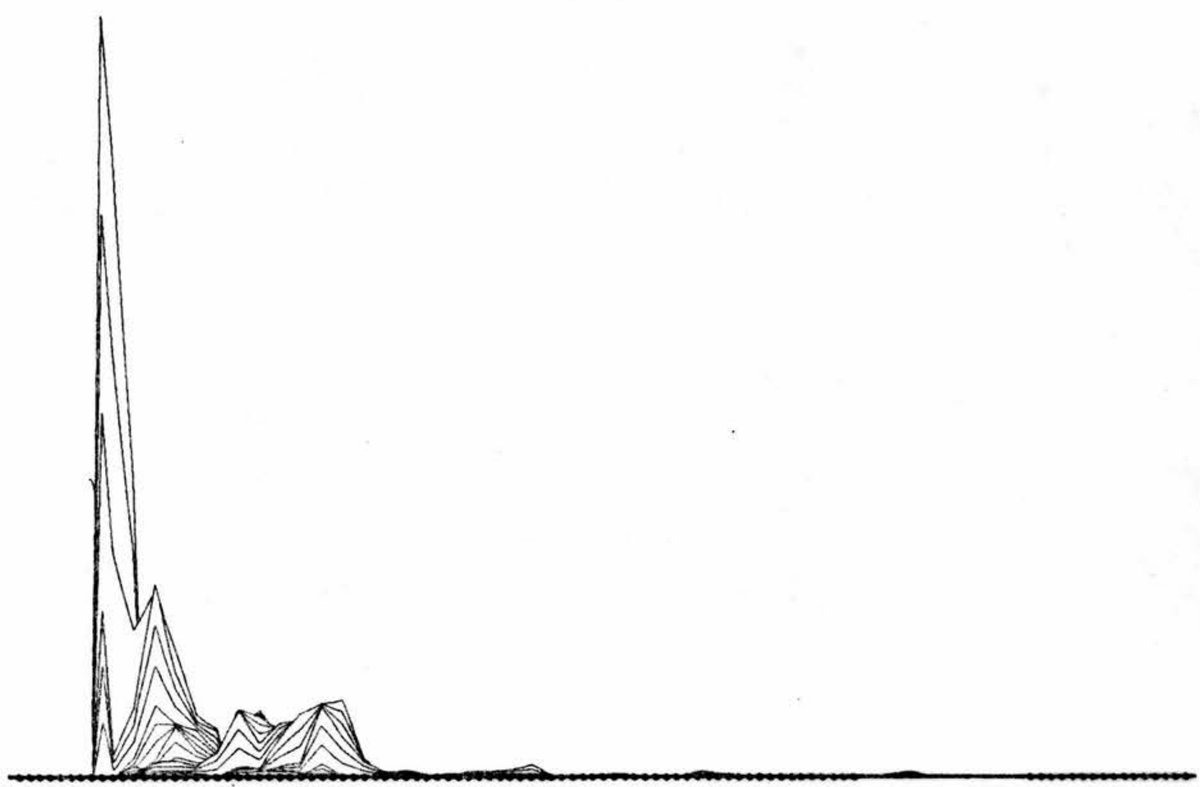


Figure 5.20

SYMVU of non-porphyritic + porphyritic (E_N) values viewed from the south-south-east.

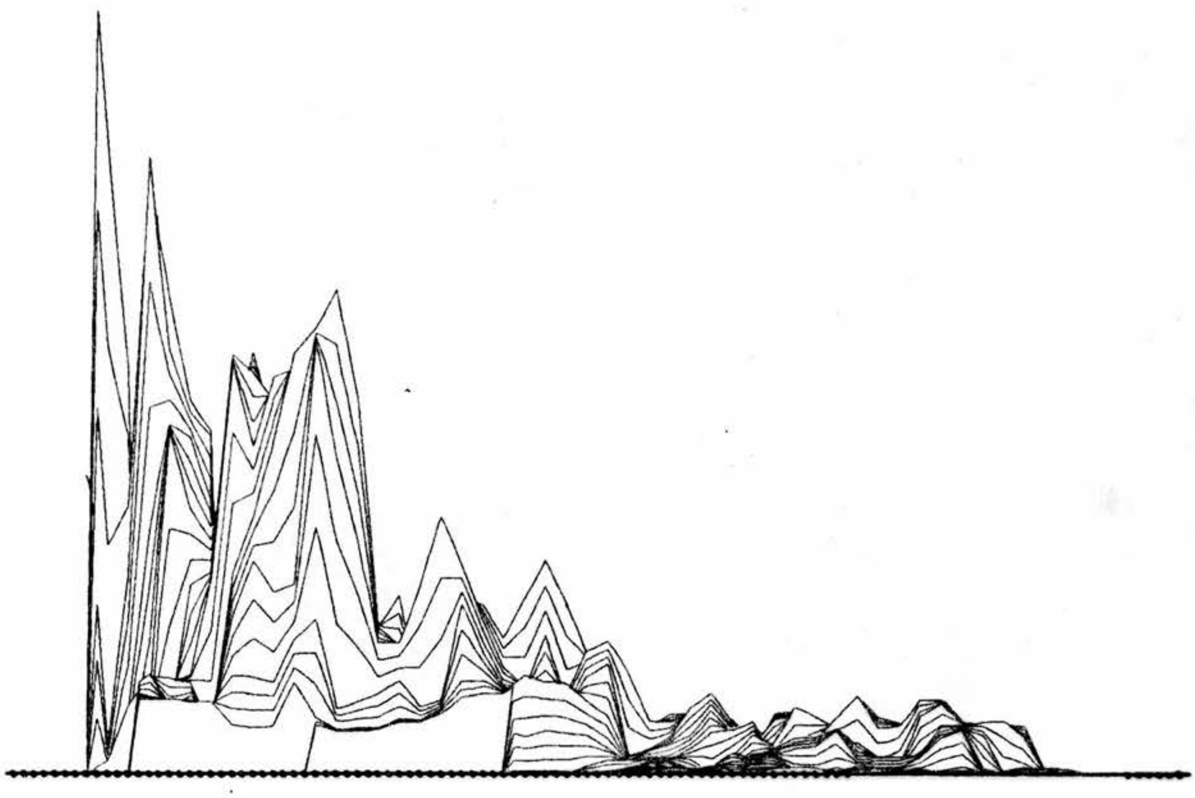


Figure 5.21

SYMVU of non-porphyritic ($\bar{E}_N$) values viewed from the south-south-east.

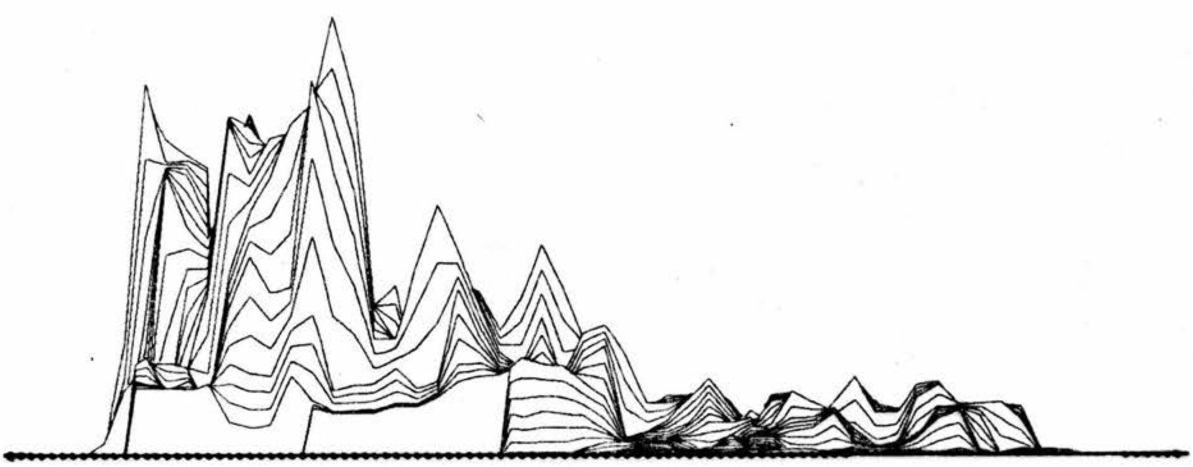
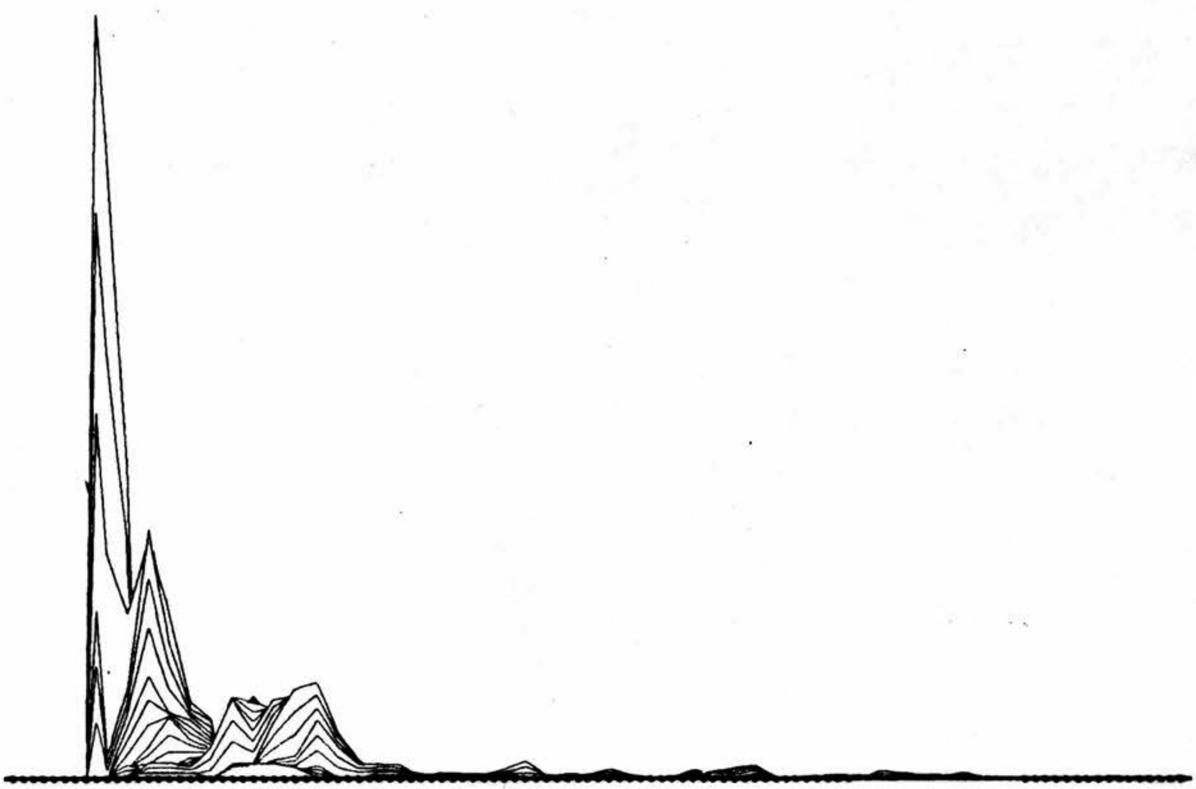


Figure 5.22

SYMVU of porphyritic (E_N) values viewed from the south-south-east.



to mean values, since the latter would vary not only with the distance from the source but also according to the number of low data point values in the peripheral areas of the train. The values chosen therefore effectively represent the decay along the central axis of the train.

Linear regressions of E_N and $\log_e E_N$ on distance from the source were carried out for both porphyritic and non-porphyritic essexite types. Natural logarithms, with a base of 2.7182, were chosen rather than common logarithms so that the results are directly comparable with those of Krumbein(1937) and Gillberg(1965,1967,1968a). Correlation coefficients were -0.78 (significant at above the 99% level) for the transformed values of porphyritic stones and -0.75 (significant at above the 99% level) for the transformed values of non-porphyritic stones. These results in both cases gave higher correlation coefficients than for the linear regression of the untransformed data values against distance, although for the non-porphyritic variety this difference was slight.

Krumbein(1937) expressed the negative exponential function as

$$y = mb^{-ax}$$

where m is the value of y when x=0, b is the base of the exponential function and a is a constant. The equations of this form that were fitted to the data by linear regression are shown in Figs 5.23 and 5.24 beside the curve they represent.

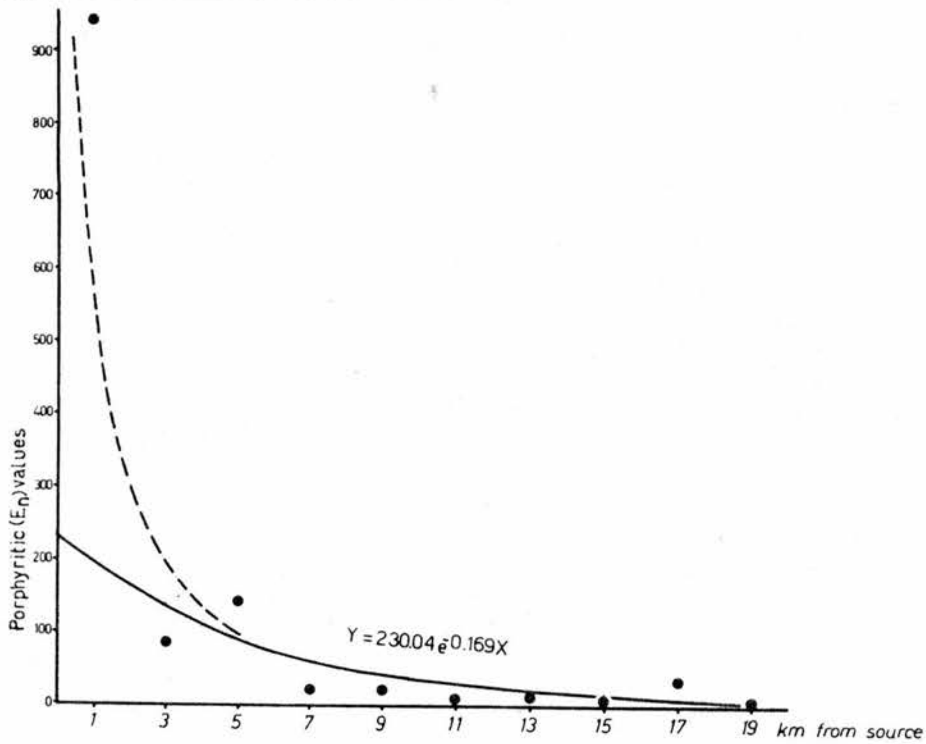
The constant a determines the decline of the function. Krumbein(1937) referred to this term as the "coefficient of boulder concentration". Gillberg(1965) considered that a whole group of factors such as topography, nature of the erratic material and glacial processes affected this term. These factors are almost identical to those suggested by Anderson(1955,1957) when discussing the dispersion of rock types in till, although he also included the nature of the source outcrop and a factor he called dilution.

The value of a that Krumbein(1937) determined for the Mount Ascutney boulder train falls between the values of a for porphyritic and non-porphyritic essexite stones. Gillberg(1965) calculated a number of exponential functions for size grades of various rock types in southern Sweden, using at least two curves with different values of a to describe the decayof size grades of each rock type. He found that 0.060 was a common value for a. The value of 0.0745 for non-porphyritic essexite stones is a close approximation to this figure.

It can be seen from Figs 5.23 and 5.24 that the data values in many cases do not lie near to the exponential curve in contrast to the close correspondence Krumbein(1937) calculated between the points and the fitted curve(Fig.2.1a), and a similar relationship in many diagrams given by Gillberg(1965,1967). In the case of the curve for porphyritic essexite the dotted line drawn in by eye would appear to represent the decline of the stones better than the calculated exponential curve. The decline of non-porphyritic stones(Fig.5.24) seems to be as likely as not linear as curvilinear, though as has already been pointed out, the linear regression gave a marginally lower correlation coefficient for the untransformed compared to the transformed data. If it had been possible to obtain an E_N value for non-porphyritic essexite stones closer to the outcrop, as was derived for porphyritic stones, the nearest data value to the source might well have been considerably higher.

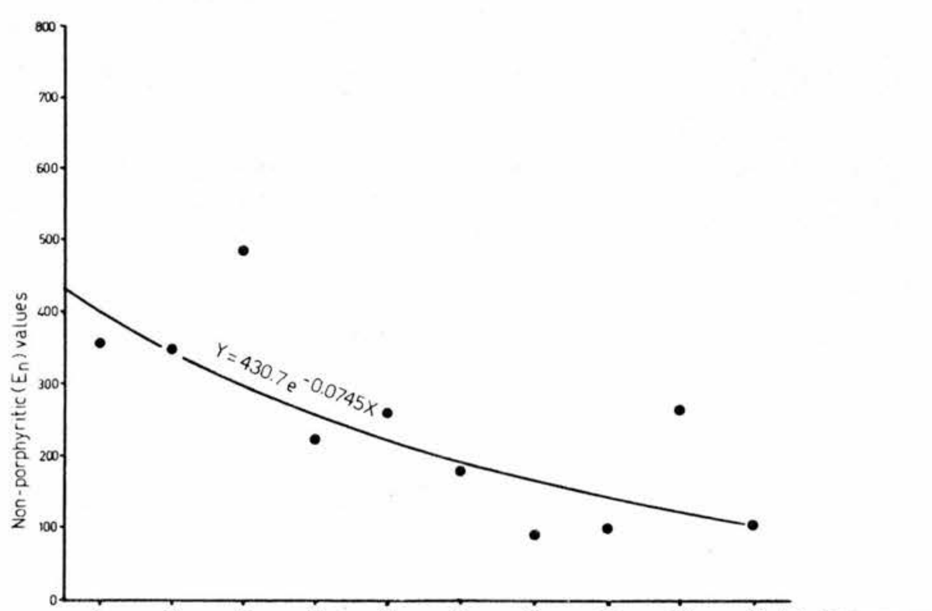
It seems therefore that the calculation of the exponential functions offers little extra in terms of an aid to interpretation of the rates of essexite dispersion than the SYMVU drawings (Figs 5.17 - 5.22) and in the case of non-porphyritic essexite E_N values, the curve is a poor approximation of the data. The calculation of further data points, which would have helped to define a more representative curve, was not viable since intervals between data points of less than 2km would have given rise to E_N values corresponding to the peripheral areas of the train rather than the major axis, as is the case with points in Figs 5.23 and 5.24.

Apart from the few essexite fragments that had been broken during construction of the walls, fieldwork indicated that the size of non-porphyritic essexite stones in the walls decreased with distance from the source. Shaler(1893) found that ore fragments forming the Iron Hill boulder train decreased from an average diameter of 95cm and a maximum of 170cm at the source to an average of 17cm and a maximum of 32cm at a distance of 22km. Drake(1972) observed that the b-axis length of



<u>Figure 5.23</u>

Distance decay plot of porphyritic (E_N) values.



<u>Figure 5.24</u>

Distance decay plot of non-porphyritic (E_N) values.

subglacial till pebbles of 29 lithologies diminished with distance from the source. Both these workers attributed the decrease in size to comminution as a result of crushing by glacier ice.

In order to determine whether non-porphyritic stones diminished in size away from the outcrop, the erratics train was divided into 2km radial bands as for the calculation of data values for the negative exponential curve. The (d x e) value for each non-porphyritic stone was allotted to one of the ten bands according to its distance from the outcrop. The stones are not always placed in the same position in the wall with respect to their long, intermediate and short axes. However, there seems little reason to suppose that there is any systematic change in the orientation of stones within the walls over the Main Study Area. Thus the (d x e) value can be regarded as an index of stone size.

The smallest number of (d x e) values occurred in the most distant 2km band from the outcrop (18 to 20km) where only 58 non-porphyritic wall stones were recorded. To obviate the possibility of varying sample sizes affecting the results, 58 randomly-picked (d x e) values were derived for the remaining nine bands. Inspection of the data indicated that each group of 58 stones had a positively-skewed distribution. Therefore prior to testing for a linear relationship between size and distance from the source, each (d x e) value was transformed by obtaining the square root in order to approximate each of the ten groups to a normal distribution (Poole & O'Farrell, 1971; Till,1973). A linear regression of mean (d x e) values in each group on distance from the source was carried out. A correlation coefficient of -0.78 was obtained which was significant at above the 99% level. The slope of the best-fit line (Fig.5.25) indicates that the mean (d x e) value declines with distance from the source. Calculated best-fit lines for the regression of distance on the mean values of the ten highest and five highest of the random samples, and of the entire samples in each 2km band indicated a similar trend. This result suggests that the non-porphyritic stones underwent comminution during glacial transport.

A decrease was also found in the size of porphyritic stones recorded in the walls with distance from the source. However the small size of the sample (446) and uneven distribution over 20km meant that the division of the stone sample into 2km radial bands was not feasible. Instead the data were divided into stones found within 6km and those found beyond this distance from the outcrop. The percentage frequency histograms of the two samples are shown in Fig.5.26. The percentage number of stones ($< 300 cm^2$) almost doubles beyond 6km from the source. Using a Kolmorogov-Smirnoff two-sample test the difference between the two distributions was found to be significant in the two-tailed test at above the 99% level (Siegel, 1956). This result corroborates the evidence of the decrease in size of non-porphyritic essexite stones in indicating that the porphyritic stones have also undergone

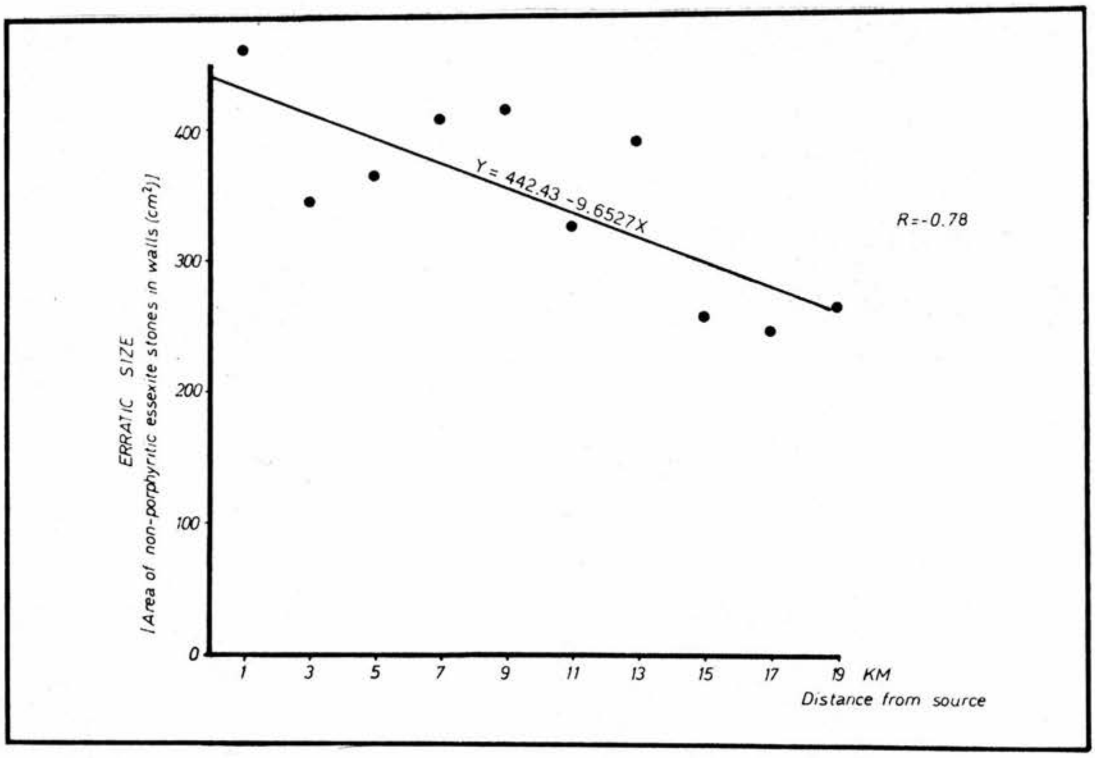


Figure 5.25

Decrease in size of non-porphyritic erratics with distance from the source.

comminution as a result of glacial processes during transportation.

To determine whether, as a result of crushing, the essexite stones also became less asymmetrical with distance from the source a simple index of elongation of wall stones was derived. This index is expressed as d/e and was calculated for the 58 randomly-picked non-porphyritic stones in each of the ten 2km radial bands. Mean values for each band were derived and a regression of elongation on distance was carried out. A statistically significant correlation coefficient was not found. The lack of any trend can be explained in terms of the nature of the index, which represents a three-dimensional form in two dimensions only. Whereas with the size index the position of the stone was not important, with the elongation index this factor would be crucial. The resulting loss of information would have caused the index to be too crude to indicate any underlying trend in changing shape with distance from the source.

Further evidence of the crushing of non-porphyritic stones, however, is given by other measurements made on joint-controlled stones in the walls. After some experience of "wall-mapping" it was noted that many non-porphyritic stones were placed in the walls such that two parallel, joint-controlled faces were presented. It was decided that the perpendicular distance between such faces should be recorded along with the d and e values already described. In all, 325 joint values were measured to the nearest 1cm. The erratics train was divided in two along a line approximately 12km from the source, giving rise to 200 measurements within 12km from the outcrop and 125 beyond this distance. The two percentage frequency histograms are shown in Fig.5.27. A Kolmorogov-Smirnoff two-tailed test was applied to the two distributions and the difference between them was found to be statistically significant at above the 99.9% level, indicating that the joints measured near the source tended to be farther apart than those measured beyond 12km. These results suggest that crushing was concentrated on the smaller joint-controlled blocks during glacial transport. It can be argued therefore that these smaller stones were less able to withstand the forces acting on them than the larger joint-controlled stones which became proportionally larger in number with the greater distance travelled.

Trend surface analysis of the data from the dry stone walls

Trend surface analysis was developed during the late 1950's and early 1960's in the fields of geology and geophysics (Krumbein,1959; Krumbein & Graybill,1965). In geography it has been increasingly used since that time due to its relevance to the examination of spatial trends in phenomena (e.g. Chorley & Haggett,1965; Marcus & Vandermeer,1966; King,1967,1969; Vincent,1969; Beaumont,1971; Unwin & Lewin,1971; Unwin & Hepple,1975). It is "a procedure for separating... large-scale systematic changes in mapped data from the non-systematic, small-scale variation attributable to local effects" (Gittins,1968,

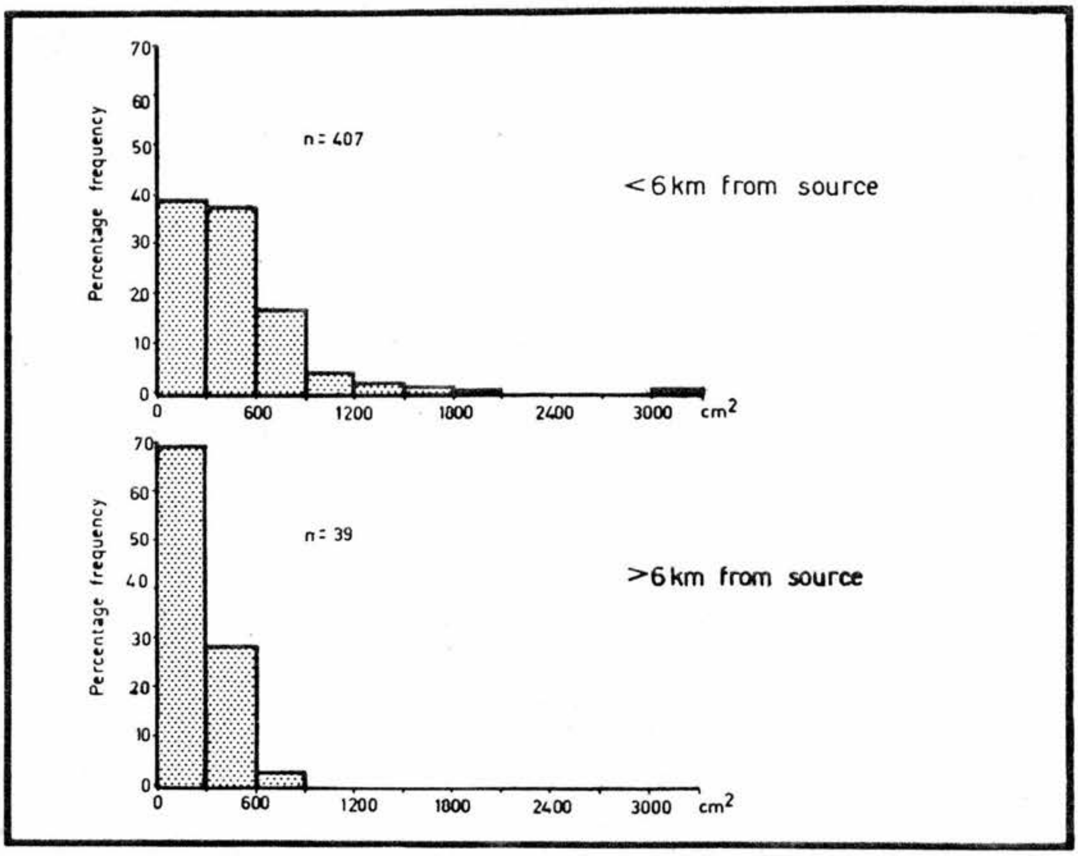


Figure 5.26

Histograms showing decrease in the size of porphyritic essexite erratics with distance from the source.

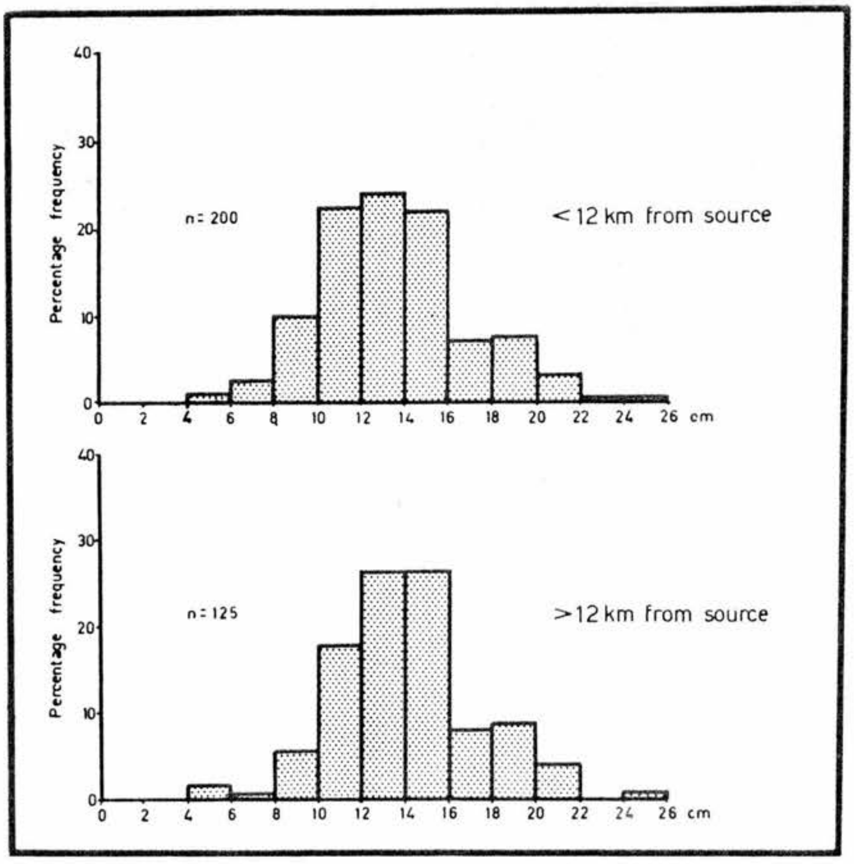


Figure 5.27

Histograms showing decrease in the distance between parallel joints of non-porphyritic erratics with distance from source.

p.845). Whereas in simple isarithmic mapping (e.g. SYMAP contour maps) each control point only contributes information for an area immediately adjacent to it, in a trend surface local values are damped down and "sacrificed" to the overall trend (Chorley & Haggett, 1965). King(1967) gives four uses of trend surface analysis; as a descriptive tool, for testing a conceptual model, as a means of predicting and as a search procedure for unsuspected aspects of the data.

The basic aim is to fit surfaces of increasing complexity to sets of points in three dimensions. Each data point is defined by two spatial co-ordinates (U,V) and a value (z) of the mapped variable. If a trend varies smoothly over space its value (i.e. height) at any particular point can be expressed in terms of U and V. The simplest surface that is fitted to the data is an inclined plane. This linear trend surface is fitted by minimising the sum of the squared differences between the data point values (z) and the surface in an analogous manner to fitting a regression line in two dimensions (Baird _et al_., 1971). The general form of the linear or first order trend surface is given by

$$z = a + bU + cV$$

where U and V are co-ordinates defining z and a, b and c are polynomial coefficients. The direction of the trend can be calculated from the expression

$$\cos \theta = \frac{b}{\sqrt{b^2 + c^2}}$$

where θ is the angle between the azimuth of the trend and the co-ordinate axis associated with b.

More complex surfaces of greater flexibility can be fitted by least squares method to the data set and they require further coefficients. The quadratic or second order trend surface assumes four basic shapes; a dome, a saddle, a ridge and a tongue (Chorley & Haggett, 1965). It is described by an additional three coefficients in the form

$$z = a + bU + cV + dU^2 + eUV + fV^2$$

The cubic or third order trend surface is even more complex and is expressed by ten coefficients

$$z = a + bU + cV + dU^2 + eUV + fV^2 + gU^3 + hU^2V + iUV^2 + jV^3$$

Surfaces up to the octic have been used (Bassett & Chorley,1971), but generally surfaces of higher order than cubic are regarded as of little value since they defeat the object, which is, to reduce complex reality to its more simplified, basic components for easier analysis (Vincent,1969).

The first, second and third order trend surfaces for the E_A and E_N values of non-porphyritic plus porphyritic, porphyritic and non-porphyritic stones are shown in Figs 5.28, 5.29 and 5.30 respectively. A subroutine of the Choropleth Mapping System developed by T.C. Waugh at the Edinburgh Regional Computing Centre was used to produce the trend surface maps (Waugh,1972).

The goodness of fit of a trend surface can be determined using the statistic of the percentage reduction in the sum of squares (%RSS) achieved. This is expressed as the percentage ratio of the corrected sum of squares of the computed trend values to the corrected sum of squares of the observations (Krumbein & Graybill, 1965; Unwin,1975). The %RSS for the eighteen trend surfaces produced from the wall data are shown in Table 5.1. To determine whether the fit is merely a chance phenomenon or a significant result indicating a real spatial trend, a test based on F-ratios can be used. The significance levels shown in Table 5.1 were obtained from a table by Norcliffe(1969) in which the minimum %RSS required for surfaces based on up to 500 data points to be regarded as significant at the 95% and 99% level is given.

It can be seen that all the trend surfaces are significant at above the 99% level. Tinkler(1969), however, has pointed out that a large number of data points, such as were used in the present analysis, more or less guarentees a statistically significant surface. This statistic should therefore not be regarded as of great analytical value in the present circumstances, the %RSS being of greater diagnostic value in deciding the goodness of fit.

From previous work on erratics trains and from the SYMVU line drawings depicting the essexite erratics train, the most likely surface to approximate to the data would appear to be the quadratic "tongue-shaped" pattern. Table 5.1, however, indicates that the %RSS attributable to the quadratic component of the second order trend surface is in all cases lower than the %RSS attributable to the linear component and only exceeds the cubic component in the case of the non-porphyritic (E_N) and porphyritic plus non-porphyritic (E_N) surfaces.

<u>Table 5.1</u> <u>%RSS and explanation level for the trend surfaces of the wall data</u>

	LINEAR		PURE QUAD.	LINEAR + QUADR'TIC		PURE CUBIC	LINEAR + QUADR'TIC + CUBIC	
Type	%RSS	Explan. level	%RSS	%RSS	Explan. level	%RSS	%RSS	Explan. level
P(E_A)	3.97	0.01	2.35	6.32	0.01	0.96	7.28	0.01
P(E_N)	4.99	0.01	2.61	7.60	0.01	1.00	8.60	0.01
N(E_A)	17.42	0.01	8.26	25.68	0.01	9.50	35.18	0.01
N(E_N)	17.21	0.01	11.26	28.47	0.01	9.63	38.10	0.01
N + P (E_A)	16.27	0.01	4.72	20.99	0.01	4.91	25.90	0.01
N + P (E_N)	17.85	0.01	6.51	24.36	0.01	6.00	30.36	0.01

P = Porphyritic   N = Non-porphyritic

The tongue form nevertheless underlies the pattern shown in all the second order trend surfaces (Figs 5.28, 5.29 & 5.30). The low %RSS explanation can in part be attributed to the inclusion of nil data point values immediately west and north-west of the essexite outcrops contrasting with the high values immediately east of the outcrops. The cubic surfaces in all cases possess a downward gradient west of the outcrops and a complex tongue

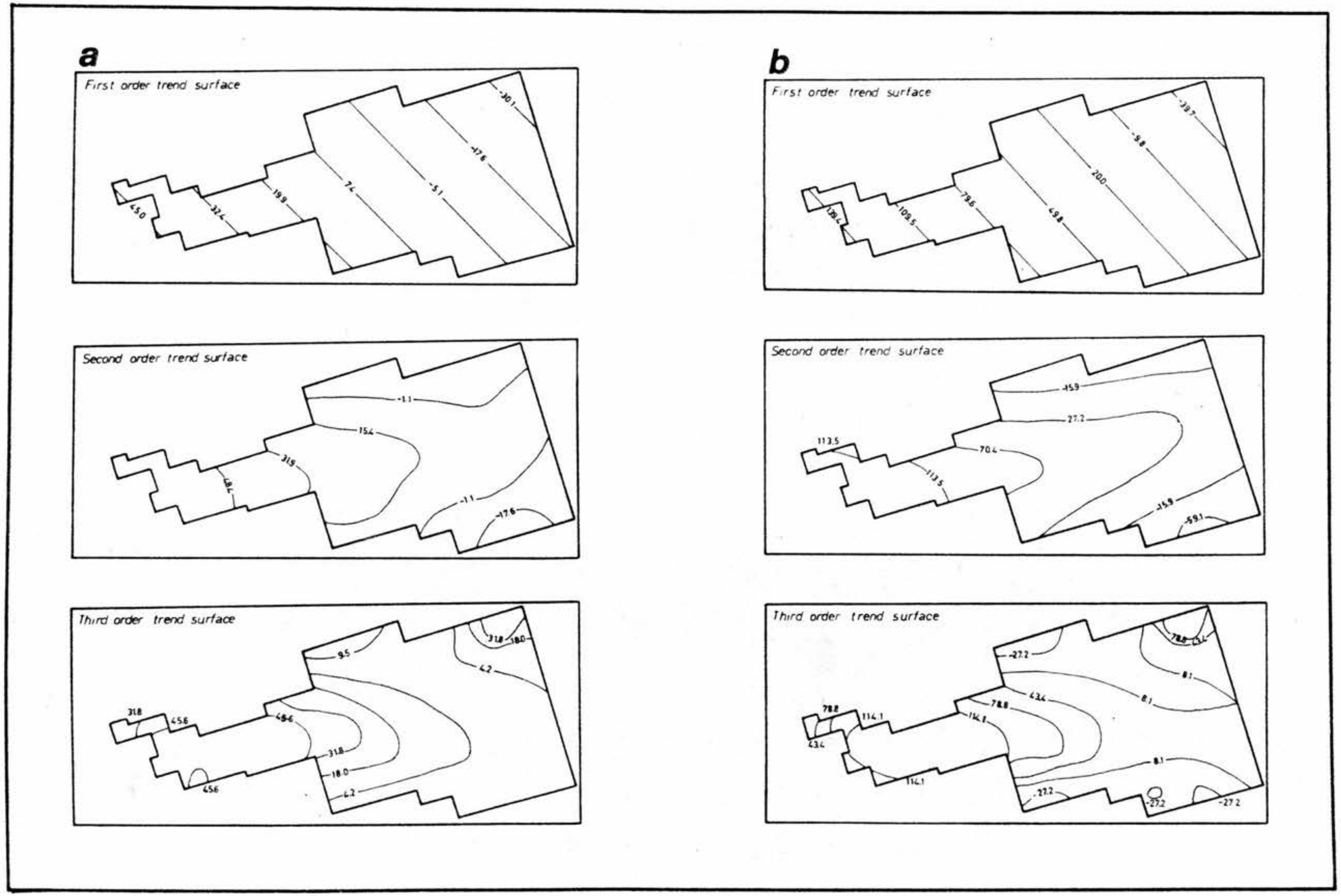


Figure 5.28

Trend surfaces of non-porphyritic + porphyritic a) E_A and b) E_N values.

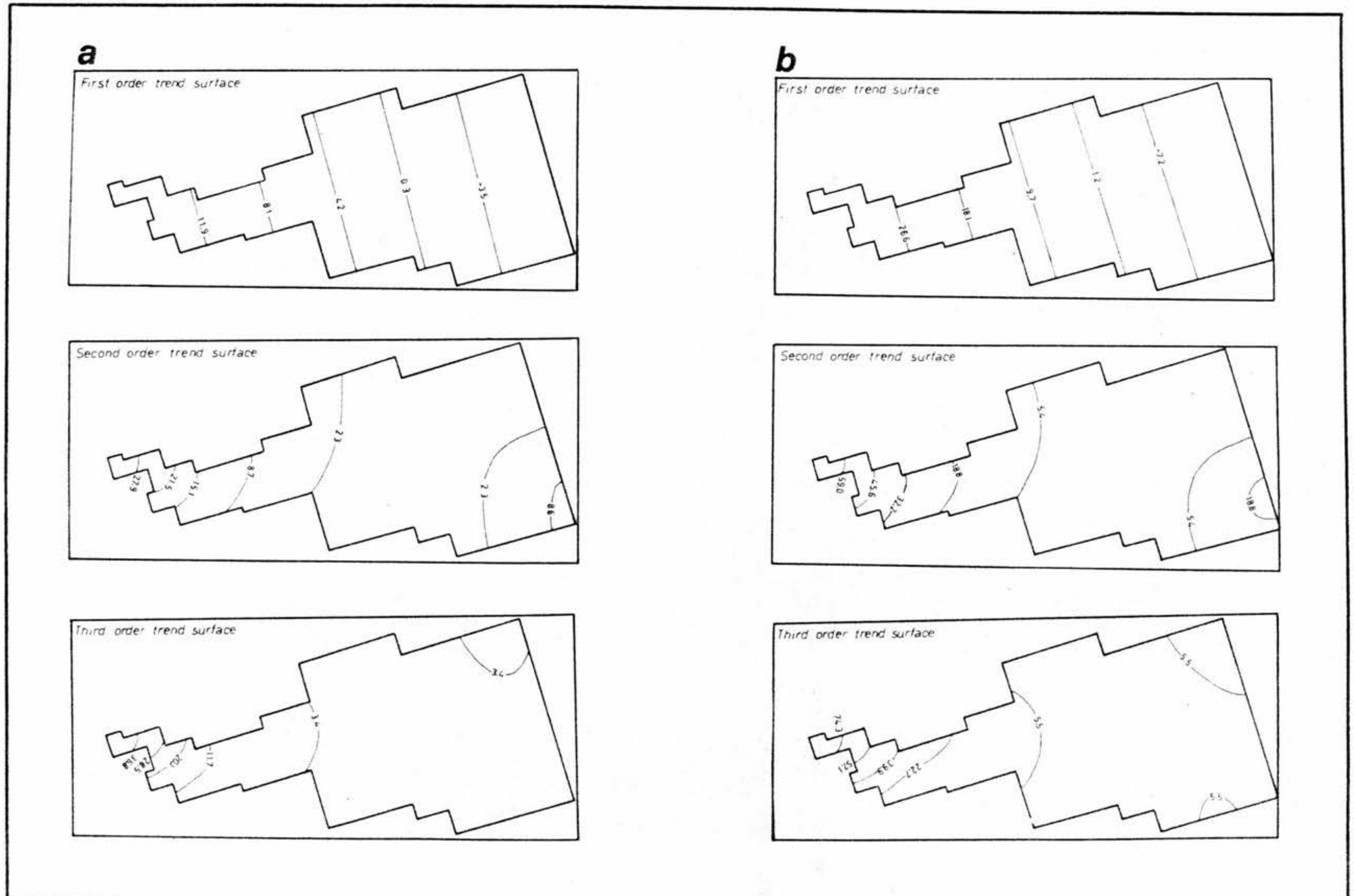
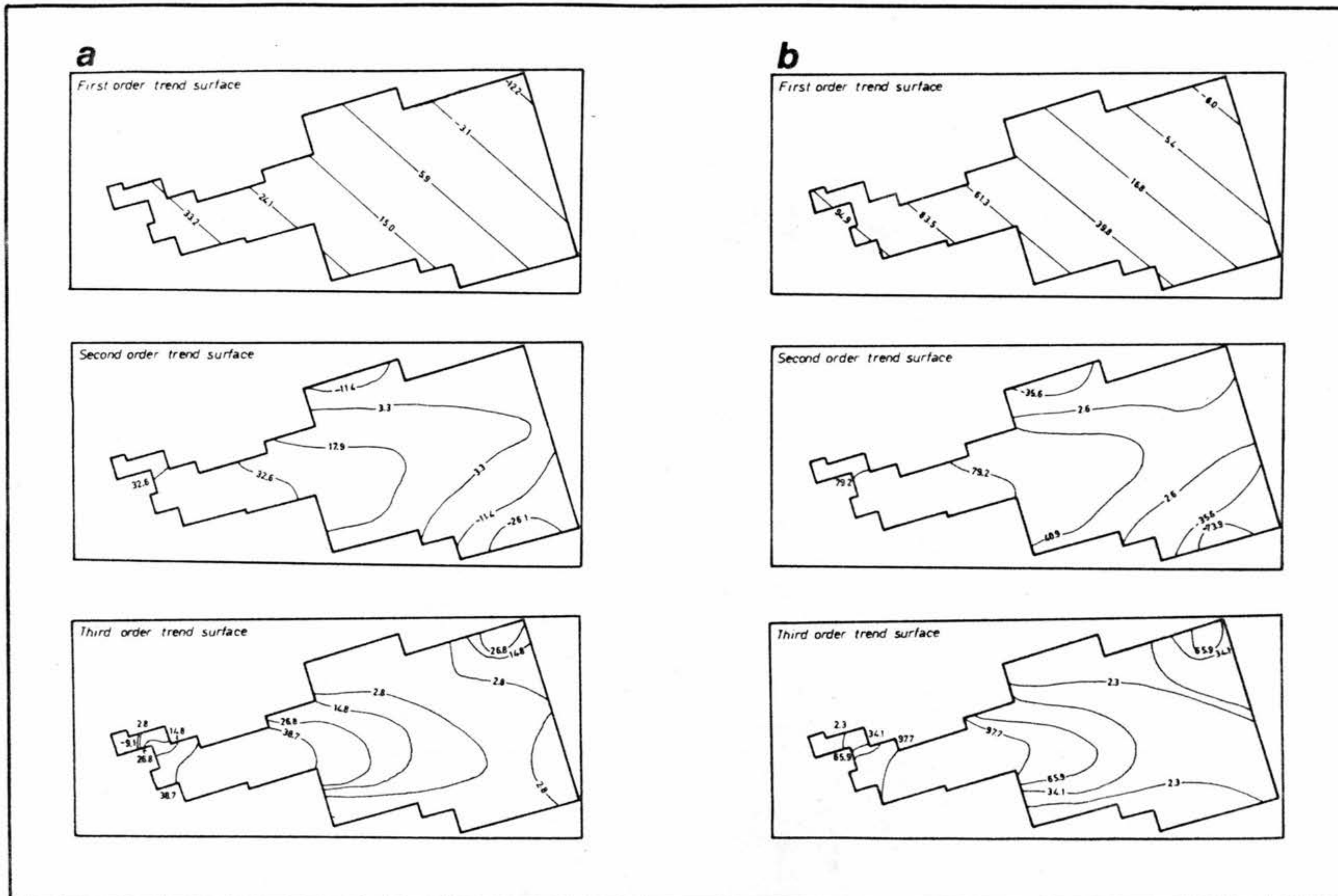


Figure 5.29

Trend surfaces of porphyritic a) E_A and b) E_N values.



<u>Figure 5.30</u>

Trend surfaces of non-porphyritic a) E_A and b) E_N values.

form to the east and north-east of Kilsyth.

Despite the fact that the first order trend surface records the highest %RSS of all three trend surface components, it does not seem to be the most appropriate model describing the porphyritic and non-porphyritic data values on theoretical and observational grounds. Although the major trend of the values is a decline from west-south-west to east-north-east, which all the trend surfaces reflect, there is also a regional downward gradient to the north and south of the major axis, which the linear surfaces cannot portray. Only the linear trend surfaces of the porphyritic (E_A & E_N) data values show the major west-south-west to east-north-east alignment, the remaining linear trend surfaces recording a south-west to north-east alignment.

These differences do not reflect different directions of transport for porphyritic and non-porphyritic essexite stones but are a function of the manner in which the trend surfaces have been derived. Ideally data points for trend surface analysis should be evenly distributed (Merriam & Harbaugh,1964; Unwin & Hepple,1975). In practice, however, this is rarely possible in the sampling of spatial phenomena (Krumbein & Graybill,1965). The result of uneven representation of data is to give undue influence to areas containing many points relative to areas in which points are far apart. Some workers have attempted to lessen the effect of clustered data points by using geographic-mean samples (e.g. Robinson,1972; Gray,1972).

The distribution of data points shown in Fig.5.1 was analysed as regards its degree of aggregation. A nearest neighbour statistic developed by Clark and Evans (1954) was used. This takes the form

$$R_n = \bar{D}obs/\{0.5(A/N)^{-\frac{1}{2}}\}$$

where $\bar{D}obs$ is the observed mean distance between points and their nearest neighbour, A is the area and N is the number of points. A value of 0 for R_n indicates all points at the same location, a value of 1 represents a random distribution of points and 2.15 denotes a hexagonal pattern of points which gives rise to the most even distribution possible (Haggett,1965). The degree of aggregation was 0,51 for the area of the smallest rectangle enclosing the SYMAP border. The data points are therefore aggregated, both R_n values being on the clustered side of a random distribution.

The aggregation of low value data points to the north compared to the scarcity of such points to the south of the major axis may well have had a controlling effect particularly on the linear trend surfaces of the non-porphyritic (E_A & E_N) and non-porphyritic plus porphyritic (E_A & E_N) data sets. As has already been noted these surfaces trend south-west to north-east and this is attributed to the uneven distribution of data points. The porphyritic (E_A & E_N) linear trend surfaces on the other hand show a west-south-west to east-north-east trend which reflects the lack of a major axis beyond c.6km east of the source, leaving therefore a contrast in values in this direction only.

The paucity of data points in the north-eastern corner of the area enclosed in the SYMAP border has given rise to a spurious dome in the cubic trend surfaces in this region. This dome can therefore be disregarded in interpreting these diagrams as it clearly does not relate to the original data.

Another effect of the distribution of the data points lies in the shape of the boundary surrounding them, in this case the SYMAP border. Elongated areas tend to produce contours on higher order surfaces that are aligned parallel to the longer side (Unwin,1975). The tongue-shaped contour pattern on the second order and third order trend surfaces may therefore be a function in part of the elongated shape of the analysed area.

In the case of a narrow erratics train the usefulness of trend surface analysis seems questionable. The shape of the analysed area and the inevitable aggregation of the data points introduce a number of undesirable effects. The contrast in values up-ice and down-ice of the outcrops reduces the %RSS due to the extreme values. High value areas appear in the higher order surfaces that do not reflect the original data. Agterberg(1964) considered that beyond 500 data points matrix smoothing methods are to be preferred to the power series trend surface model. In the present analysis this number of data points was almost attained. Since the interest lies in the local components rather than the overall trend, which is clear in any case, the SYMAP interpolation method is regarded as of far greater value than the trend surface technique in analysing the wall stone data.

CHAPTER 6

SIZE AND MORPHOMETRIC PROPERTIES OF ESSEXITE STONES

> "SPHERICAL AND ROUND- Also note that there is a difference between 'spherical' and 'round', since anything spherical is round and not *vice versa*; for something may be round like an egg, yet it is not spherical unless it is completely so." (Robertus Anglicus,1271; quoted by Krynine,1956,p.1661)

In chapter 4, values for roundness, sphericity and Zingg shape were derived for erratics from the distinct outcrop of Dalmahoy Hill at different distances down-ice from their source. Elongate particles were shown to decrease proportionally in numbers compared to less easily crushed shapes, but sphericity and roundness showed no specific trends. This was attributed to the short distance over which the train of erratics was traced. Initial fieldwork carried out in the area down-ice of the Lennoxtown essexite outcrops revealed that glacially and fluvioglacially transported essexite stones were sufficiently plentiful in dry stone walls and exposed sections to allow an investigation of their size and morphometric properties to be undertaken. Inspection of the modern beaches along the Firth of Forth indicated that essexite stones were also abundant on the foreshore.

From the literature, the most important factors affecting particle morphometry are as follows. Firstly, the shape of the particle on leaving its source has a significant bearing on its shape at the point of deposition (Tester,1931; Pettijohn,1957; Blatt,1959; Drake,1970). Secondly, the lithological characteristics of the rock are important in determining the susceptibility of a particle to processes such as abrasion and crushing (Pettijohn, 1957). Thirdly, the size of a particle at all stages during its transport is important in that particles of different sizes respond in different ways to processes acting in the same environment. This has been noted by Sorby(1880), Zingg(1935), Russell and Taylor(1937), Plumley (1948) and Pettijohn(1957) amongst others. Fourthly, the nature of the transporting medium is important in determining particle morphometry. Von Engeln(1930) and Wentworth(1936) considered that glacially transported particles had a characteristic shape. Waskom(1958), Sames(1966), King and Buckley(1968), Bergesen(1973) and Gregory and Cullingford(1974) considered that particles in different transporting modes had definable morphometric characteristics. Fifthly, the distance of transport and the effectiveness and duration of processes acting in the transporting mode affect the ultimate particle shape. Sixthly and finally, there are chance factors that can influence the shape of particles such as chipping against obstacles.

In order, as in the present analysis, to investigate the differences in size and morphometry of particles in relation to the nature of the transporting medium and the distance of travel, the other factors (except chance) should be controlled. In many studies where these relationships have been investigated however, little attention has been paid particularly to the influence of initial shape and lithology. For instance, Drake(1972) used particles from 29 lithologies to draw general conclusions about mechanisms of particle attrition in a subglacial environment, although he conceded that ideally "studies should be carried out separately for each lithology" (Drake,1972,p.2164).

In the present analysis these factors have been controlled so that variation in particle morphometry and size could be studied within and between the glacial, fluvioglacial and beach environments. Subdivision of essexite stones into porphyritic and non-porphyritic types meant that the factors of initial shape and lithology could be controlled. As regards the factor of size, although no restrictions were placed on the size of essexite stones to be measured in the field, the stones were subsequently divided into size grades for comparison of their morphometric properties.

Field methodology

The majority of techniques for measuring morphometric parameters on particles were developed with a view to investigating fluvial or marine deposits. Consequently, they were designed to deal with particles ranging from sand to cobble sizes. A large number of essexite stones in fluvioglacial deposits and on the modern beaches fall within this size range but many glacially transported stones are more than 100cm in length

(Plate 4). Thus it was clear that either modifications to existing methods would have to be made or new techniques devised to cope with the large range of particle sizes. The first alternative was considered preferable since the use of pre-existing techniques would mean that comparison could be made with results from similar studies.

For the measurement of shape it was proposed that the method of Krumbein(1941a), already outlined in chapter 4, should be used, in which the long(a), intermediate(b) and short(c) axes are measured. Although other methods of deriving particle shape have been proposed (e.g. Rittenhouse,1943; Williams,1965; Ehrlich & Weinberg,1970), they have never received the wide acceptance that Krumbein's method has. The usual procedure for measuring particles involves laying a transparent rule over the particle and reading off the length by eye, and this is claimed to be tolerably accurate despite the problems associated with parallax. However, errors resulting from this cause would be too great when measuring boulder-sized particles of essexite. In order to measure accurately such large particles the device shown in Plate 5 was constructed. It consists basically of a piece of dowelling and two blade-shaped pieces of wood. One of the blades was fixed at right-angles to one end of the dowelling and the other was free to move along the dowelling by means of a hole the same diameter as the dowelling. Another small piece of wood was fixed to this movable blade so that it too moved along the dowelling in order to ensure that the blade remained perpendicular to the dowelling. The instrument was found to have an accuracy of ± 2mm and, due to the free rotation of the movable blade about the dowelling, it was possible to measure between points out of line with the correct direction of axial measurement yet still maintain this direction with the dowelling. For particles with an a-axis of c.25cm or less the measuring box described in chapter 8 was used.

Whilst the method of Krumbein(1941a) for measuring particle shape is generally accepted, the measurement of roundness has for long been the subject of much discussion. Roundness is said by many to be geometrically independent of shape (e.g. Wadell,1932; Krumbein,1941a; Powers,1953; Van Andel et al.,1954; Curray & Griffiths, 1955; Lees,1964; Fleming,1965; Whalley,1972). However Schwarz and Shane(1969) considered that roundness depended on sphericity, Russell and Taylor(1937) felt that sphericity and roundness were interdependent, and Ehrlich and Weinberg(1970) argued that the independence of these two parameters was an a priori assumption and that it would be better to think that "shape characteristics operate over a continuum" (Ehrlich & Weinberg,1970,p.205). Lees(1964) and Whalley(1972) felt that angularity should be regarded as a separate concept from roundness, but most workers consider them as degrees of the same measure.

For the purposes of this analysis, roundness "is defined as a dimensionless function of the radius of curvature of one or more corners" (Fleming,1965,p.385). Its independence of shape can be seen in that "chipping of a particle may increase the sphericity, but it decreases the roundness" (Wadell,1932,p.449).

Three main approaches to measuring roundness have been made. Firstly, there are the visual comparison charts which consist of a series of silhouettes or photographs representing varying degrees of particle roundness (e.g. Trowbridge & Mortimer,1925; Russell & Taylor,1937; Krumbein,1941a; Powers,1953; Reichelt,1961; Lees,1964). A second technique that has not been so widely used is that of Szadeczky-Kardoss(1933) in which the percentage of convex parts of the particle are estimated. Thirdly, there are techniques involving direct measurement. Wadell(1932) suggested expressing roundness as the ratio of the mean radius of curvature of corners to the radius of the inscribed circle. The other major technique involving direct measurement is that of Cailleux(1945), which is essentially the same as the technique of Wentworth (1922a), where the radius of curvature of the sharpest corner of the particle in the maximum projection plane is determined. A target of concentric circles of known diameter is used to measure the radius of curvature (Dobkins & Folk,1970; Folk,1972), and roundness is expressed as

$$R = \frac{2r}{a} \times 1000$$

where r is the minimum radius of curvature in the maximum projection plane and a is the long axis. This technique has been used by many workers (e.g. Wentworth, 1922b; Tricart & Schaeffer,1950; Rivière & Ville,1967; King & Buckley,1968; McCann & Owens,1969; Dobkins & Folk,1970; Hollerman,1971; Dugdale,1972; Gregory & Cullingford,1974). Dobkins and Folk(1970) measured the minimum radius of curvature in three dimensions but found no difference from results in two dimensions, and therefore recommended measurement in two dimensions because of its greater speed.

For the present analysis the method of Cailleux (1945) was used to measure the roundness of essexite stones for two reasons. Firstly, it is rapid and involves direct measurement and it has been noted that "simple techniques comprising direct measurements" (Griffiths, 1961,p.497) should be used wherever possible in research work. Schwarz and Shane(1969), for instance, conceded that their Fourrier method was tedious, and the technique of Wadell(1932) is likewise laborious. Secondly, a great deal of subjectivity is involved in using visual comparison charts (Trowbridge & Mortimer,1925; Rosenfeld & Griffiths,1953; Griffiths,1967; Folk,1972; Whalley,1972) not only in selecting the class division (Russell & Taylor, 1937), but also because there is a "psychological tendency to make the data fit theoretical predictions" (Sneed & Folk,1958,p.117). Some workers have attempted to overcome this problem by arranging for associates to renumber samples so that no preconceived ideas influence the results (Beal & Shepard,1956; Sneed & Folk,1958). In the present analysis this was not possible since measurement had to be completed in the field due to the size of the stones.

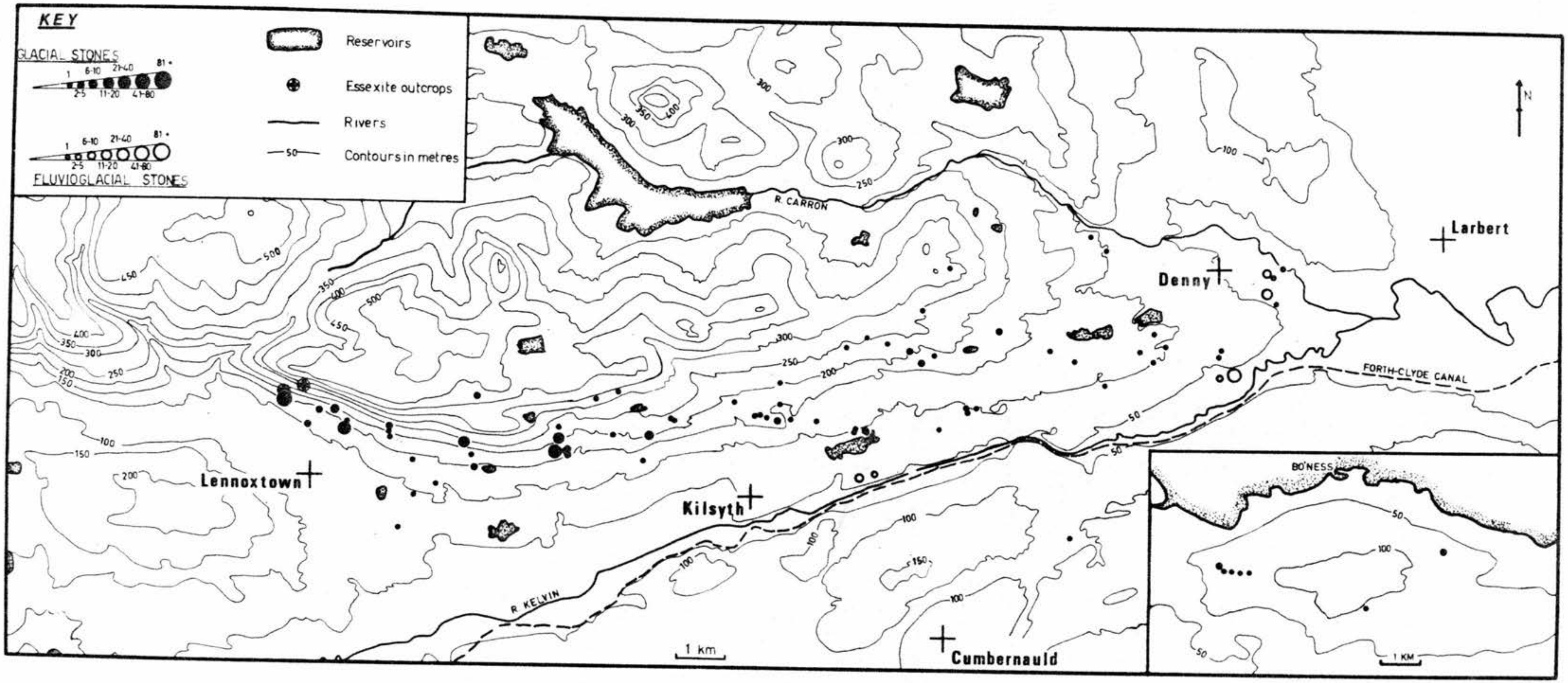
Despite these advantages over other methods, that of Cailleux(1945) has four main drawbacks. Firstly, not all workers select the same corner to measure (Folk,1972). Secondly, difficulty can result from estimating the radius of curvature using a template of concentric circles, especially when dealing with boulder-sized particles. Thirdly, corners may approach segments of parabolas or hyperbolas rather than a true circle, and it is therefore difficult to decide which of the target circles matches best. Fourthly, with decreasing size and rounding the accuracy of the technique diminishes (Van Andel et al., 1954; Whalley,1972).

The first problem does not introduce error into the present analysis because all roundness measurements were made by the same operator. Errors caused by the second and third drawbacks were considerably reduced by the use of a series of templates constructed from stiff plastic sheeting with a notch cut away in the corner of each template corresponding to a portion of the circumference of a circle of known radius. Twenty templates with radii ranging from 0.5cm to 10.0cm were made. It was possible with these templates to compare circumferences of known radii directly with the selected sharpest corner on an essexite stone. Wentworth(1919) used the same basic concept to produce a gauge for measuring the sharpest corner of experimentally abraded particles, but this is the only other known example in the literature of the use of templates, the majority of workers relying on target circles. For radii of curvature smaller than 0.5cm, as it was not possible to cut notches in the plastic sheeting with sufficient accuracy, comparison was made with a target of circles of radii ranging from 0.1mm to 0.5cm in 0.1cm intervals. For circles of such small radii the problem of parallax is not very great.

The locations where essexite stones were found, and the manner in which they were recorded, varied between the three categories of glacial, fluvioglacial and beach stones. Glacial stones, so called because they have undergone direct transport by the ice without subsequent fluvioglacial transport, were usually found in association with till. A variety of types of locations provided the glacial stones that were measured. The majority of stones in the Main Study Area were derived from the uppermost line of stones in the dry stone walls. Most of the rest were found in piles of stones that had been removed from the fields following ploughing (Plate 3) and in spoil heaps alongside drainage ditches. In the Secondary Study Area glacial essexite stones were found in the spoil heap from an oil-pipeline trench excavated during summer 1974 between Dalmeny near Edinburgh and Grangemouth, and in till sections formed during road improvements near Bo'ness. Only those essexite stones that had not suffered breakage as a result of human interference were measured. Although many glacial essexite stones displayed surface weathering, the titanaugite crystals remained more or less unaltered so that measurement of the three axes and the minimum radius of curvature was still feasible. The location of each glacial stone measured was plotted on 1:25,000 scale maps and their generalised distribution is shown in Fig. 6.1.

Fluvioglacial essexite stones, i.e. those essexite stones associated with fluvioglacial gravels, were found chiefly in abandoned and operating commercial gravel pits (Plate 6) though dry stone walls built on fluvioglacial deposits also provided a few stones. The distribution of measured fluvioglacial stones is shown in Fig. 6.2. One stone not shown in Fig.6.2 was found in a gravel pit at Straiton (GR 027 665) c.6km south of Edinburgh.

Marine-modified essexite stones measured in the present analysis were found on the foreshore of modern beaches on both sides of the Firth of Forth. No attempt was made to locate individual stones on large-scale maps, the beaches being divided into five zones with the locations of essexite stones being assigned to them (Fig.6.3). The extent of these zones on both sides of the Firth of Forth indicates the traceable limits of beach essexite stones. A comparison of Fig.6.3 with Fig.3.2 shows that the limits of the distribution extend slightly farther east on the southern shore in the present analysis than in Peach's map. It was decided that no attempt should be made to derive measures of frequency of essexite stones so that the analysis of the distribution pattern of the erratics train could be continued from the Main into



<u>Figure 6.1</u>

Location of glacial and fluvioglacial porphyritic erratics measured.

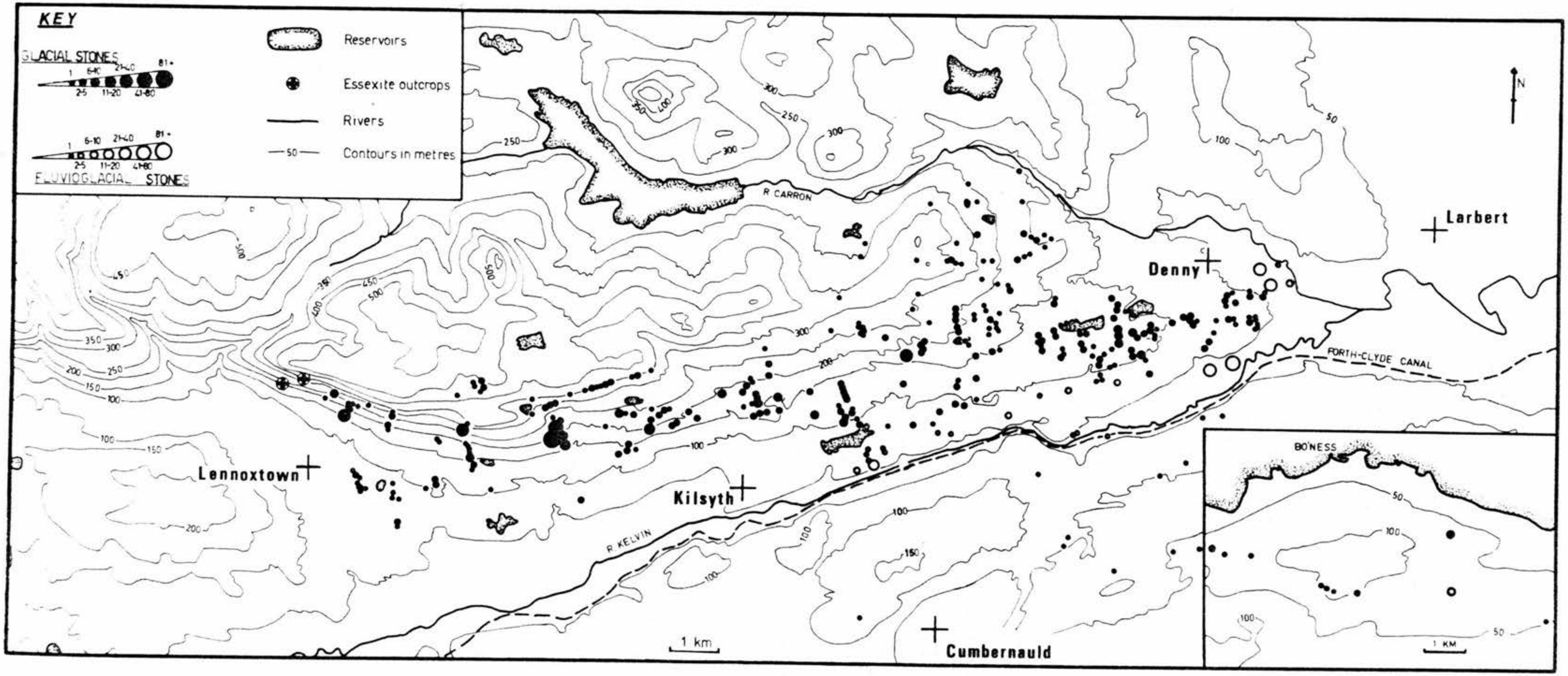


Figure 6.2

Location of glacial and fluvioglacial non-porphyritic erratics measured.

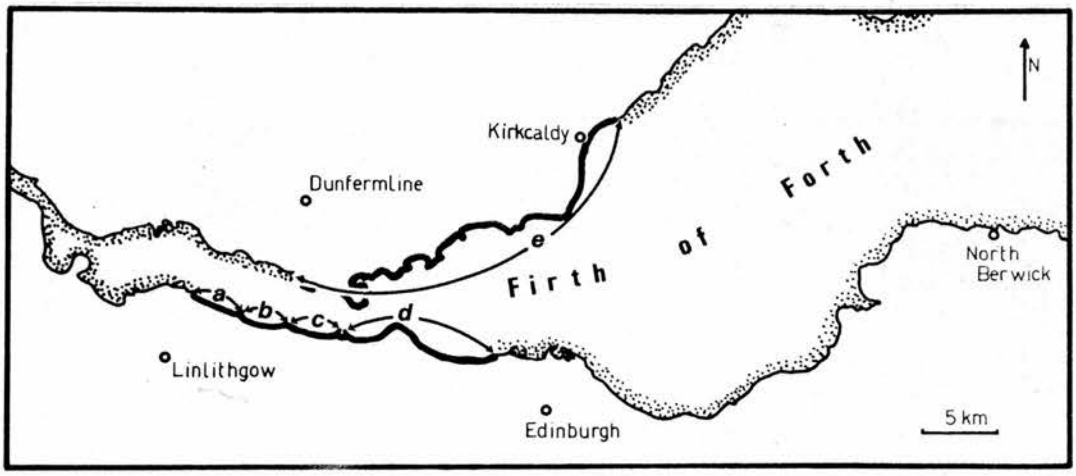


Figure 6.3

Division of beaches of the Firth of Forth into zones.

the Secondary Study Area, since these would tend to reflect beach, as well as glacial processes that have distributed the essexite erratics.

Results and discussion

Using the data derived from field measurement of essexite stones, various size and morphometric indices were calculated for each stone by means of a modified version of the PEBPROB computer program (Thornes & Howard,1967). Data input consisted of the a, b and c measures and minimum radius of curvature of each stone in centimetres, from which the program calculated the phi values of a, b and c, where phi is $-\log_2$ of the length (King,1966). The program also determined the ratios b/a, c/a and c/b, sphericity ($S = \sqrt[3]{c^2/ab}$), axial ratio ($AR = a-b/a-c$), flatness ($F = a+b/2c$), roundness ($R = (2r/a) \times 1000$), maximum projection volume ($MPV = (\pi/6) \times abc$) and maximum projection area ($MPA = (\pi/4) \times ab$).

Mean values of all except the b/a, c/a and c/b ratios for various groupings of glacial stones are shown in Table 6.1. A comparison of the size indices for porphyritic and non-porphyritic stones suggest that there are distinct differences between these two types (Table 6.1a). Mean values of MPV and MPA are considerably higher for non-porphyritic stones than for porphyritic ones. This can be accounted for in terms of the contrast in bedrock jointing pattern of both essexite types described in chapter 3. The close spacing of the porphyritic variety has tended to give rise to smaller joint-controlled blocks than the more massively jointed non-porphyritic rock.

Mean values of F also differ for both varieties of essexite. The greater flatness of the porphyritic stones is explained by the closer spacing of the bedrock joints giving rise to oblate-shaped, joint-controlled stones compared to non-porphyritic stones which are less asymmetrical. Since sphericity and flatness are inversely related, the lower sphericity values for porphyritic stones compared to non-porphyritic ones support this evidence.

Although mean values of R for different size grades of stones increase with decreasing size (Table 6.1b), the mean value for the smaller porphyritic stones is lower than for the comparitively larger non-porphyritic stones (Table 6.1a). This suggests that the porphyritic stones, as a result of the bedrock jointing characteristics, have been less able to withstand the crushing forces operating during glacial transport than the non-porphyritic stones, and are consequently more angular.

It was pointed out at the beginning of this chapter that shape and roundness are dependent on size. Therefore morphometric indices should, strictly speaking, only be compared for similarly-sized material before making inferences concerning the nature of processes operating in an environment. A comparison of the frequency (N) of stones in each size grade of both varieties of essexite illustrates the contrast in sizes; the mode

Table 6.1 Mean values of morphometric and size variables for glacial essexite stones

(a)

Type	N	A(phi)	B(phi)	S	AR	F	R	MPV	MPA
P + NP	1153	-7.73	-7.27	0.68	0.74	1.90	123.0	4631	413
P	274	-7.33	-6.86	0.67	0.73	1.95	111.1	1899	236
NP	879	-7.86	-7.40	0.69	0.74	1.88	126.7	5483	468

(b) Different size grades of porphyritic stones

1.6-3.2cm	4			0.81	0.67	1.41	159.1		
3.2-6.4cm	30			0.72	0.70	1.74	139.1		
6.4-12.8cm	121			0.67	0.71	1.96	113.2		
12.8-25.6cm	100			0.66	0.76	1.99	102.9		
25.6cm+	19			0.62	0.77	2.17	86.6		

(c) Different size grades of non-porphyritic stones

1.6-3.2cm	4			0.71	0.74	1.76	192.8		
3.2-6.4cm	36			0.73	0.72	1.68	141.5		
6.4-12.8cm	161			0.71	0.72	1.81	142.3		
12.8-25.6cm	525			0.69	0.73	1.88	127.0		
25.6cm+	153			0.65	0.79	2.05	103.9		

Type	N	A(phi)	B(phi)	S	AR	F	R	MPV	MFA
(d) Values for different distances from the source : porphyritic stones									
0-5km	154	-7.27	-6.76	0.66	0.71	2.02	89.8	1731	222
5-10km	60	-7.55	-7.10	0.69	0.74	1.87	133.9	2488	295
10-15km	36	-7.28	-6.83	0.70	0.74	1.83	155.8	1582	205
15-20km	13	-7.70	-7.35	0.68	0.79	1.88	106.8	3339	338
20km +	11	-6.68	-6.38	0.65	0.82	2.02	144.9	379	93
(e) Values for different distances from the source : non-porphyritic stones									
0-5km	149	-7.73	-7.29	0.70	0.75	1.86	108.9	4970	443
5-10km	274	-7.89	-7.41	0.68	0.73	1.91	130.9	6942	515
10-15km	196	-7.85	-7.39	0.68	0.74	1.90	115.5	5020	457
15-20km	234	-8.01	-7.55	0.69	0.74	1.87	143.2	4592	456
20km +	26	-6.99	-6.59	0.71	0.78	1.75	120.5	4589	309
(f) Sphericity and roundness values for different size grades at different distances : porphyritic stones									
0-5km									
<6.4cm	23			0.72			131.1		
6.4-12.8cm	73			0.67			89.4		
12.8cm+	58			0.64			76.1		
5-10km									
<6.4cm	5			0.73			163.9		
6.4-12.8cm	19			0.72			181.9		
12.8cm+	36			0.67			123.6		
10-15km									
<6.4cm	3			0.75			155.1		

Type	N	A(phi)	B(phi)	S	AR	F	R	MPV	MPA
6.4-12.8cm	19			0.70			170.8		
12.8cm+	14			0.67			135.5		
15-20km									
<6.4cm	-								
6.4-12.8cm	4			0.62			89.1		
12.8cm+	9			0.70			114.6		
20km +									
<6.4cm	3			0.81			170.0		
6.4-12.8cm	6			0.59			133.6		
12.8cm+	2			0.60			140.9		

(g) Sphericity and roundness values for different size grades at different distances:non-porphyritic stones

Type	N	A(phi)	B(phi)	S	AR	F	R	MPV	MPA
0-5km									
<6.4cm	12			0.73			180.6		
6.4-12.8cm	33			0.72			136.9		
12.8cm+	104			0.68			91.6		
5-10km									
<6.4cm	14			0.73			154.1		
6.4-12.8cm	52			0.70			155.5		
12.8cm+	208			0.68			123.1		
10-15km									
<6.4cm	6			0.75			89.0		
6.4-12 12.8cm	44			0.70			134.1		
12.8cm+	146			0.68			111.0		

Type	N	A(phi)	B(phi)	S	AR	F	R	MPV	MPA
15-20km <6.4cm	-								
6.4-12.8cm	25			0.73			148.6		
12.8cm+	146			0.68			142.6		
20km + <6.4cm	5			0.72			113.3		
6.4-12.8cm	7			0.67			97.6		
12.8cm+	14			0.73			134.6		

for the porphyritic stones is in the 6.4 - 12.8cm class (based on the b-axis length) compared to the 12.8 - 25.6cm class for the non-porphyritic stones. The mean values of R for each size grade of porphyritic stones are consistently lower than for the corresponding size grades of non-porphyritic stones, which supports the view mentioned above that the porphyritic variety has been subject to more comminution than non-porphyritic stones as a result of the closer jointing pattern of the bedrock. Mean values of R and S generally increase with decreasing size for both varieties of essexite whilst mean values of AR and F tend to decrease with decreasing size.

Mean values of the morphometric and size indices subdivided into distances of 5km intervals from the source do not indicate any specific trend for either variety of essexite (Table 6.1d & e). Although the wall data showed that crushing of both essexite types had occurred during glacial transport, mean values of MPA and MPV do not indicate any progressive reduction in size with distance from the source. Mean values for other indices likewise fail to show any systematic trends. The lack of a trend in size indices may be explained in terms of the variety of locations where the measured stones were found. Whereas the evidence for the reduction in size of essexite stones was based on data from only the dry stone walls, the stones represented in Table 6.1 were found in a number of different locations.

Mean values of R and S for three size grades of essexite stones are shown in Table 6.1f & g. The mean sphericity of porphyritic stones up to 6.4cm in size increases with distance from the outcrop. For the remaining size grades of porphyritic, and for all size grades of non-porphyritic stones, mean values of S show no general trend with distance from the source. Mean values of R for all size grades of both varieties, except non-porphyritic ($<$6.4cm), tend to increase over the first 10km but thereafter show no general trend. Drake(1972) found that the mean roundness of pebbles from till tended to maintain a steady value after an initial rise in a short distance down-ice of the source. He attributed this to successive crushing and abrasion during glacial transport such that pebbles rapidly attained a dynamic equilibrium state for rounding. Beaumont(1967) expressed an alternative view and considered that the equilibrium state was indicative of no further change in particle roundness. Since independent evidence of crushing is available in terms of the wall stone data, it seems that the lack of a general trend beyond 5km from the source can be attributed to successive cycles of crushing and abrasion.

Mean values of different groupings of fluvioglacial stones are shown in Table 6.2. All size indices (i.e. A(phi), B(phi), MPV and MPA) are considerably lower for fluvioglacial stones than for glacial stones (Table 6.2a). This can be explained by the fact that the size of stones in the meltwater environment is limited by the stream competence whereas the size of glacial stones can be extremely large (see chapter 2). The mean value of R is considerably higher for fluvioglacial stones than for glacial stones and this is attributed to the greater effectiveness of abrasion in fluvioglacial compared to glacial transport (King & Buckley,1968). The mean value of S is higher for fluvioglacial stones than for glacial stones whilst the mean value of F is lower for fluvioglacial stones. This again indicates the importance of abrasion in the fluvioglacial environment.

The mean MPV values for both essexite types show that there is an approximate threefold difference in the volumes, which can be attributed to the contrast in bedrock jointing.

Mean values of R for different size grades of the porphyritic stones (Table 6.2b) show a different pattern to that of glacially transported porphyritic stones. Although no stones of size 1.6-3.2cm were found, R increases from 180.5 (3.2-6.4cm) to 219.1 (6.4-12.8cm) and still remains higher in the 12.8-25.6cm than the value for the 1.6-3.2cm size grade. This contrasts with the pattern for glacial porphyritic stones where R progressively declines with increasing size. Mean values of R for different size grades of non-porphyritic stones (Table 6.2c), on the other hand, do show a similar trend to glacial stones except that values are consistently higher for each size grade of fluvioglacial stones than for corresponding size grades of glacial stones.

In contrast to the glacial stones, too few fluvioglacial stones were measured to enable a division of the data to be made into five classes representing different distances from the source. Therefore to investigate the effect of distance of transport on the size and morphometric indices, both varieties of fluvioglacial essexite stones were divided in two at a distance of approximately 15km from the source. Mean MPV values for porphyritic stones (Table 6.2d) indicate that the size of stones is considerably smaller at distances greater than 15km than at less than this distance from the source. Mean MPV values for non-porphyritic stones are similarly lower for stones farther than 15km from the source compared to ones at less than this distance. It is suggested that the reduction in size is not the result of intense comminution of stones during fluvioglacial transport but rather a result of stream sorting. Large stones picked up near the source by meltwater streams would not have tended to travel far whereas smaller stones would have undergone more prolonged transport.

Division of the two types of fluvioglacial

Table 6.2 Mean values of morphometric and size variables for fluvioglacial essexite stones

(a)

Type	N	A(phi)	B(phi)	S	AR	F	R	MPV	MPA
P + NP	258	-6.95	-6.54	0.71	0.76	1.75	208.3	1327	165
P	65	-6.82	-6.44	0.73	0.78	1.68	208.1	582	103
NP	193	-7.00	-6.58	0.71	0.76	1.78	208.4	1578	186

(b) Different size grades of porphyritic stones

1.6-3.2cm	-								
3.2-6.4cm	14			0.77	0.72	1.53	180.5		
6.4-12.8cm	40			0.72	0.77	1.71	219.1		
12.8-25.6cm	10			0.72	0.86	1.71	191.8		
25.6cm+	1								

(c) Different size grades of non-porphyritic stones

1.6-3.2cm	9			0.77	0.70	1.54	252.2		
3.2-6.4cm	37			0.75	0.76	1.61	222.3		
6.4-12.8cm	84			0.70	0.76	1.87	221.6		
12.8-25.6cm	56			0.69	0.76	1.86	178.9		
25.6cm+	7			0.68	0.84	1.87	154.6		

<u>Type</u>	<u>N</u>	<u>A(phi)</u>	<u>B(phi)</u>	<u>S</u>	<u>AR</u>	<u>F</u>	<u>R</u>	<u>MPV</u>	<u>MPA</u>
(d) <u>Values for different distances from the source : porphyritic stones</u>									
<15km	10	-6.73	-6.47	0.73	0.84	1.64	205.3	1150	149
>15km	55	-6.84	-6.43	0.73	0.76	1.68	208.6	479	95
(e) <u>Values for different distances from the source : non-porphyritic stones</u>									
<15km	38	-7.19	-6.81	0.68	0.78	1.86	196.6	2258	243
>15km	155	-6.95	-6.52	0.71	0.75	1.76	211.2	1411	172
(f) <u>Sphericity and roundness values for different size grades at different distances from source : porphyritic stones</u>									
<u>≤15km</u> <6.4cm	3			0.75			124.1		
6.4-12,8cm	5			0.75			224.4		
12.8cm+	2			0.64			279.1		
<u>≥15km</u> <6.4cm	11			0.77			195.9		
6.4-12.8cm	35			0.72			218.4		
12.8cm+	9			0.72			186.1		
(g) <u>Sphericity and roundness values for different size grades at different distances from source : non-porphyritic stones</u>									
<u>≤15km</u> <6.4cm	5			0.75			227.7		
6.4-12.8cm	18			0.66			218.0		
12.8cm	15			0.69			159.1		

Type	N	A(phi)	B(phi)	S	AR	F	R	MPV	MPA
>15km									
<6.4cm	41			0.75			227.7		
6.4-12.8cm	66			0.71			222.6		
12.8cm+	48			0.68			181.1		

essexite stones (Table 6.2f & g) reveals no specific trends for sphericity and roundness. Only for the group of non-porphyritic stones farther than 15km from the source is there a trend towards a progressive decrease in R and S with increasing size. For the remaining groupings, R and S fluctuate with no apparent systematic trend.

Mean values for size and morphometric indices of different categories of beach essexite stones are shown in Table 6.3. The mean value of R for all 941 beach stones is 212.2, which is slightly higher than the corresponding value for fluvioglacial stones. The mean MPV value is less than 1/4 of the fluvioglacial MPV mean value and less than 1/50 of the glacial MPV mean value.

Mean values of R for porphyritic stones decrease with increasing size (Table 6.3b). On the other hand, values of R for non-porphyritic stones (Table 6.3c) rise to a peak in the 6.4-12.8cm size grade and decline in the 12.8-25.6cm grade. On beaches in South Wales and Scotland, Bluck(1969) investigated the rounding of the beach stones in the same size grades that have been used in the present analysis. He found that "abrasion is more effective in...

the 64-128mm size range where the highest roundness values are recorded" (Bluck,1969,p.8). The angular nature of stones larger than 12.8cm, he felt, was a result of breakage during storm conditions. This explanation appears to account for the relationship of roundness and size of non-porphyritic beach stones. Although the Firth of Forth is comparatively sheltered, an eastward movement of beach material is indicated by the accumulation of beach material on the western side of obstructions on the beaches. This movement of beach stones would lead to abrasion. Fragmentation of larger stones (>12.8cm) would be possible under the right conditions, as Geikie (1865) noted. "It might have been supposed that the comparatively sheltered estuary of the Firth of Forth would be free from any marked abrasion by the sea, yet even as far up as Granton, near Edinburgh, during a fierce gale from the north-east, stones weighing a ton or more have been known to be torn out of a wall and rolled to a distance of thirty feet" (Geikie,1865,p.49).

The fact that the porphyritic stones do not show the same pattern of R values may be accounted for in terms of the different bedrock structure. Since the porphyritic stones were broken down into small sizes by glacial action prior to their arrival on the beaches, the majority of stones of size 3.2-6.4cm are undergoing secondary abrasion having already been subjected to glacial or fluvioglacial abrasion. Non-porphyritic stones of this size, on the other hand, are more likely to consist of a mixture of previously abraded material and fragments

Table 6.3 Mean values of morphometric and size variables for beach stones

(a)

Type	N	A(phi)	B(phi)	S	AR	F	R	MPV	MPA
P + NP	941	-6.37	-5.98	0.74	0.78	1.64	212.2	302	59
P	326	-6.28	-5.90	0.74	0.77	1.63	209.0	241	51
NP	615	-6.41	-6.03	0.74	0.78	1.65	213.8	334	63

(b) Values for different sizes of porphyritic stones

1.6-3.2cm	15			0.76	0.66	1.57	272.7		
3.2-6.4cm	177			0.75	0.76	1.62	206.6		
6.4-12.8cm	125			0.73	0.81	1.66	206.5		
12.8-25.6cm	8			0.73	0.84	1.66	188.6		
25.6cm +	1								

(c) Values for different sizes of non-porphyritic stones

1.6-3.2cm	12			0.76	0.73	1.55	214.1		
3.2-6.4cm	284			0.75	0.76	1.62	219.1		
6.4-12.8cm	286			0.73	0.79	1.66	219.7		
12.8-25.6cm	31			0.69	0.83	1.83	148.2		
25.6cm +	2								

(d) Values at different locations : porphyritic stones

a	50	-6.31	-5.88	0.74	0.75	1.65	151.2	599	74
b	62	-6.19	-5.82	0.76	0.79	1.56	195.3	158	42

Loc.	N	A(phi)	B(phi)	S	AR	F	R	MPV	MPA
c	185	-6.33	-5.95	0.74	0.78	1.64	216.4	195	50
d	23	-6.16	-5.73	0.73	0.76	1.68	312.1	101	35
e	6	-6.26	-5.68	0.67	0.67	1.93	211.7	84	34
(e) Values at different locations : non-porphyritic stones									
a	66	-6.20	-5.84	0.75	0.79	1.60	195.3	185	45
b	109	-6.27	-5.89	0.73	0.78	1.67	183.6	241	52
c	378	-6.46	-6.06	0.74	0.77	1.64	223.3	278	62
d	40	-6.44	-6.09	0.72	0.80	1.74	269.2	396	68
e	22	-6.97	-6.67	0.74	0.82	1.64	156.5	2095	185

derived from the fragmentation of beach stones larger than 12.8cm, since the supply of large non-porphyritic stones on the beaches is greater than that of porphyritic stones (Plates 7 & 8).

The mean values of stones from different zones of the coastline shown in Fig.6.3 indicate that the size of porphyritic stones tends to decrease from west to east whilst that of non-porphyritic stones increases (Table 6.3 d & e). An explanation of this relationship is problematical but it is more likely the result of beach sorting than of any glacial processes.

Correlation of morphometric and size indices

Tables 6.4 and 6.5 show correlation matrices of the 14 morphometric and size indices of all the porphyritic and non-porphyritic stones respectively. Both tables indicate that the majority of the indices are interrelated to some extent. For both essexite types there is a strong negative correlation of -0.96 and -0.94 between S and F. King and Buckley(1968) also found that these indices were highly correlated and suggested as a result that only one of them is needed as an index of stone shape. On the same basis it is clear that only one of MPA and MPV needs to be calculated since correlation coefficients of 0.89 and 0.96 are recorded. The ratios b/a, c/a and c/b are highly correlated with AR, F and F respectively and can therefore be discarded. A(phi) and B(phi) are highly correlated with a, b and c and therefore appear to be superfluous. There is a relatively high correlation between R and a for porphyritic stones (+0.85) but for non-porphyritic stones the correlation coefficient is negative and low (-0.21). Therefore, including R, the critical indices appear to be S or F and MPV or MPA.

Comparison of morphometric indices for glacial, fluvio-glacial and beach stones

To illustrate the differences in morphometric indices between the three categories of essexite stones, graphical plots of overall and individual mean values of different size grades of porphyritic and non-porphyritic stones for some of the indices are shown in Fig.6.4. These plots indicate firstly that the areas enclosing mean values for glacial stones have a small overlap with

Table 6.4 Correlation matrix of all porphyritic essexite stones measured

N = 665

Brackets indicate correlation coefficients not significant at above the 99.9% level.

	a	b	c	A(phi)	B(phi)	b/a	c/a	c/b	S	AR	F	R	MPV
b	0.92												
c	0.84	0.85											
A(phi)	-0.92	-0.86	-0.80										
B(phi)	-0.84	-0.92	-0.81	0.92									
b/a	-0.14	0.20	(0.05)	0.15	-0.24								
c/a	-0.21	(-0.08)	0.25	0.25	(0.09)	0.41							
c/b	-0.12	-0.25	0.21	0.14	0.28	-0.35	0.69						
S	-0.18	-0.17	0.26	0.22	0.19	(0.05)	0.92	0.91					
AR	(0.01)	-0.27	(0.05)	(0.01)	0.32	-0.84	(0.08)	0.74	0.43				
F	0.18	0.16	-0.28	0.20	-0.17	-0.08	-0.88	-0.85	-0.96	-0.35			
R	0.85	(-0.08)	(-0.06)	0.19	(0.09)	0.23	0.22	(0.04)	0.15	-0.15)	-0.15		
MPV	0.93	0.85	0.81	-0.65	-0.64	(0.02)	(-0.02)	(-0.04)	(-0.02)	(-0.04)	((0.00)	(-0.06)	
MPA	0.93	0.93	0.80	-0.76	-0.76	(0.02)	-0.13	-0.16	-0.15	(-0.01)	0.15	(-0.09)	0.96

Table 6.5 Correlation matrix of all non-porphyritic essexite stones measured

N = 1687

Brackets indicate correlation coefficients not significant at above the 99.9% level.

	a	b	c	A(phi)	B(phi)	b/a	c/a	c/b	S	AR	F	R	MPV
b	0.91												
c	0.81	0.83											
A(phi)	-0.88	-0.81	-0.76										
B(phi)	-0.81	-0.88	-0.78	0.93									
b/a	-0.19	0.16	(0.03)	0.21	-0.16								
c/a	-0.26	-0.11	0.26	0.27	0.11	0.44							
c/b	-0.12	-0.24	0.26	0.12	0.23	-0.30	0.71						
S	-0.21	-0.19	0.28	0.22	0.18	0.09	0.93	0.91					
AR	(0.07)	-0.22	0.11	-0.09	0.21	-0.82	(0.07)	0.71	0.40				
F	0.23	0.18	-0.27	-0.21	-0.17	-0.11	-0.87	-0.84	-0.94	-0.32			
R	-0.21	-0.15	-0.14	0.24	0.16	0.22	0.16	(0.01)	0.10	-0.14	-0.11		
MPV	0.62	0.64	0.57	-0.35	-0.36	(0.02)	(-0.02)	(-0.04)	(-0.03)	(-0.03)	(0.03)	(-0.05)	
MPA	0.86	0.87	0.70	-0.60	-0.60	(0.00)	-0.14	-0.16	-0.16	(-0.07)	0.17	-0.11	0.89

areas enclosing beach stone mean values. On the other hand, the areas enclosing mean values for fluvioglacial stones tend to overlap to a large extent with those enclosing mean values for beach stones. This relationship is perhaps better illustrated in the overall mean values of the three categories; in each plot the two overall mean values for fluvioglacial stones (F,f) are located closer to the beach mean values (B,b) than to the glacial mean values (G,g). The juxtaposition of the overall mean values for the three categories can be explained in the following manner. The processes acting on glacial and beach stones produce particles with relatively distinctive morphometric properties. Glacial processes include crushing and abrasion whilst abrasion is the dominant process acting on beach material. Abrasion is also the dominant process in the fluvioglacial environment but apparently has not brought about the same degree of rounding as beach abrasion since the overall mean values for fluvioglacial stones lie between those of beach and glacial stones, which suggests that they retain some of the characteristic morphometric properties associated with glacial stones.

The overall mean values also suggest that the effect of lithology in determining the morphometry of stones derived from that source remains high in the glacial and fluvioglacial environments but is significantly reduced when subject to beach processes. This is shown by the relative distances between the overall mean values for the two essexite types in the three categories.

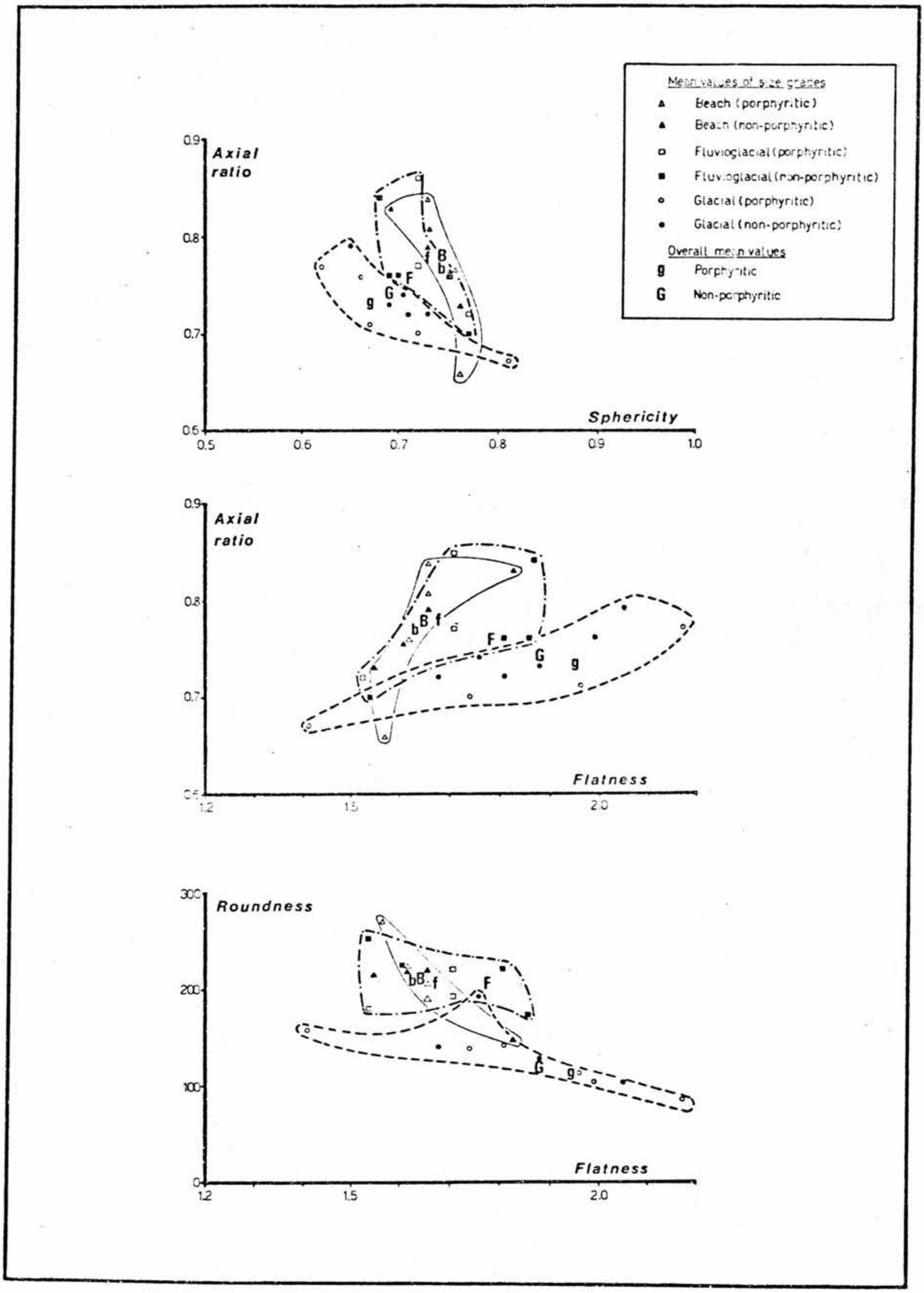


Figure 6.4

Graphical plots of axial ratio against sphericity and flatness, and roundness against flatness.

Glacial and fluvioglacial values are consistently farther apart in all the plots than the beach overall mean values. This suggests that the initial difference in shape caused by the contrast in the jointing characteristics of both essexite types has been minimised. Beach stones, however, have been derived from till and fluvioglacial deposits flanking the shores of the Firth of Forth. They have therefore already undergone processes acting in one or both of these environments so that the effect of beach processes has been superimposed on the morphometric properties resulting from glacial and fluvioglacial activity. Considering the probable long exposure of the beach essexite stones to beach processes (McCann & Owens,1969; Crofts, 1974) and the similarity of the morphometric properties of these stones to those of fluvioglacial stones, the results from the present analysis support the view expressed by King and Buckley(1968) that despite the short-lived nature of the meltwater environment it is very effective in rounding stones.

Multiple discriminant analysis

Although the plots in Fig.6.4 indicate that the glacial, fluvioglacial and beach environments can be differentiated according to certain morphometric properties, the consideration of any single index does not satisfactorily distinguish between them. A similar situation is represented in Fig.6.5. If M_1 and M_2 are two morphometric indices, A and B are clusters of individual stones from two environments and a and b represent the two overall means or centroids, there is clearly a large degree of overlap along the M_1 and M_2 axes. However by projecting a line through the intersecting points of the two clusters, the degree of overlap on the line F is reduced to a minimum. This search for the measurement giving the maximum separation between two populations is the basic principle of multiple discriminant analysis. This is a technique that has only recently been used in geography (e.g. May,1972; Anderson,1974; Matthews,1976). The technique is most beneficial when there are more than two populations of objects, with several measurements made on each object. The distinctiveness of each population can be determined in terms of a weighted combination of the measurements.

In Fig.6.5 line F is a discriminant axis since it achieves the best separation between the two clusters by minimising d/σ, where d is the distance between two overall means and σ is the common standard deviation. For each additional cluster a new discriminant axis is required. This d/σ measure is known as the Mahalonobis distance and two-dimensional representation of Mahalonobis distances between clusters can be made by projecting the centroids on to the first two discriminant axes, which account for as much as possible of the discrimination between the clusters (Webster & Burrough ,1974). Since Mahalonobis distance is approximately distributed as chi-square, the degree to which an individual object is characteristic of its class can be defined statistically.

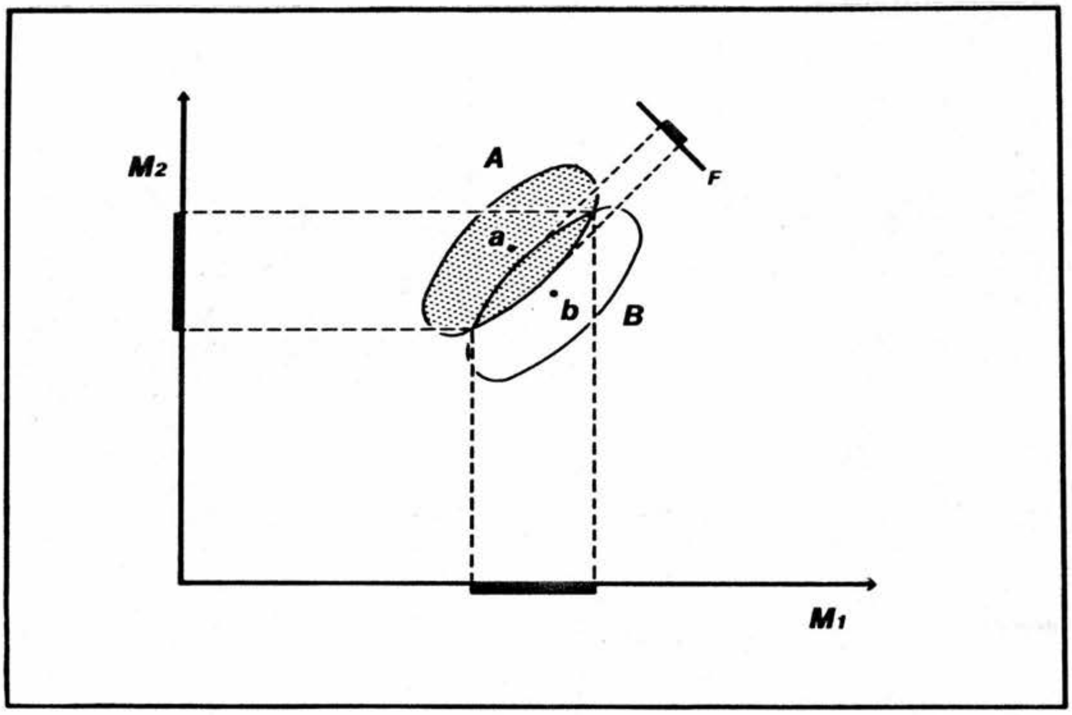


Figure 6.5

Definition of discriminant axis.

Where individuals are widely scattered about the class mean they may be closer to the means of other classes than to their own class mean. Confidence circles at given levels of probability can be placed around the centroids to indicate the degree of overlap between clusters. Fuller explanation of the technique and examples of its use are given in Casetti(1964), Healy(1965) and Webster and Burrough(1974). The biomedical computer program BMDO7M was used to carry out multiple discriminant analysis on the glacial, fluvioglacial and beach data (Dixon,1973). The calculation is carried out in a stepwise manner and a variable is selected or deleted according to its F-ratio. The two-dimensional plots on the first two discriminant axes of different categories of essexite stones are shown in Figs 6.6 to 6.9.

Fig 6.6a and 6.6b show individual plots for the porphyritic and non-porphyritic stones using all 14 morphometric and size indices. The centroids and 95% confidence circles for the different size categories are indicated. For both plots the size index A(phi) accounts for more than 90% of the total dispersion with E accounting for the rest. Tables 6.6a and 6.6b are similar in that a greater proportion of the beach and glacial stones are closer to their centroids than the fluvioglacial stones are to the fluvioglacial centroid. The large degree of overlap of the confidence circles indicates that the differentiation between the three categories is not large.

Fig.6.6c reveals a similar pattern of the centroids to that shown in Fig.6.4 in that the beach centroids (B,b) for both essexite types are closer together than the glacial (G,g) and fluvioglacial (F,f) centroids. What is not evident in Fig.6.4, but is illustrated in Fig.6.6c is the progressive decrease in distance between the centroids for both essexite types from a comparatively large gap between the glacial centroids to a progressively smaller gap between fluvioglacial and beach centroids. Since a size index (A(phi)) accounts for most of the dispersion (Table 6.6), this progressive decrease indicates that the differentiation in size between stones of the two essexite types is most pronounced for glacial stones and becomes progressively less for fluvioglacial and beach stones. This supports the view that crushing is the dominant glacial process, which tends to accentuate the size contrast between the two essexite types by breaking up stones into joint-controlled blocks. The dominant process in the fluvioglacial and beach environments, on the other hand, is abrasion which no longer brings about further differentiation in terms of size between the two essexite types. Furthermore, the sorting action in both these environments would tend to lead to essexite stones of the same size being found together in the same deposits. The fact that the centroids for porphyritic stones are closer together than the centroids for non-porphyritic stones can be attributed to the smaller range of sizes of porphyritic stones over the three categories compared to non-porphyritic ones.

Fig.6.7 shows plots using the seven size indices

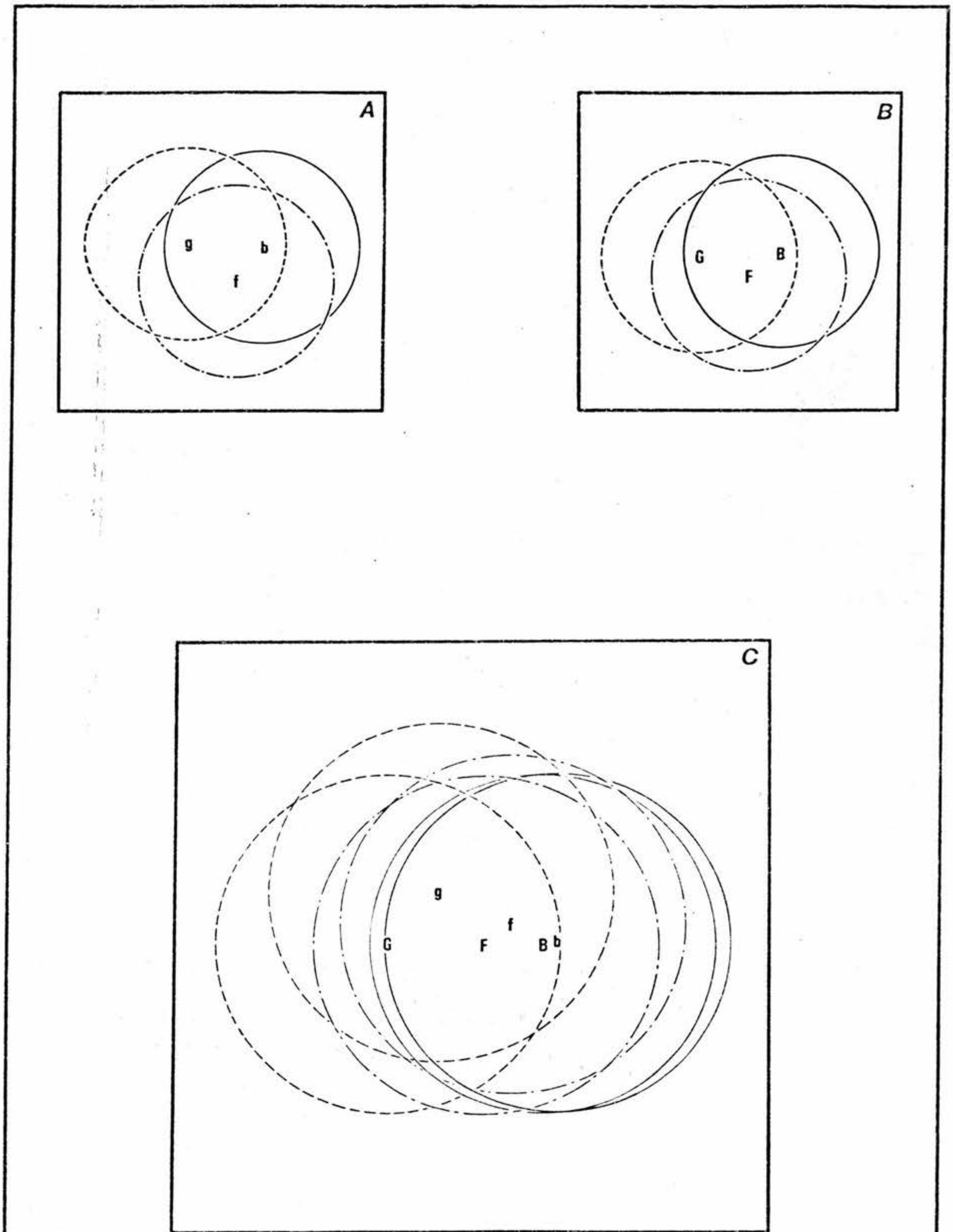


Figure 6.6

Beach ,glacial and fluvioglacial centroids and 95% confidence circles for A) porphyritic B) non-porphyritic and C) porphyritic and non-porphyritic stones using size and morphometric indices.

only (i.e. a, b, c, A(phi), B(phi), MPV & MPA). Individual plots for the two essexite types (Figs 6.7a & 6.7b) indicate similar distributions of the three centroids. Once more A(phi) accounts for most of the dispersion with a accounting for the rest (Table 6.7). The glacial and beach stones again record the highest numbers of stones closest to these centroids, whereas fluvioglacial stones are scattered between the three categories.

Fig.6.7c shows a progressive decrease in the distance between the centroids in the glacial, fluvioglacial and beach categories. A(phi) accounts for the majority of the dispersion (95.5%) with c accounting for most of the rest (3.8%). The numbers of stones closer to their own centroids (Table 6.7) illustrates once more that beach and glacial stones record the highest number, suggesting that these two categories are the most distinctive, whereas fluvioglacial stones to a large extent display the size characteristics of the other two categories.

Fig.6.8 shows plots using only the seven morphometric indices (i.e. b/a, c/a, c/b, S, AR, F & R). In Figs 6.8a and 6.8b the fluvioglacial and beach centroids are close together while the glacial centroids are some distance apart. Table 6.8 indicates that R accounts for most of the dispersion with F accounting for the rest. Once more many glacial and beach stones are nearer their own centroids than the other two centroids whereas fluvioglacial stones are widely dispersed between the three categories.

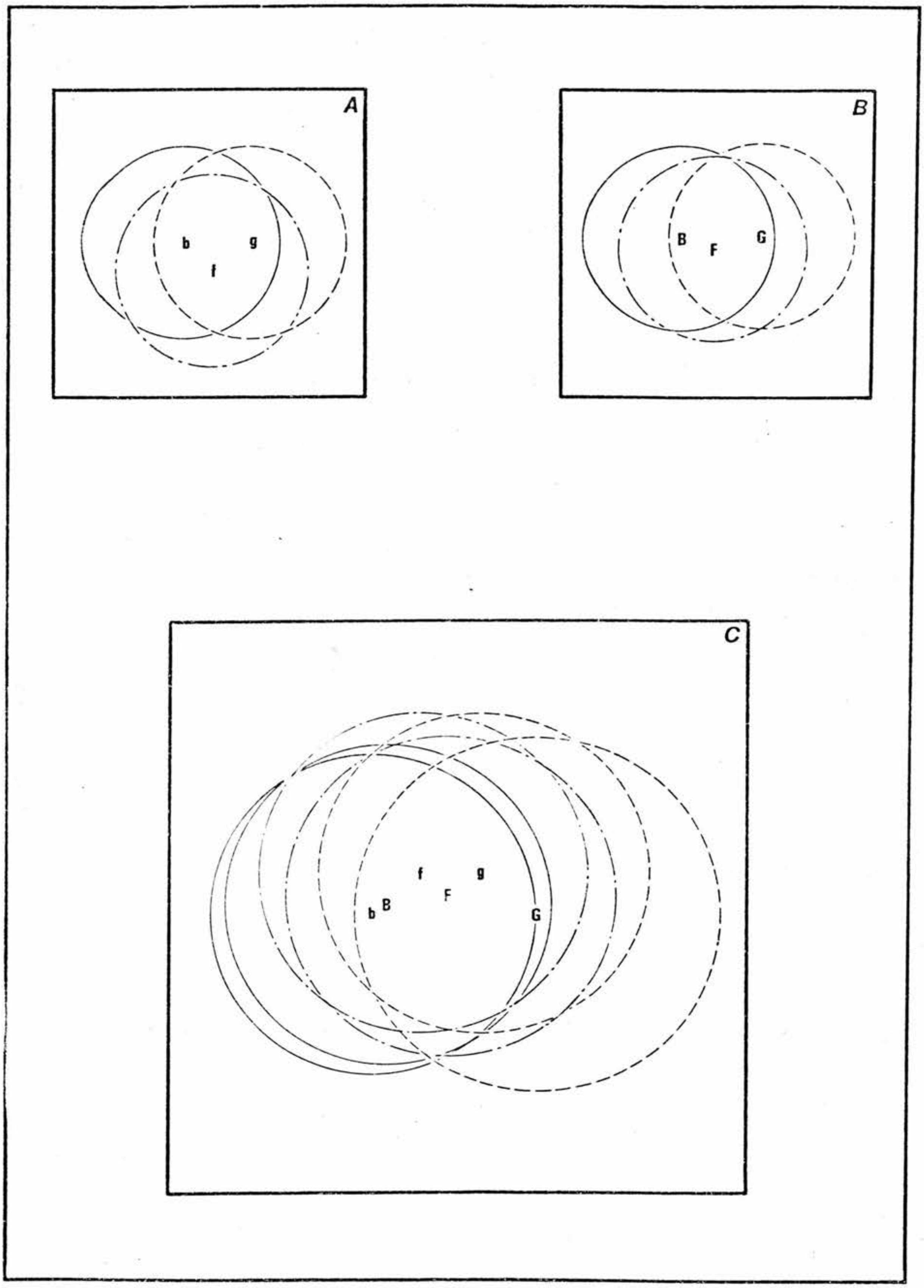


Figure 6.7

Beach, glacial and fluvioglacial centroids and 95% confidence circles for A) porphyritic B) non-porphyritic and C) porphyritic and non-porphyritic stones using size indices only.

Fig.6.8c again indicates the progressive decrease in the distance between glacial, fluvioglacial and beach centroids, though it is not as marked as in Figs 6.6c and 6.7c. Since R accounts for most of the dispersion (Table 6.8c), the close proximity of the centroids of both essexite types in each category suggests that roundness does not distinguish lithological contrasts between the two essexite types as well as the size indices. Fig.6.8c also shows that the centroid of one essexite type lies closer to the centroid of the other essexite type in the same category than to centroids of the other two categories. Roundness therefore appears to be the best measure discriminating between the glacial, fluvioglacial and beach environments. Andrews and King(1968), McCann and Owens(1969), Sames(1966) and Gregory and Cullingford(1974) also found that roundness was the most useful measure that distinguished between processes acting in different environments. Andrews and King(1968) and McCann and Owens(1969) considered that measures of shape, such as sphericity and flatness, depend on rock type whereas roundness is a product of process. This conclusion is confirmed by the present analysis.

Fig.6.9 shows plots using the seven morphometric indices with each category subdivided into size grades for both essexite types. Roundness again accounts for the majority of the dispersion with c/b accounting for most of the rest. The glacial centroids are a comparatively distinctive group but the close proximity of the fluvioglacial and beach centroids indicates that they

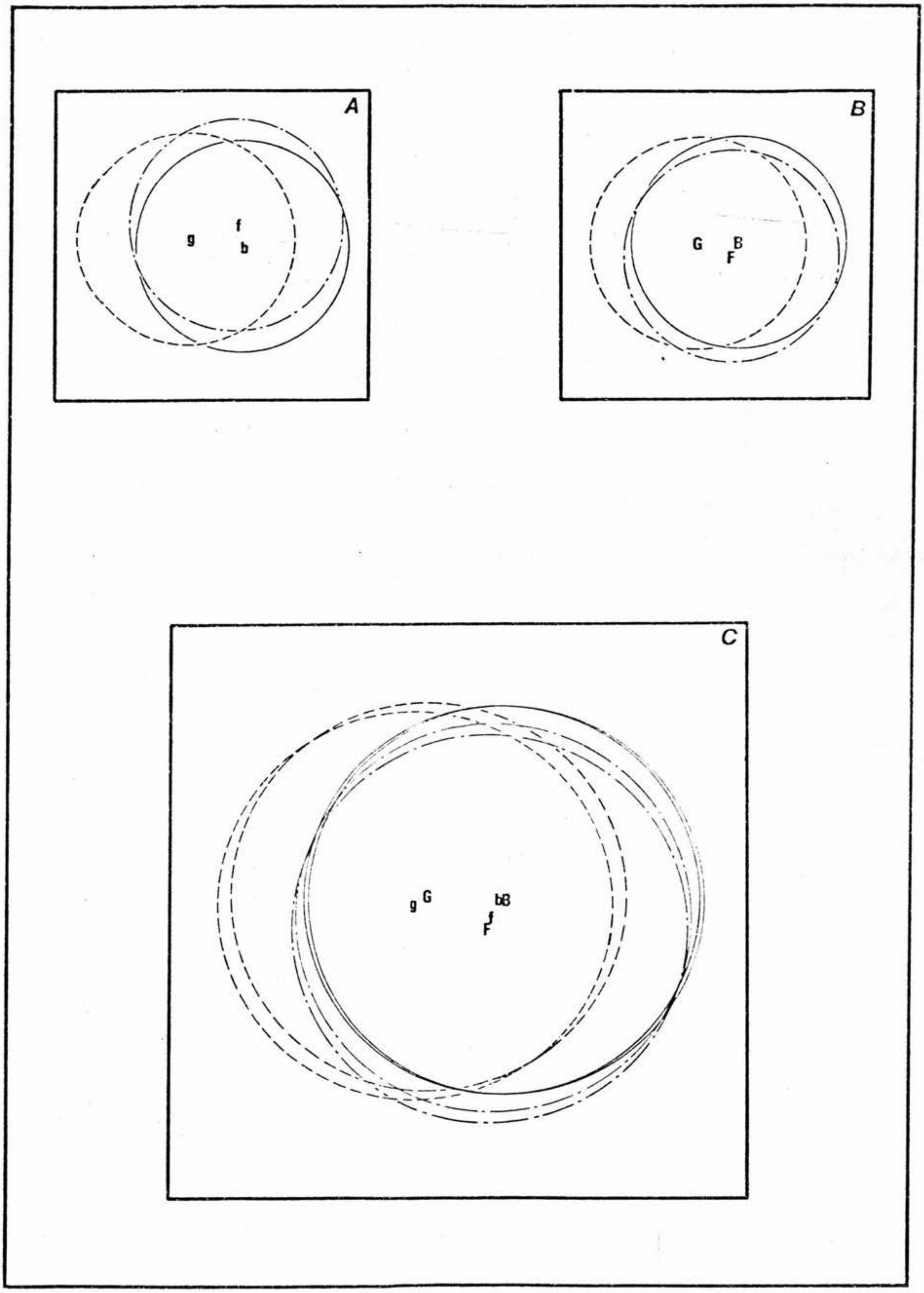


Figure 6.8

Beach, glacial and fluvioglacial centroids and 95% confidence circles for A) porphyritic B) non-porphyritic and C) porphyritic and non-porphyritic stones using morphometric indices only.

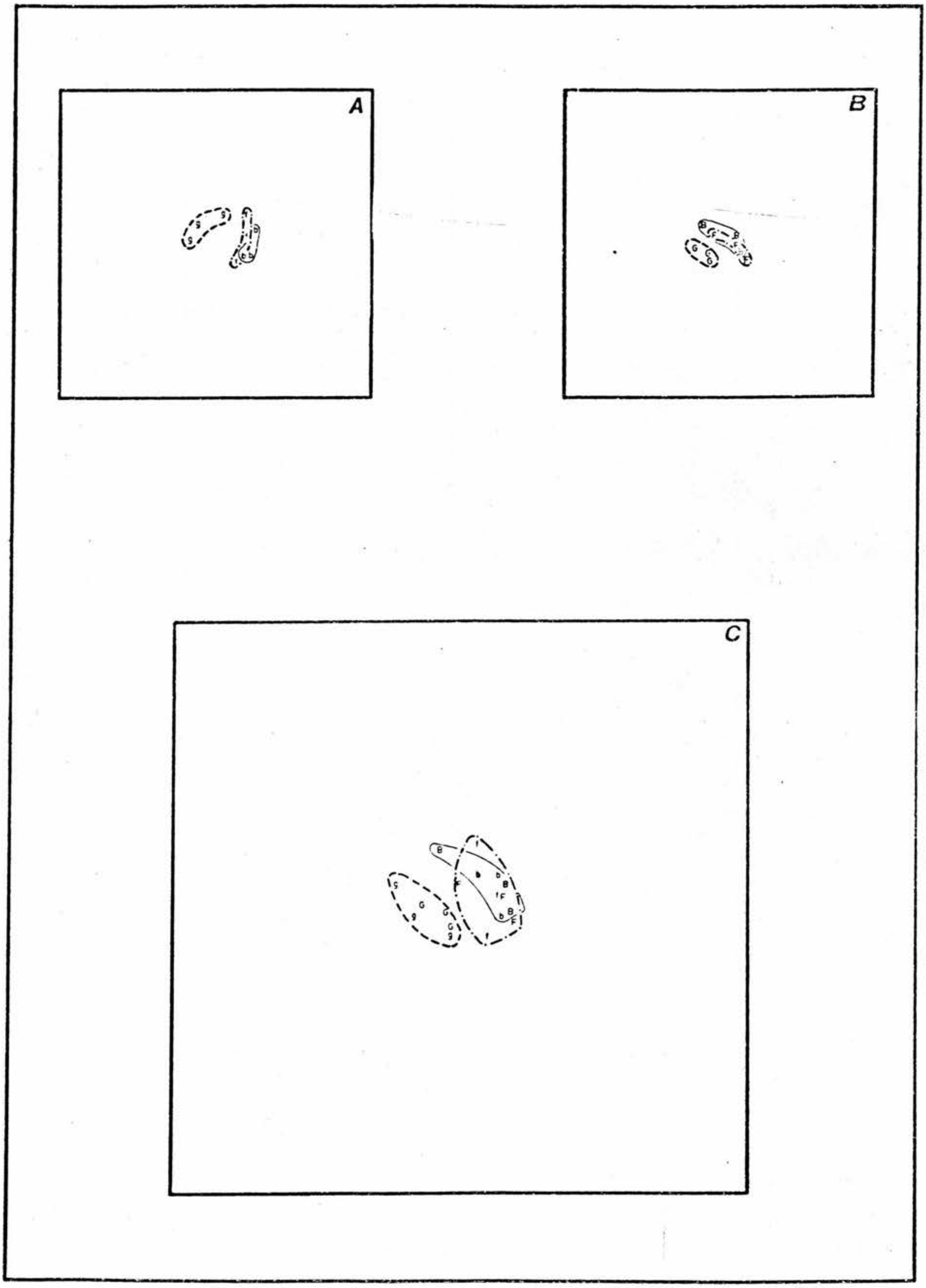


Figure 6.9

Beach, glacial and fluvioglacial centroids and 95% confidence circles for A) porphyritic B)non-porphyritic and C) porphyritic and non-porphyritic stones using only morphometric indices for three size grades.

have similar roundness characteristics.

As roundness appears to be the best measure that distinguishes between stones subject to glacial, fluvioglacial and beach processes, differences should be apparent in frequency histograms of the data. Percentage frequency histograms of various size grades of stones of both essexite types are shown in Figs 6.10, 6.11 and 6.12. It is clear that histograms for glacial stones are distinct from those for the other two categories in that the majority of values for glacial stones are grouped into low roundness classes. The histograms for fluvioglacial and beach stones, on the other hand, have fewer stones of low roundness and a greater range of roundness values than for glacial stones. The histograms for fluvioglacial and beach stones are also difficult to distinguish from one another and this supports the view expressed earlier that the dominance of abrasion in these two environments combined with the low efficiency but long duration of beach processes on the one hand, compared to the short duration but high efficiency of fluvioglacial processes on the other have led to a close correspondence in the roundness characteristics of stones in these two environments.

<u>Bulk density and uniaxial compressive strength of essexite</u>

In chapter 5, evidence for the crushing of non-porphyritic essexite stones, chiefly along bedrock joints, was presented. However, the fact that few essexite

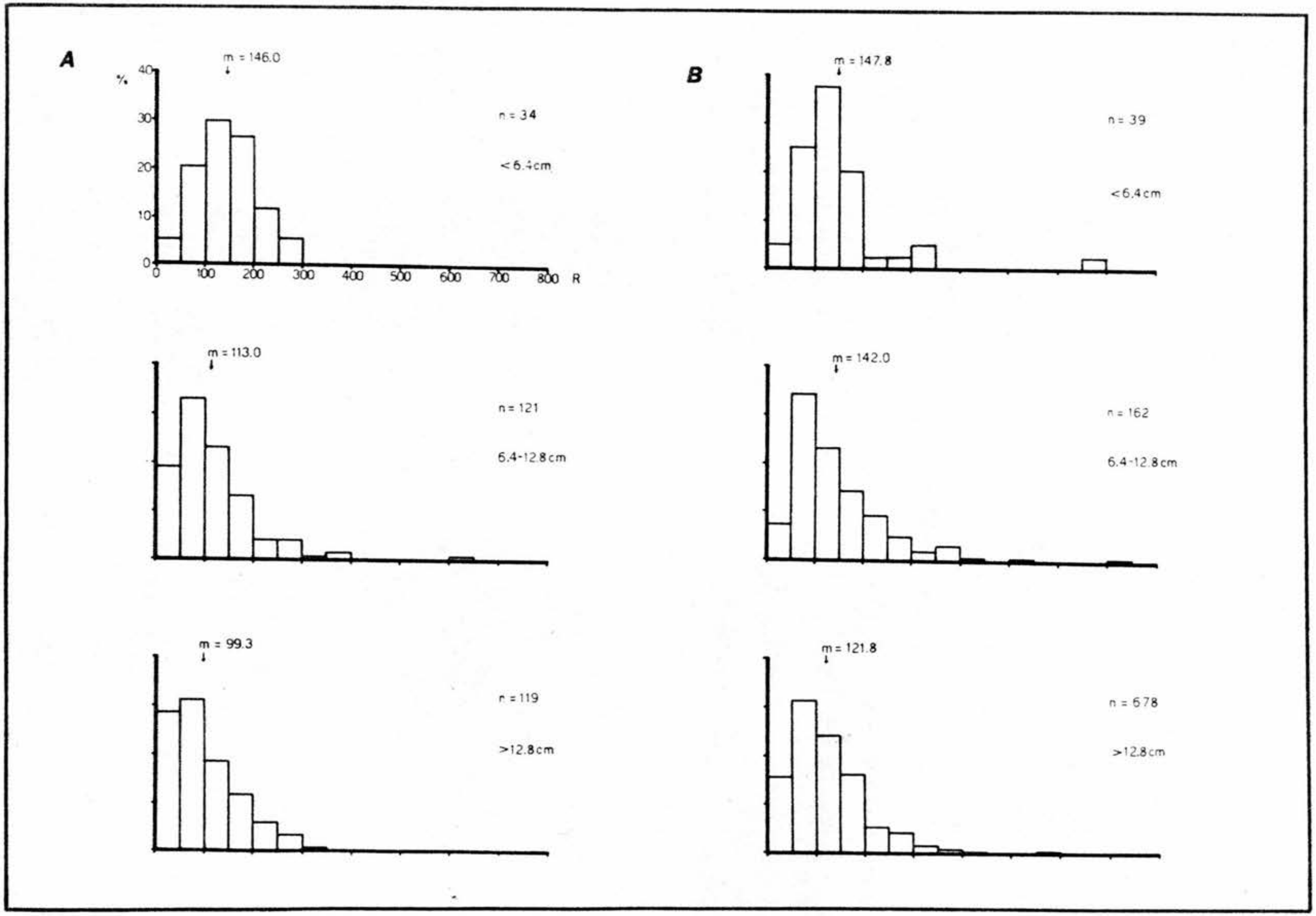


Figure 6.10

Histograms of roundness for A) porphyritic and B) non-porphyritic glacial stones.

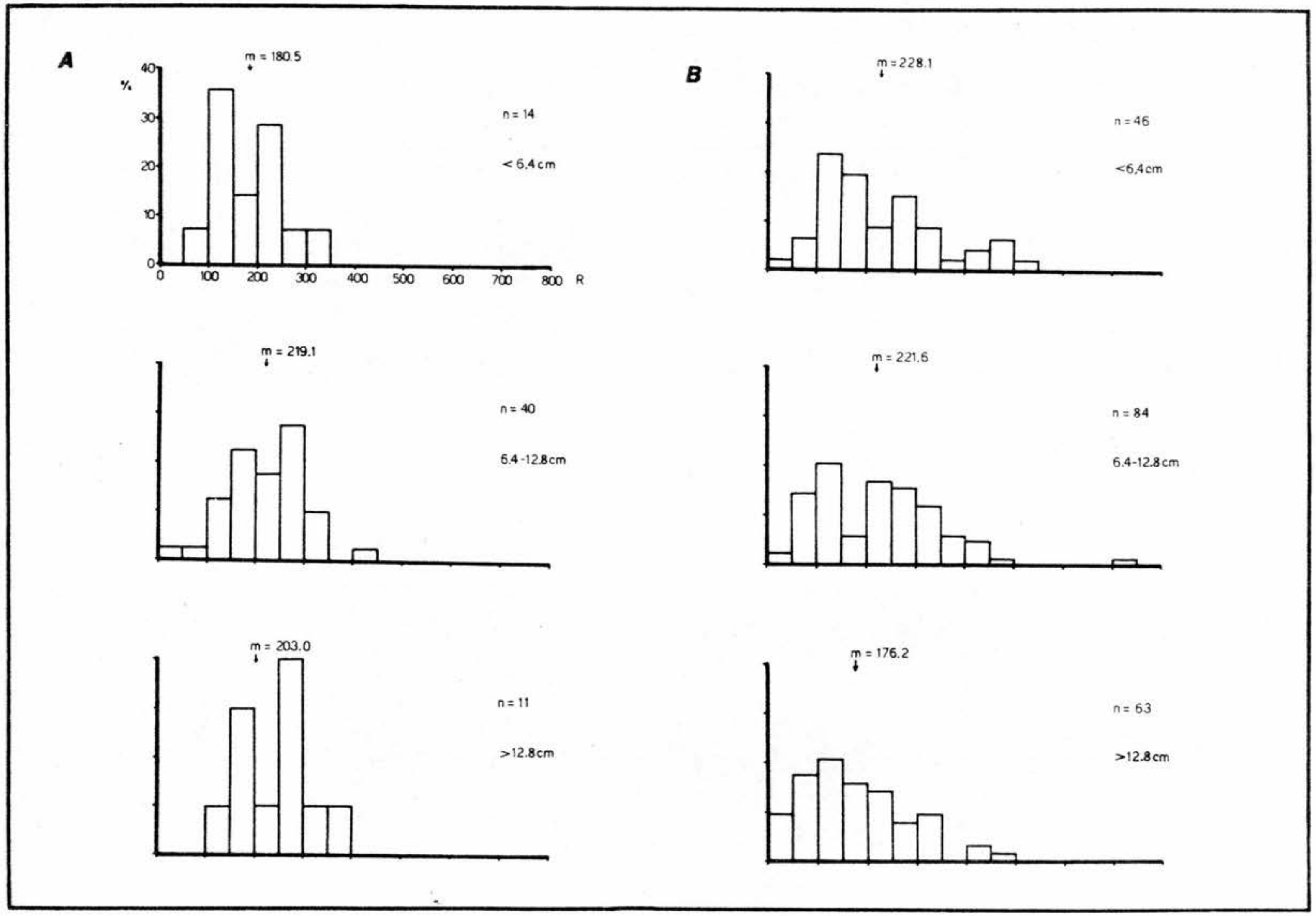
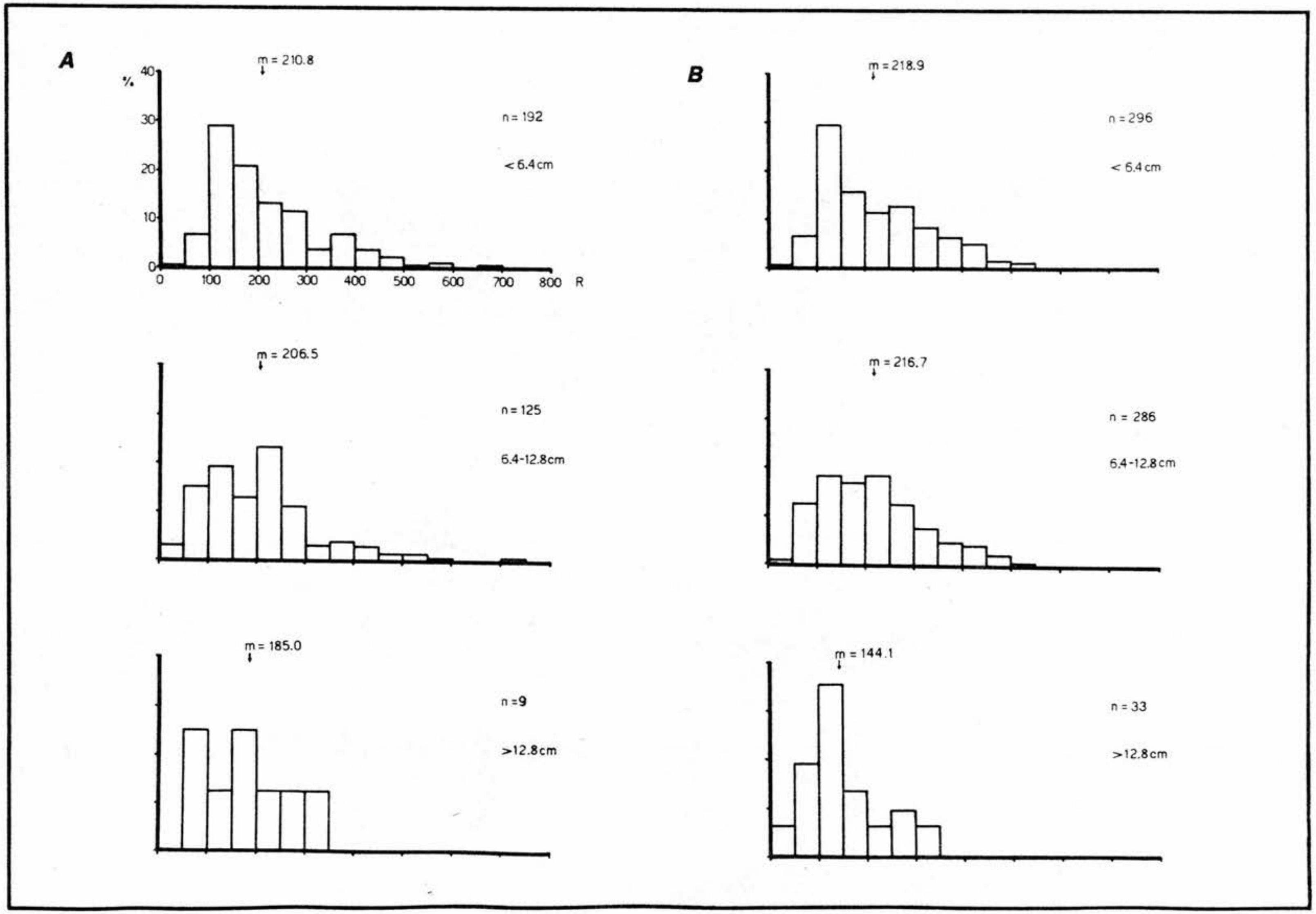


Figure 6.11

Histograms of roundness for A) porphyritic and B) non-porphyritic fluvioglacial stones.



<u>Figure 6.12</u>

Histograms of roundness for A) porphyritic and B) non-porphyritic beach stones.

Table 6.6 Data from multiple discriminant analysis: all variables

(a) Centroids to which porphyritic stones are nearest

	g	b	f
g	180	41	53
b	16	229	81
f	11	21	33

(b) Proportion of total dispersion accounted for:-

A(phi)=92.8%

R= 7.2%

(c) Centroids to which non-porphyritic stones are nearest

	G	B	F
G	674	75	130
B	36	431	148
F	52	65	76

(d) Proportion of total dispersion accounted for:-

A(phi)=98.2%

R= 1.8%

(e) Centroids to which porphyritic and non-porphyritic stones are nearest

	G	B	F	g	b	f
G	524	11	45	192	41	66
B	13	92	39	61	257	153
F	34	13	32	28	43	43
g	69	7	12	24	31	31
b	6	50	13	23	175	59
f	2	6	10	9	12	26

(f) Proportion of total dispersion accounted for:-

A(phi)=92.1%

B= 4.8%

<u>Table 6.7</u> <u>Data from multiple discriminant analysis: size variables</u>

(a) Centroids to which porphyritic stones are nearest

	g	b	f
g	165	40	69
b	16	224	86
f	13	19	33

(b) Proportion of total dispersion accounted for:-

A(phi)=95.4%

B= 4.6%

(c) Centroids to which non-porphyritic stones are nearest

	G	B	F
G	653	66	160
B	25	430	160
F	47	70	76

(d) Proportion of total dispersion accounted for:-

A(phi)=99.4%

A= 0.6%

(e) Centroids to which non-porphyritic and porphyritic stones are nearest

	G	B	F	g	b	f
G	526	18	0	194	30	111
B	14	101	2	43	253	202
F	34	22	1	46	37	53

	G	B	F	g	b	f
g	71	12	0	94	27	70
b	6	57	4	15	168	76
f	2	10	2	11	9	31

(f) Proportion of total dispersion accounted for:-

A(phi)=95.5%

c= 3.8%

Table 6.8 Data from multiple discriminant analysis: morphometric variables

(a) Centroids to which porphyritic stones are nearest

	g	b	f
g	188	41	45
b	83	149	94
f	9	27	29

(b) Proportion of total dispersion accounted for:-

R=95.0%

F= 5.0%

(c) Centroids to which non-porphyritic stones are nearest

	G	B	F
G	617	120	142
B	199	230	186
F	77	54	62

(d) Proportion of total dispersion accounted for:-

R=95.7%

F= 4.3%

(e) Centroids to which non-porphyritic and porphyritic stones are nearest

	G	B	F	g	b	f
G	214	28	93	365	98	81
B	97	81	114	81	135	107
F	22	15	47	48	35	26
g	44	7	26	153	23	21
b	52	39	53	48	86	48
f	10	2	19	4	11	19

(f) Proportion of total dispersion accounted for:-

R=94.2%

F= 3.9%

Table 6.9 Data from multiple discriminant analysis: morphometric variables for different size grades

(a) Centroids to which porphyritic stones are nearest

	g_1	g_2	g_3	b_1	b_2	b_3	f_1	f_2	f_3
g_1	9	8	3	0	1	2	10	2	3
g_2	17	29	31	2	4	7	14	4	13
g_3	10	21	44	1	4	10	10	4	11
b_1	27	13	15	16	17	23	44	16	21
b_2	6	6	14	5	23	22	18	16	15
b_3	0	1	1	1	0	2	1	2	1
f_1	1	0	0	0	1	2	7	1	2
f_2	5	2	2	1	6	2	8	4	10
f_3	0	0	2	1	0	2	0	0	6

(b) Proportion of total dispersion accounted for:-

R=71.9%

c/b=18.9%

(c) Centroids to which non-porphyritic stones are nearest

	G_1	G_2	G_3	B_1	B_2	B_3	F_1	F_2	F_3
G_1	9	6	6	0	1	9	4	1	3
G_2	27	14	40	10	2	28	17	11	13
G_3	87	55	229	20	19	124	41	44	59
B_1	20	25	27	30	17	40	84	35	18
B_2	13	21	28	27	30	44	55	41	27
B_3	3	1	7	0	0	16	3	1	2
F_1	4	3	7	5	1	3	15	6	2
F_2	5	3	13	3	6	9	23	16	6
F_3	8	2	12	3	2	7	8	11	10

(d) Proportion of total dispersion accounted for:-

R=81.6%

c/b= 8.9%

(e) Centroids to which non-porphyritic and porphyritic stones are nearest

	G_1	G_2	G_3	B_1	B_2	B_3	F_1	F_2	F_3	g_1	g_2	g_3	b_1	b_2	b_3	f_1	f_2	f_3
G_1	7	0	0	0	0	8	1	1	2	5	2	2	0	1	4	5	0	1
G_2	20	1	3	3	0	18	9	10	8	17	13	26	1	1	6	19	1	6
G_3	59	1	15	3	1	75	9	30	28	51	100	142	0	19	28	77	2	38
B_1	14	0	4	8	2	23	56	21	11	22	8	11	0	10	24	45	13	24
B_2	10	0	2	13	2	25	31	29	13	25	6	21	0	19	11	37	9	33
B_3	1	0	0	0	0	10	1	1	0	2	2	10	0	0	0	2	0	4
F_1	4	0	0	3	0	3	10	5	1	3	2	4	0	1	3	6	1	0
F_2	4	0	1	2	2	4	18	12	2	4	4	13	0	7	1	5	1	4
F_3	6	0	0	1	1	5	3	7	3	4	3	12	0	3	1	5	3	6

	G_1	G_2	G_3	B_1	B_2	B_3	F_1	F_2	F_3	g_1	g_2	g_3	b_1	b_2	b_3	f_1	f_2	f_3
g_1	2	0	1	1	0	0	1	1	3	8	7	3	0	1	1	7	0	2
g_2	15	0	0	1	0	9	3	4	4	12	18	28	0	1	4	16	1	5
g_3	7	0	2	0	1	15	0	6	4	5	14	38	0	3	2	11	0	7
b_1	16	0	3	6	3	17	32	7	2	14	8	16	0	8	10	31	2	17
b_2	4	0	4	2	3	18	6	13	2	3	4	12	0	15	9	16	3	11
b_3	0	0	0	1	0	1	0	1	1	0	1	1	0	0	1	1	0	1
f_1	1	0	0	0	0	0	3	1	0	0	0	0	0	1	2	4	0	2
f_2	1	0	0	0	0	2	5	5	2	4	1	2	0	2	0	5	1	10
f_3	0	0	1	0	0	2	1	0	1	0	0	1	0	1	1	0	0	3

(f) Proportion of total dispersion accounted for:-

R=77.7%

c/b=11.8%

Key to symbols

Porphyritic essexite

g_1=glacial stones <6.4cm
g_2= " " 6.4-12.8cm
g_3= " " >12.8cm

b_1=beach stones <6.4cm
b_2= " " 6.4-12.8cm
b_3= " " >12.8cm

f_1=fluvioglacial stones <6.4cm
f_2= " " 6.4-12.8cm
f_3= " " >12.8cm

Non-porphyritic essexite

G_1=glacial stones <6.4cm
G_2= " " 6.4-12.8cm
G_3= " " >12.8cm

B_1=beach stones <6.4cm
B_2= " " 6.4-12.8cm
B_3= " " >12.8cm

F_1=fluvioglacial stones <6.4cm
F_2=fluvioglacial stones 6.4-12.8cm
F_3=fluvioglacial stones >12.8cm

particles were present in the till immediately down-ice of the essexite outcrops implies that this process has not been vigorous. In chapter 4 it was suggested that one of the reasons for lack of essexite fragments may have been the strength of the essexite stones which enabled them to resist the crushing forces operating during glacial transport. Since no data on the strength of essexite was available, it was considered desirable to carry out a standard uniaxial compressive strength test. In this test the force is gradually increased on the unconfined specimen in one direction until failure occurs.

Four non-porphyritic and five porphyritic essexite blocks were cut from bedrock masses. Care was taken to ensure that bedrock joints were avoided and, since compressive strength alters according to the dimensions of the specimen (Obert <u>et al</u>.,1946), the blocks were accurately measured prior to being tested using a Losenhausen compressive strength test apparatus (Plate 9). It was possible with this equipment to read off the exact load being applied at the time of failure. The results (Table 6.10) indicate that the mean compressive strengths of the two essexite types are similar. However the standard deviation for the strength of the porphyritic blocks is considerably higher than for the non-porphyritic blocks. This can be explained in terms of the different structure of the two essexite types. In the non-porphyritic variety the titanaugite crystals are large and therefore their tendency to fail depends on the alignment of the crystal faces (Farmer,1968); hence the large dispersion of individual compressive strengths. The titanaugite crystals in the non-porphyritic variety, on the other hand, are small and less well formed and

Table 6.10 Results of uniaxial compressive strength test on porphyritic and non-porphyritic essexite

(a) Non-porphyritic blocks

	Compressive strength(kg/cm^2)
	1302
	1572
	1563
	1444

mean = 1470 standard deviation = 140.0

(b) Porphyritic blocks

	Compressive strength(kg/cm^2)
	1366
	1704
	997
	1591
	1755

mean = 1497 standard deviation = 208.9

Table 6.11 Uniaxial compressive strength of some common rocks (after Farmer,1968,p.57)

Rock type	Compressive strength(kg/cm^2)
Granite	1,000-2,500
Diorite	1,800-3,000
Dolerite	2,000-3,500
Gabbro	1,800-3,000
Basalt	1,500-3,000
Sandstone	200-1,700
Shale	100-1,000
Limestone	300-2,500
Dolomite	800-2,500

Table 6.12 Bulk density of some common rocks (Farmer, 1968,p.15)

Rock type	Bulk density (gm/cc)
Granite	2.6-2.7
Dolerite	3.0-3.05
Rhyolite	2.4-2.6
Andesite	2.2-2.3
Gabbro	3.0-3.1
Basalt	2.8-2.9
Sandstone	2.0-2.6
Shale	2.0-2.4
Limestone	2.2-2.6
Dolomite	2.5-2.6
Gneiss	2.9-3.0

therefore a difference in their alignment is unlikely to affect the compressive strength of the block to such an extent.

A comparison of the results in Table 6.10 with examples of the range of values derived for other rock types (Table 6.11) indicates that essexite is a rock of moderately high strength.

Bulk density has a positive curvilinear relationship with compressive strength (Farmer,1968) and is therefore another indicator of the resistance of a rock to crushing. By accurately weighing unweathered fragments of non-porphyritic and porphyritic essexite and then immersing them in a graduated flask, the bulk densities of both essexite types were determined. A value of 3.05 gm/cc was obtained for porphyritic essexite and 3.06gm/cc for the non-porphyritic variety. Table 6.12 shows bulk densities of other common rock types. Only the values for two other rock types (dolerite and gabbro) equal or exceed the values obtained for essexite.

Experimental abrasion of essexite fragments

It has been shown that abrasion is a particularly important process in the fluvioglacial and beach environments. In order to study abrasion and its effect on the roundness of essexite stones it was decided that a laboratory experiment should be carried out. In the field, a controlled situation is difficult to achieve especially when dealing with fossil deposits as with fluvioglacial and glacial material. However, in the laboratory a controlled situation can be attained by subjecting rock particles to artificial abrasion in a revolving drum or similar apparatus.

A number of workers have abraded rock fragments experimentally in the laboratory. Daubrée(1879) was the first to use a tumbling barrel to investigate the rate of wear on rock particles. The most important of his discoveries were that the rate of wear is greater for angular and large particles than for rounded and small particles, that wear is a function of abrasion and breakage and that the observed decrease in the size of particles along a stream is a result of selective transport as well as of wear.

Wentworth(1919,1922b,1922c) studied abrasion using a metal drum lined with soft wood. He emphasised that many factors control the change in shape, size and surface texture including size, angularity, rock type, nature of motion, distance, size and number of associated particles. He demonstrated that roundness increases rapidly at first and then more gradually, and found that it was a function of size as well as of hardness.

Marshall(1927) attempted to simulate the processes operating in a beach environment. He considered that "wear" consisted of three separate processes; abrasion, impact and grinding.

Krumbein(1941b) used a tumbling barrel with a water feed to study the effect of abrasion on the size, sphericity and roundness of crushed limestone fragments. His main findings, that size is continuously reduced until ultimately the particle wears away, and that "roundness and sphericity approach asymptotes" (Krumbein, 1941b,p.493) are shown diagrammatically in Fig.6.13.

Sarmiento(1945) carried out a similar study to that of Krumbein(1941b) on the abrasion of limestone fragments. Kuenen(1956), in a study of abrasion using a concrete basin with differently textured floors, subdivided the process of wear into splitting, crushing, chipping, cracking and grinding (i.e. abrasion). He found that large material tends to lose a greater proportion of its weight per unit distance of travel than small material.

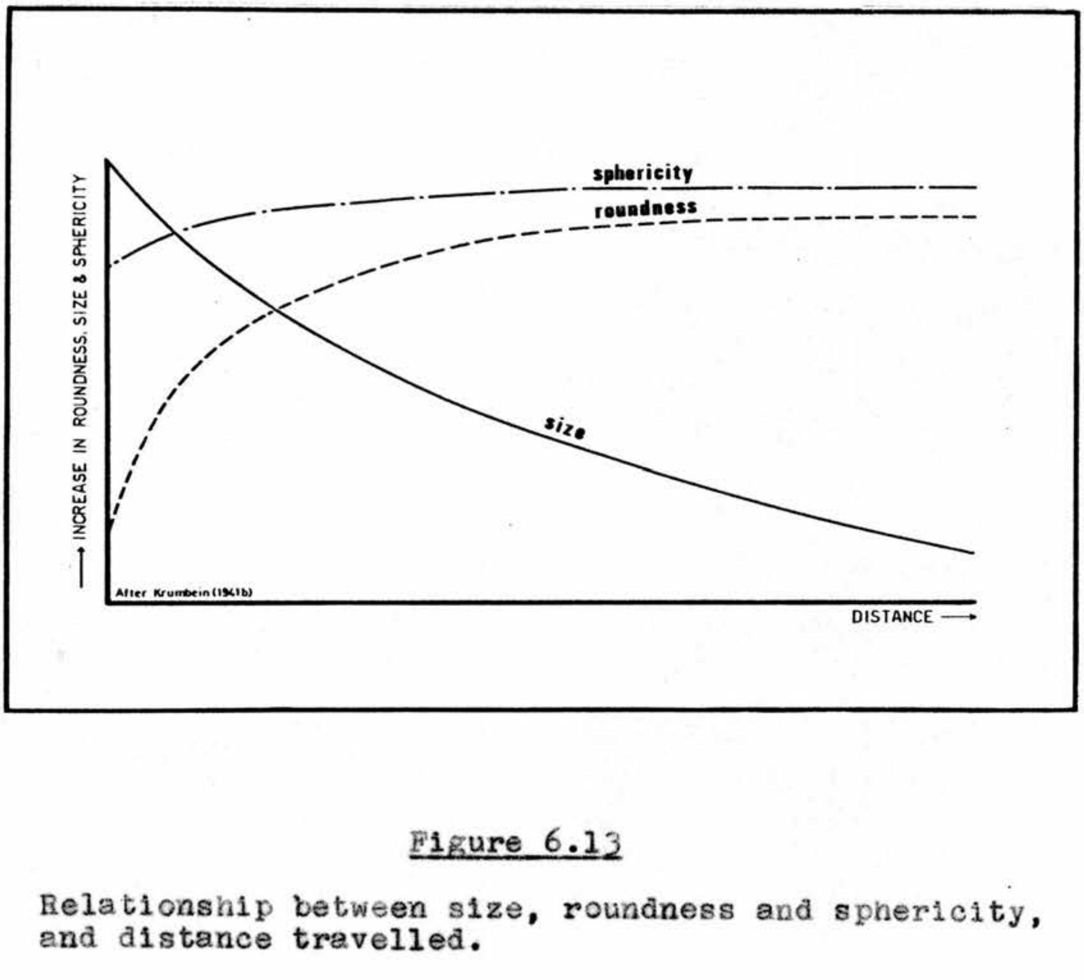


Figure 6.13

Relationship between size, roundness and sphericity, and distance travelled.

He also showed that the rate of rounding varies according to the rock type.

Attempts have been made by Beaumont(1967) and Drake(1968), for example, to simulate subglacial abrasion but the correspondence of these experimental processes to those occurring beneath great thicknesses of ice seems doubtful due to their inability to simulate processes that are little understood. Indeed, the simulation of any natural processes by tumbling experiments is bound to be a poor imitation as Bonney(1888), Krumbein(1941b) and Kuenen(1956) realised. Nevertheless, it does allow the effects of abrasion to be studied in isolation.

For the experimental abrasion of essexite material it was decided that the revolving drum that had been used for breaking up the clay aggregates of the till samples described in chapter 4 should be used. Since an important factor in determining the shape, sphericity and roundness of rock particles is size, different sizes of essexite fragments were used. Originally two size grades of essexite particles, produced by hammer blows on bedrock blocks, were abraded in the drum. However, after only a short period of revolution many particles were found to have been broken into pieces.

To avoid this rapid breakage of fragments which did not allow a controlled study to be carried out, variously shaped essexite fragments of two sizes were cut from a block of the non-porphyritic bedrock using a "Cutrock" machine. Three basic shapes in two different sizes were cut, making a total of four large and four small "blocks", "blades" and "triangular blocks".

The total weights of each of the six categories of shape were derived and the particles placed inside the drum together with a weighed amount of particles from a till sample collected for the determination of its content of Dalmahoy material (see chapter 4). The till particles used were those retained on the 32mm, 16mm and 8mm sieves in order that the essexite particles would be subjected to wear from a range of sizes of material. The steel drum had a diameter of 17.5cm and rotated at 40 r.p.m.

After an hour in motion the drum was stopped and the essexite particlesremoved. They were accurately measured using calipers with a vernier scale which allowed an accuracy of ± 0.1mm in the measurements. The distance between the sides, edges and corners of all of the cubes was measured and the long(a), intermediate(b) and short(c) axes of the blades and triangular blocks were also recorded. The minimum radius of curvature of the particles was measured by comparison with a target of concentric circles of radii 0.1cm to 0.5cm. The total weights of each group of four essexite particles and the total weight of the till particles were recorded. The steel drum was reloaded and rotated for further periods of 1, 2, 4, 8, 16 and 32 hours, each period of rotation being preceded by weighings of till and essexite particles and measurement of various axes of the essexite particles.

The results are shown in Table 6.13. Size (i.e. weight) and roundness values for the two size categories are shown, but sphericity was not calculated because the artificial shapes changed little during the experiment. The roundness of the blocks (Fig.6.14; Plates 13 & 14) rises rapidly from an assumed value of 0 up to 2 to 4 hours of rotation, thereafter increasing more slowly up to 64 hours. For the small blocks, and to a lesser extent the small blades, roundness appears to reach an asymptote after 64 hours of rotation. Roundness values of the remaining categories of particle shapes do not appear to be approaching a maximum value after 64 hours of rotation. The roundness values for all three shapes of essexite particles are consistently higher for the large particles than for the small particles. This corroborates the results of experimental abrasion given by Krumbein(1941b) and Sarmiento(1945) who likewise found that the rate of rounding was proportional to size. Krumbein(1941b) however noted that under natural conditions the competence of a stream may not permit transportation of large particles which will consequently not be as rounded as smaller fragments. The deviations of the points representing roundness of particles from a smooth curve as in Fig.6.13 can be explained by the chipping of small fragments which resulted in a reduction in roundness and size values. The large blocks and blades of both sizes were the only categories not to undergo chipping. The small triangular blocks suffered the most chipping as a result of their angular corners.

The size of each of the six categories of particles expressed as percentage weight are shown in Figs 6.14 and 6.15. Size decreases rapidly within the first few hours of rotation but thereafter maintains a slow, steady decline. This supports the evidence of Wentworth (1919), Krumbein(1941b), Sarmiento(1945) and Kuenen(1956) by indicating that "size will be continuously reduced until ultimately the particles will be worn away" (Krumbein,1941b,p.493).

Fig.6.14 indicates that the corners of both small and large blocks are worn down more rapidly than the edges and sides. Values for all three measures decline at a faster rate for the small blocks than for the large blocks. It might be expected that the edges and corners of the large blocks should conversely be reduced more rapidly as they tend to have a greater roundness than the small blocks. This apparent anomaly can be explained in terms of the difference in the nature of wear on the large blocks, where it was mainly abrasion, compared to the small blocks, where chipping also occurred which led to increased angularity.

Kuenen(1956) observed that the percentage loss in weight of a coarse grained igneous rock was far less than for limestone and lavas. The till particles used in the present analysis consisted mainly of a mixture of sedimentary and fine grained igneous rock. The percentage loss in weight of this material was 41.6% compared to only 10.5% for the essexite particles. This indicates that, despite the chipping and abrasion that the essexite fragments underwent, they were far better able to withstand these processes than the till particles of mixed lithology.

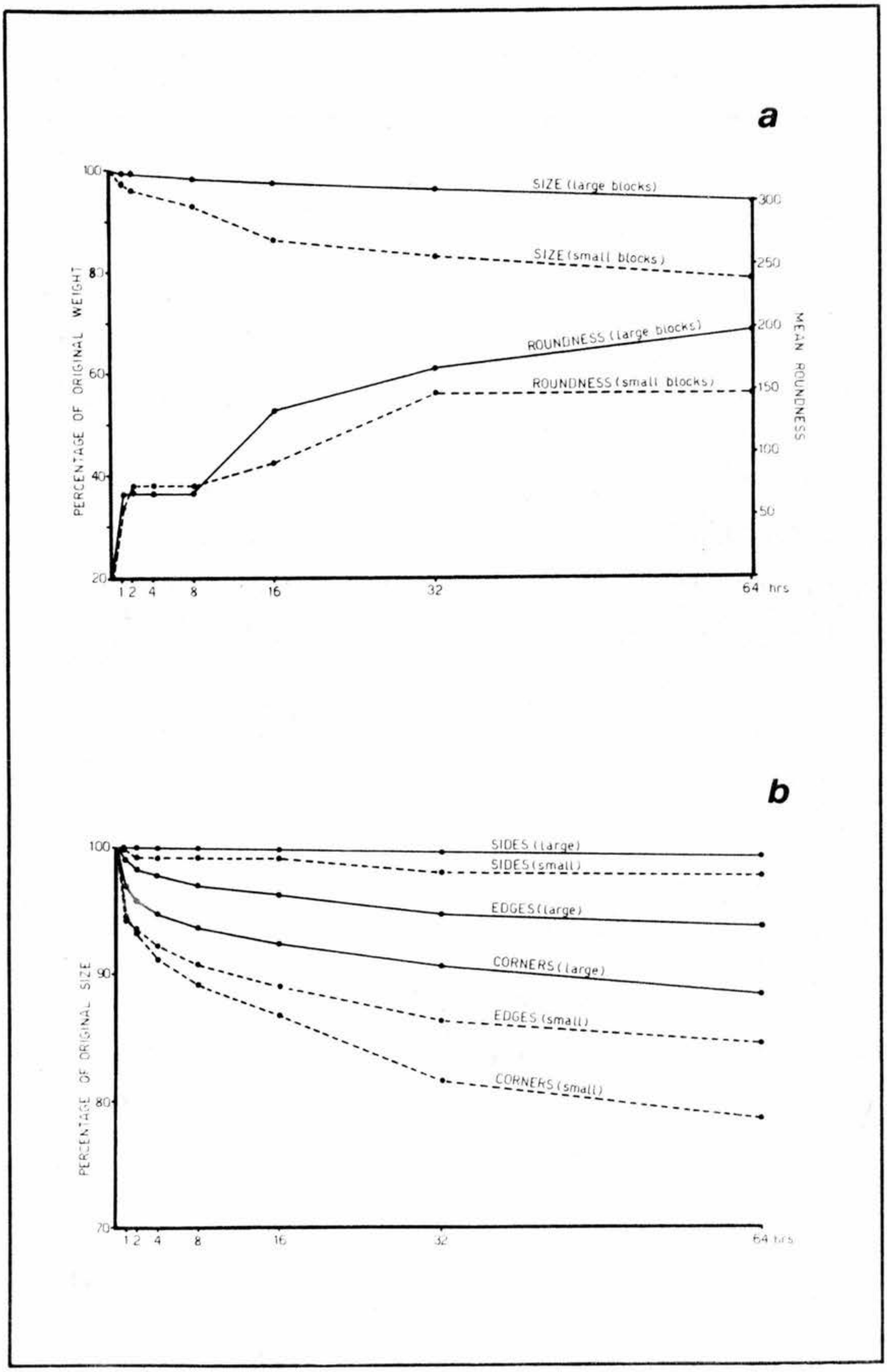


Figure 6.14

Plots of a) roundness and size of blocks against time and b) decrease in size against time.

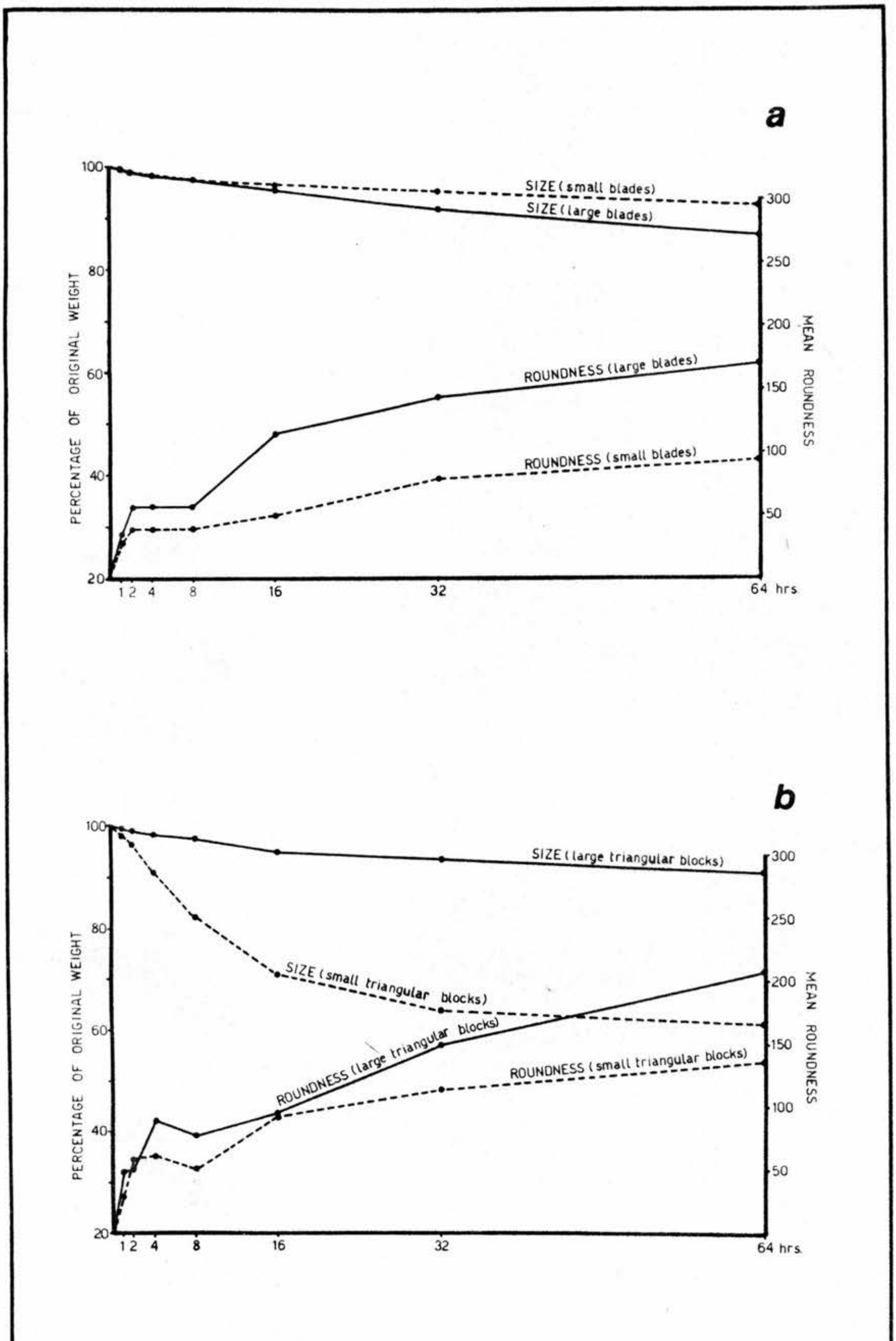


Figure 6.15

Plots of roundness and size against time for a) blades and b) triangular blocks.

Table 6.13 Results of experimental abrasion of essexite particles

	Hours of rotation							
	0	1	2	4	8	16	32	64
(a) Blocks(large)								
sides($\bar{x}$)	3.022	3.022	3.022	3.022	3.022	3.015	3.013	3.010
edges($\bar{x}$)	4.221	4.181	4.148	4.130	4.094	4.067	4.007	3.917
corners ($\bar{x}$)	5.085	4.920	4.866	4.815	4.741	4.700	4.611	4.507
wt. (gm)	160.1	159.3	159.1	158.6	158.1	157.0	155.2	152.4
R	0	66.4	66.4	66.4	66.4	132.7	166.3	199.3
(b) Blocks(small)								
sides($\bar{x}$)	1.381	1.378	1.370	1.370	1.370	1.370	1.358	1.355
edges($\bar{x}$)	1.984	1.867	1.857	1.830	1.800	1.765	1.714	1.680
corners ($\bar{x}$)	2.281	2.159	2.123	2.077	2.032	1.954	1.861	1.792
wt. (gm)	30.1	29.4	29.0	28.6	28.1	26.1	25.2	24.0
R	0	54.8	73.0	73.0	73.0	90.3	147.6	147.3
(c) Blades(large)								
a-axis($\bar{x}$)	3.532	3.532	3.532	3.525	3.525	3.522	3.517	3.506
b-axis($\bar{x}$)	1.887	1.877	1.872	1.872	1.872	1.872	1.862	1.860
c-axis($\bar{x}$)	1.345	1.345	1.345	1.345	1.342	1.342	1.335	1.320
wt. (gm)	103.4	103.0	102.4	101.7	101.0	99.1	95.7	91.0
R	0	35.3	56.6	56.8	56.8	113.6	142.2	171.1
(d) Blades(small)								
a-axis($\bar{x}$)	2.557	2.557	2.555	2.542	2.542	2.542	2.527	2.522
b-axis($\bar{x}$)	1.245	1.225	1.225	1.225	1.222	1.222	1.212	1.212
c-axis($\bar{x}$)	0.947	0.947	0.947	0.945	0.945	0.942	0.942	0.935
wt. (gm)	33.3	33.2	33.0	32.8	32.5	32.3	32.0	31.3
R	0	29.3	39.1	39.3	39.3	49.5	79.1	79.3

(e) <u>Triangular blocks(large)</u>

a-axis($\bar{x}$)	4.115	4.037	3.977	3.930	3.865	3.810	3.705	3.612
b-axis($\bar{x}$)	2.790	2.787	2.787	2.787	2.787	2.782	2.782	2.780
c-axis($\bar{x}$)	2.072	2.062	2.047	2.045	2.020	2.005	1.982	1.957
wt. (gm)	142.6	141.4	141.0	140.1	139.0	134.1	134.1	130.5
R	0	49.5	50.3	88.9	76.9	94.4	150.2	208.1

(f) <u>Triangular blocks(small)</u>

a-axis($\bar{x}$)	2.665	2.582	2.532	2.512	2.435	2.162	1.970	1.887
b-axis($\bar{x}$)	1.440	1.440	1.437	1.437	1.375	1.359	1.357	1.350
c-axis($\bar{x}$)	1.407	1.395	1.387	1.372	1.295	1.287	1.157	1.130
wt. (gm)	31.6	31.0	30.5	28.7	26.0	22.5	20.3	19.5
R	0	33.7	58.8	60.9	50.7	92.5	114.0	136.6

$\bar{x}$ = mean length measured in cm.

Before applying the results of the experimental abrasion of essexite particles to the data derived for essexite stones in the field, a number of limitations should be noted. Firstly, as has been mentioned earlier, the process of abrasion in natural conditions involves a whole range of complexities with which the results from a tumbling experiment are not always reconcilable (Bonney, 1888; Gregory & Cullingford,1974). Secondly, some aspects of the present study differ significantly from other studies of experimental abrasion. In the majority of other studies the sides of the drum are lined with soft wood in order that attrition between particles can be investigated, or else the particles are made to move across for instance, a simulated stream bed (Kuenen,1956). In the present study, however, wear has occurred on the essexite particles from contact with the steel drum and other particles. There is also the point that most experiments have been carried out with a water feed (e.g. Wentworth,1919; Marshall,1927; Krumbein,1941b; Sarmiento, 1945; Kuenen,1956), but in the present study water was absent. Thirdly, only certain shapes of particles were used, and the extent to which the results are applicable to the essexite stones measured in the field is not entirely clear. Fourthly, the relation of the size of mineral grains to the size of particles in the experiment is different to that in the real world situation where the mineral grains are proportionally smaller. The relatively large size of minerals compared to the size of the particles in the experiment has been partly responsible for the chipping along cleavage planes.

The most significant result to emerge from the experimental abrasion of essexite particles is that roundness values are generally higher for large particles than for small particles. When the roundness values for different size grades of glacial, fluvioglacial and beach stones are viewed in the light of this statement, many of the apparent anomalies can be resolved and a number of the tentative views supported. Firstly, the fact that roundness for different size grades of glacial stones (Table 6.1b & c) decreases steadily with size, thereby contradicting the evidence from the experimental abrasion, supports the idea that crushing is the dominant process in the glacial environment. For porphyritic fluvioglacial stones (Table 6.2b) roundness tends to increase with size which agrees with the experimental abrasion results. This suggests not only that abrasion is the dominant process in the fluvioglacial environment but also that material up to 25.6cm in size was included in the stream bedload. For beach non-porphyritic stones, roundness increases slightly up to the 6.4-12.8cm size grade, and although this is not repeated for porphyritic stones it implies that abrasion is the important process for material of this size on the modern beaches (Table 6.3b & c). However in the 12.8-25.6cm size grade for both essexite varieties, roundness falls below the values for the same size grades of fluvioglacial stones. This supports the view that fragmentation has occurred on beach stones larger than 12.8cm as a result of storm conditions whereas for fluvioglacial stones of this size abrasion remains the dominant process.

The results from the experimental abrasion, from the compressive strength test and from the bulk density analysis have shown that essexite is a rock of relatively high strength that is able to withstand wear to a greater extent than many other rock types. This ability to withstand wear helps to explain why essexite stones in the fluvioglacial and beach environments, although more rounded than glacial stones, nevertheless record comparatively low values for the respective environments (cf. King & Buckley,1968; Crofts,1974). The relative high strength of both essexite types is consistent with the view expressed in chapter 5 that glacial crushing of essexite fragments has been mainly concentrated along bedrock joints.

C H A P T E R 7

HEAVY MINERAL ANALYSIS

The results of the dispersion of erratic fragments in till (chapter 4) indicated that essexite material was present in the till down-ice of the essexite rock outcrops. In chapter 5 it was shown that essexite stones in the walls had undergone crushing during glacial transport and in chapter 6, measurements of roundness on essexite stones showed that abrasion had taken place during fluvio-glacial transport. Dreimanis and Vagners(1965,1969,1971) argued that crushing of rock fragments or clasts during glacial transport leads to the formation of a terminal grade represented by one or a number of matrix modes. With a greater distance of travel the matrix mode (or modes) increases proportionally to the clast mode. Similar results were obtained by Gaudin(1926) experimentally.

As a result of crushing of essexite stones during glacial transport it might be expected therefore that a multimodal terminal grade would be produced, each mode representing an individual mineral comprising the essexite rock (see chapter 3). In order to determine the nature of the dispersion of fine essexite material down-ice of the outcrops, analysis of the heavy mineral sand grains within till and fluvioglacial sand was undertaken. For the purposes of the present analysis heavy minerals have a specific gravity of more than 2.89.

The advantage of separating heavy mineral grains from a sample of sand lies in the removal of large quantities of ubiquitous minerals such as quartz and feldspar from sedimentary sources. The small residue of heavy minerals includes detrital material of igneous and metamorphic origin. There is therefore an obvious application of this technique to tracing the dispersion of fine particles derived from the igneous essexite outcrops in an area covered extensively by sedimentary strata.

The first intensive study of heavy minerals in unconsolidated materials was made by Boswell(1916) in a petrological study of North Sea drift deposits. In till studies, heavy mineral analysis has been mainly used either to differentiate between till sheets (e.g. Kruger, 1937; Dreimanis et al.,1957; Dreimanis,1960; Moss & Ritter,1962; Willman et al.,1963; Connally,1964) or to investigate provenance (e.g. Gravenor,1951; Smithson, 1953; Crampton,1959; Kaiser,1962; McDonald,1966; Pettersson,1968; Mickelson,1971; Shilts,1973b).

Since provenance was the main interest in the present study, one or a number of distinctive minerals within essexite rock was required as an indicator. As has already been pointed out in chapter 3, the Main Study Area is located within a region that includes a large number of small igneous intrusive outcrops as well as extensive areas of volcanic rock that also act as sources of heavy mineral grains and contain many of the same minerals as essexite.

Two minerals, however, occurring in both porphyritic and non-porphyritic essexite were sufficiently distinctive within the area to be regarded as indicators of these outcrops. They are nepheline and titanaugite. Nepheline is a rare detrital mineral, lighter than bromoform (S.G.=2.89) with a specific gravity of about 2.55-2.66 (Milner,1962). It is not an abundant mineral in essexite (Harker,1960), is difficult to distinguish from alkali feldspars under the microscope (Cox et al., 1967) and occurs in the Fintry phonolite, which is a small intrusive igneous outcrop situated c.6km north of the essexite outcrops. It is prone to alteration to zeolites and cancrinites, and is thus somewhat unstable and unlikely to be preserved.

Titanaugite forms the dark crystals in essexite that are large and euhedral in the porphyritic variety but small and less well formed in the non-porphyritic type. The mineral has a relatively high specific gravity of about 3.2-3.6. Although almost indistinguishable from other varieties of augite in most optical properties, its colour in plane polarised light is characteristic. The pyroxene group, to which all augites belong, occurs about halfway in a table of minerals calibrated in order of resistance to weathering. Titanaugite, however, is "probably the most resistant pyroxene to weathering" (Ollier,1969,p.56). The mineral also occurs in large quantities in the Campsie lavas (MacDonald,1965). However the grain size of the lavas is so small as to obviate the possibility of detrital titanaugite grains from that source being of sand size (MacDonald,pers.comm.).

The augite minerals occurring in the remaining igneous intrusions in the vicinity of the essexite outcrops are non-titaniferous and generally pale-brown, green or yellow in colour (Tyrrell,1909; Francis et al.,1970).

Titanaugite rather than nepheline was chosen as the indicator for analysing the dispersion of fine essexite material for the following reasons. Titanaugite is a heavy mineral whereas nepheline is not; analysis of nepheline would have posed the problem of a flood of other light minerals. Titanaugite is also far easier to distinguish under the microscope than nepheline, more resistant to weathering, occupies a far greater proportion of the essexite outcrops and is therefore likely to be in greater abundance down-ice.

During summer 1974 and spring and summer 1975 samples of till and fluvioglacial sand weighing between 1 and 2kg each were collected for subsequent heavy mineral analysis. The majority of these were from locations in the Main Study Area. Of the 117 samples analysed four were from fluvioglacial sand and the remaining 113 from till. In the Secondary Study Area five samples were analysed of which one was from fluvioglacial sand and the remaining four from till. The till samples in the Main Study Area were mainly collected from sections in till provided, for example, by streams, drainage ditches and quarrying activities. In the Secondary Study Area the till samples were either from roadworks (samples 30 & 66) or the spoil heap alongside the oil-pipeline trench from Dalmeny to Grangemouth (samples 118 & 119).

The locations from which till samples were taken in the Main Study Area were as evenly distributed as possible within and outside the train of essexite material as indicated by the previously analysed wall data. This procedure was carried out in order to define the limits of the train of titanaugite mineral grains and to produce sufficient data point values for contour map interpolation . Apart from the closely spaced string of sample points 13 to 21 and 4 to 6 already mentioned in chapter 4 in connection with tracing fragments of essexite, there is a far more regular pattern of heavy mineral sample points than of wall stone data points. This is a result of the greater flexibility in the choice of sample sites for heavy mineral analysis compared to the walls. Suitable sample sites for heavy mineral analysis are common over most of the Main Study Area whereas suitable walls, as was discussed in chapter 5, are absent from some localities. Particular attention was paid to sampling from the thin mantle of till on the Campsie Fells in order that the limits of the erratics train could be defined in this area, since no data were available here for essexite wall stones. Two samples were collected from locations a considerable distance west of the outcrops (samples 74 & 75) in addition to two immediately west of them (samples 14 & 33) in order to determine whether essexite material had been transported westwards from the outcrops and to check that there was no other source of titanaugite up-ice of the essexite outcrops. Samples 50 & 51 were collected for the same reasons.

Since no titanaugite grains were identified in the four till samples from the Secondary Study Area, no other samples outside the Main Study Area were analysed.

The samples of fluvioglacial sand in the Main and Secondary Study Areas were analysed in order to determine the nature of the dispersion of titanaugite grains within these deposits. Unfortunately it was only possible to obtain samples from peripheral areas of the erratics train to which these deposits are largely restricted.

At sample site 12, five samples were taken down an exposed vertical section of till some 230cm deep. At site 13, two samples were collected. Samples 40 and 41, 42 and 43 and 46 and 47 were also taken from different depths at three sites (Fig.7.1). The depth of sampling in till for heavy mineral analysis is important for two major reasons. Firstly, the glacial processes involved in depositing the till may lead to sequential deposition (i.e. vertical separation of material in a section of till according to distance travelled)(Boulton,1970a; Hyvarinen <u>et al</u>.,1973). Secondly, mineral grains weather at various rates. The rate of weathering depends on the crystal size, shape, perfection and accessibility to the weathering agent (Ollier,1969; Birkeland,1974). A number of workers have placed the commonly occurring minerals in an inferred order of resistance to weathering (e.g. Goldich,1938; Tyler <u>et al</u>.,1940; Brophy,1959; Van Andel,1959; Smith,1962; Bhattacharya,1963). The effect of increased weathering on a suite of mineral grains is

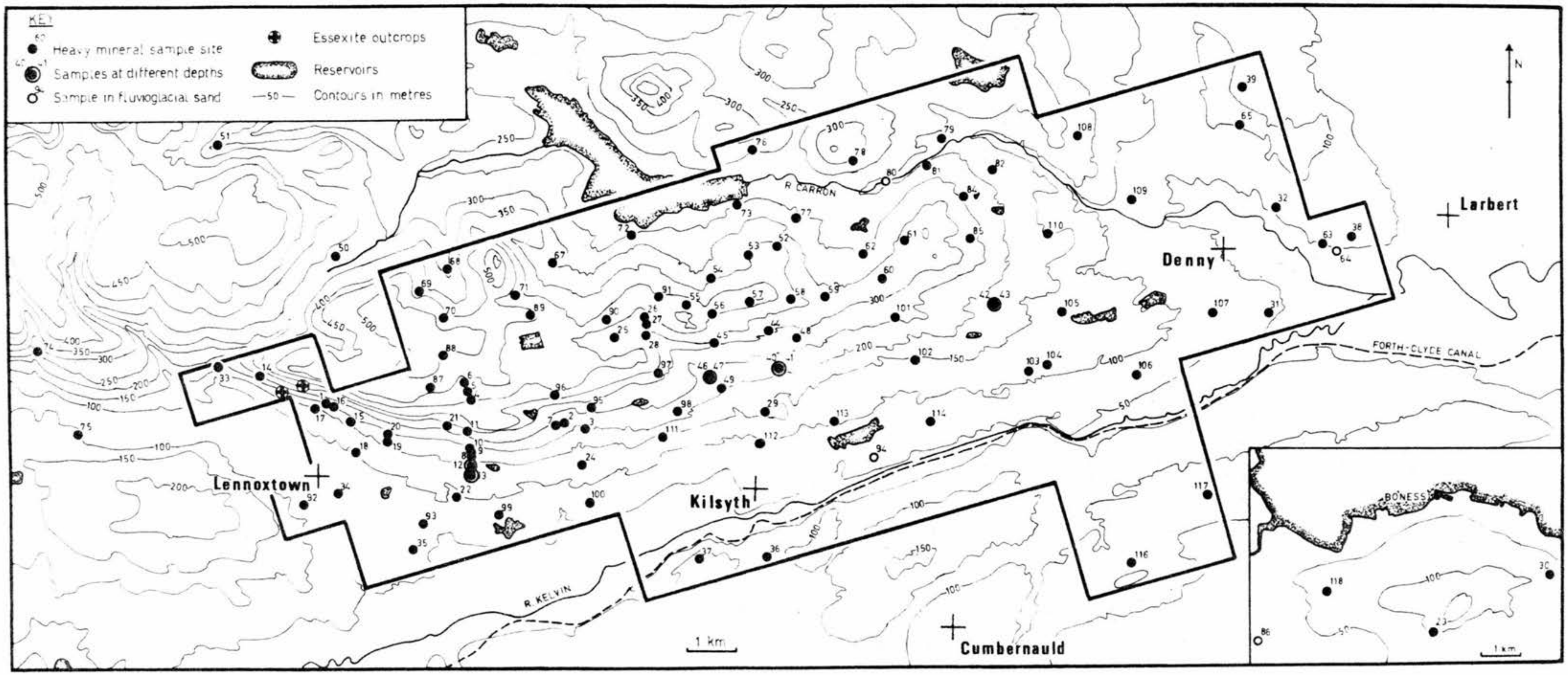


Figure 7.1

Location of sample sites for heavy mineral analysis.

to eliminate selectively the non-resistant minerals thus concentrating the resistant minerals (Dryden & Dryden, 1946; Dreimanis,1958; Van Andel,1959; Stankowska & Stankowski,1969) so that the heavy minerals are "in a sense, the survivors of selective weathering" (Sindowski,1949, p.9).

The collection of the till samples from different depths in the same location was undertaken therefore in order to determine the effect of depth on the amount of titanaugite in the heavy mineral suite. The results of this analysis will be discussed later in this chapter.

The size of sand grains used in heavy mineral analysis varies considerably from worker to worker. Sindowski(1949) used the fine sand fraction between 0.1mm and 0.05mm. Järnefors(1952) investigated the heavy mineral fraction of the material passing through the 0.125mm aperture sieve and retained on the 0.062mm sieve. Dreimanis and Beavely(1953), Dreimanis et al.(1957) and Dreimanis(1960) used the fraction 0.8mm to 0.15mm. Crampton(1959) investigated heavy minerals ranging from 0.2mm to 0.02mm in size. Milner(1962) recommended the use of material less than 0.42mm in size. Pettersson (1968) used the fraction 0.105mm to 0.053mm whilst Mickelson(1971) concentrated on material passing through the 0.25mm aperture sieve and retained on the 0.0625mm sieve.

Some workers have attempted to overcome the problem of choice of a suitable size by investigating a number of size grades. Anderson(1957) included two size grades of 0.5mm to 0.124mm and 0.991mm to 0.5mm. Willman et al.

(1966) used three grades of material; larger than 0.25mm, 0.25 to 0.125mm and 0.125mm to 0.062mm. Bhattacharya investigated heavy minerals in two size grades, 0.24mm to 0.12mm and 0.12mm to 0.06mm on the basis that it "has been recognised that certain minerals tend to occur in larger or smaller sizes than others" (1963,p.789).

In the present analysis time did not permit investigation of more than one size grade of heavy minerals. A size grade of 0.25mm to 0.125mm was used throughout the present study. This size grade has also been used by other workers involved in the analysis of heavy minerals in till (e.g. McDonald,1966; Shilts,1973a).

The selection of this size grade was made for four reasons. Firstly, it was preferable that the size chosen should conform to the geometric scale of size grades (Wentworth,1922a) that was used in the analysis of fragments of essexite material described in chapter 4. Secondly, this size grade meant that single mineral grains rather than mineral aggregates would be studied. Järnefors(1952) and Young(1966) both used this factor in choosing a size grade for heavy mineral analysis. Thirdly, this size of material was convenient for the laboratory procedure of heavy mineral separation. Larger mineral grains tended to become jammed in the base of the separating flask. Fourthly, under the microscope, the size of the minerals was adequately large to enable identification to be made for the most part under low power magnification.

Laboratory procedure and microscopic analysis

The colour of each moist till sample was recorded in the laboratory using the notation of the Munsell Color Chart (Table 7.1). Each sample was then washed through a nest of sieves of sizes 2mm, 0.25mm and 0.125mm, and the fine sand fraction retained on the latter sieve oven-dried.

This dried fine sand fraction was coned and quartered using a method described by Krumbein and Pettijohn (1938,p.357) until a sample of 15-20gm remained. This was added to about 50cc of 1N hydrochloric acid in an accurately preweighed 200cc beaker and the mixture allowed to boil. This pretreatment procedure was carried out since examination of sand grains beneath the microscope indicated that many of the mineral grains were coated with authigenic material, such as iron oxides. Since this coating interferes with the optical identification of the mineral grains it was considered necessary to remove it prior to heavy mineral separation by means of acid digestion.

When the contents of the beaker had cooled, the excess liquid was carefully poured off, distilled water added, the sand grains allowed to settle and the liquid carefully decanted. This process was repeated as often as required to remove the acid, after which the sand grains were allowed to oven-dry in the beaker. Accurate weighing of the beaker plus sand was then carried out.

The same procedure was performed on another four samples. Then a set of five retort stands and separating flasks was set up. Beneath each separating flask a filter funnel containing filter paper was attached to a retort stand by means of a clamp and a conical flask was placed beneath each funnel (Plate 10). With the stop-cocks at the base of the separating flasks closed, about 100cc of fresh bromoform (S.G.=2.89) were added to each flask. Using a dry filter funnel the sand fraction in a beaker was poured on to the surface of the bromoform in one of the separating flasks. The liquid and sand grains were thoroughly stirred with a glass rod and allowed to stand. At frequent intervals the bromoform was restirred in each flask so that all the grains with a specific gravity greater than 2.89 had a chance to sink to the bottom. After about fifteen minutes, when separation of the light and heavy sand fractions had taken place, the heavy fraction that had accumulated in the neck of the flask was run off, by means of the stop-cock, on to the paper in the filter funnel beneath.

When filtration was complete, the filter paper was removed and using an acetone wash bottle the heavy fraction was washed back into the same beaker that held the original weighed sand fraction. The excess liquid was decanted from the heavy mineral grains, the beaker refilled with acetone and the process repeated as often as required to remove the bromoform, after which the heavy mineral grains were oven-dried. The beaker and dried heavy minerals were then accurately weighed and the percentage of heavy minerals in each sample calculated. A fresh piece of filter paper was placed in each filter funnel and the light minerals run into it by opening the stop-cock. The bromoform passing through the filter paper into the conical flask was poured into darkened glass bottles for re-use.

Microscopic analysis of heavy mineral grains from initial samples indicated that of the many opaque grains present, a large proportion were magnetite and ilmenite. Since opaque grains were not the major interest in the present analysis, removal of these two minerals was considered desirable in order that a greater number of non-opaque mineral grains could be analysed on a slide. Both minerals are strongly magnetic and an ordinary horseshoe magnet or bar magnet is sufficiently strong to attract them (Krumbein & Pettijohn,1938; Dreimanis & Reavely,1953; Milner,1962; Shilts,1973). An electro-magnetic separation or a more powerful horseshoe magnet (e.g. Crook,1908; Järnefors,1952) was not used since weakly magnetic minerals including titanaugite could also have been attracted.

The heavy minerals from one sample were spread on a piece of paper and the magnetic minerals separated by means of a bar magnet placed inside a small plastic bag. As a result of using the bag the magnetic minerals could be subsequently removed from the magnet with ease. The magnetic fraction was then accurately weighed and its proportion of the total heavy mineral fraction calculated.

The grains remaining on the paper were prepared for permanent mounting on a glass slide. Where there were too many grains to fit on one slide the sample was coned and quartered until a sufficiently small number of grains were left. Canada balsam (Refractive Index = 1.54) was heated on a cover-slip over a Bunsen flame. After the balsam had boiled for a few seconds and cooled sufficiently to harden, the cover-slip was turned over and placed on a glass slide that had already been sprinkled with the heavy mineral grains. The glass slide and cover-slip were then reheated over the flame which softened the balsam once more to allow the trapped air bubbles to be eliminated. Once cool the excess balsam adhering to the glass surfaces was removed with Zylene. The slide was labelled and stored for microscopic analysis.

For analysis of the mounted heavy mineral grains a polarising microscope with standard features was used (see Kerr,1959; Milner,1962; Cox et al,1967). Each slide was scrutinised with a low power objective in a strictly observed manner. Starting in one corner of a slide a traverse was made along the length of the slide. Where the horizontal cross-hair in the eyepiece of the microscope intercepted a mineral grain it was identified and allotted to one of three categories. These were titanaugite, other non-opaque minerals and opaque minerals. Where identification was difficult a high power objective was used and the mineral grain rotated under crossed nicols in order to investigate further diagnostic features. On encountering no more mineral grains on the traverse the thumb-screw controlling vertical movement of the object slide was adjusted two graduations on the scale and the field of view made to travel in the opposite direction towards its point of origin along a line parallel to the first traverse. With repeated traverses to and fro the whole area of the slide was sampled. Owing to the extremely weathered nature of the mineral grains in some of the samples it was decided that 100 would be the minimum requirement for the total number of non-opaque grains counted on each slide although other workers have recommended a larger number (e.g. Järnefors,1952; Dreimanis & Reavely, 1953; Bayrock,1962; Willman et al.,1963,1966; Pettersson, 1968). If less than 100 non-opaque grains, including titanaugite, had been identified on completing examination of the slide the vertical thumb-screw of the mechanical stage was adjusted such that previously unexamined mineral grains intercepted the horizontal cross-hair. Investigation of the slide was continued until at least 100 non-opaque grains had been identified, except in samples 55, 70 and 85, when fewer than 100 grains were identified owing to the extremely weathered nature of the grains. The results of these analyses are however included in Table 7.1 since relatively unweathered augite grains were present on all three microscope slides. In samples 23 and 97 on the other hand, the mineral grains were weathered to such an extent that virtually no non-opaque mineral grains could be identified. These two samples were discarded: hence their absence from Table 7.1. Since non-titaniferous augite is common in the till of the area and weathers more readily than titanaugite, its presence on a slide was used as an indication that the sample

Table 7.1 Results of heavy mineral analysis

Sample	Grid ref.	Munsell colour (moist)	depth (cm)	ht. (m)	slope (o)	% heavy mins	% opaque mins	% t'gite	No. non-opaque grains
1	2	3	4	5	6	7	8	9	10
1	632 792	10YR/4/4	60	145	13	5.02	61.3	72.2	133
2	680 788	10YR/8/4	90	236	8	6.07	92.4	3.8	101
3	684 787	10YR/4/4	90	190	8	2.92	74.4	8.1	136
4	661 793	10YR/4/2	60	400	8	0.10	30.5	11.5	253
5	661 795	10YR/4/4	70	419	8	1.04	52.4	7.7	155
6	660 796	10YR/3/2	80	108	6	9.13	58.2	1.1	185
7	678 788	10YR/8/4	90	236	8	0.40	63.5	4.5	447
8	660 781	5YR/3/1	80	168	12	0.84	69.4	8.9	124
9	660 782	10YR/4/3	70	175	7	0.14	23.2	6.9	202
10	660 783	10YR/3/4	110	190	7	0.17	12.0	2.1	574
11	660 786	10YR/4/4	80	259	16	4.02	20.3	1.1	463
12A	660 780	10YR/4/3	30	152	5	0.50	16.5	3.1	228
12B	660 780	10YR/5/0	90	152	5	0.86	23.1	3.8	286
12C	660 780	10YR/5/0	130	151	5	1.53	14.1	4.4	365
12D	660 780	10YR/5/0	190	151	5	0.38	18.5	2.0	247
12E	660 780	7.5YR/4/0	220	150	5	0.59	13.5	1.6	315
13A	661 777	10YR/3/2	120	130	5	0.65	15.4	1.7	400
13B	661 777	7.5YR/3/0	180	130	5	1.53	32.0	0.9	421
14	618 797	10YR/4/4	60	130	18	1.09	38.7	-	174
15	636 788	10YR/4/4	60	122	11	1.67	58.7	19.3	150
16	633 791	10YR/3/4	60	146	14	2.19	74.8	14.0	136
17	629 791	10YR/3/3	80	131	8	5.41	50.1	31.5	200
18	637 783	10YR/3/4	60	95	3	1.88	49.8	29.6	287
19	643 784	10YR/4/3	80	145	7	1.34	56.7	21.4	220
20	644 786	7.5YR/3/2	80	145	11	2.11	48.6	17.2	197

1	2	3	4	5	6	7	8	9	10
21	657 788	5YR/3/4	80	259	24	4.13	62.2	10.4	106
22	658 774	10YR/3/4	60	91	8	0.10	55.2	4.9	204
24	659 773	10YR/4/1	60	131	1	0.38	48.7	6.1	212
25	690 805	5YR/3/3	50	381	7	2.82	23.6	1.8	279
26	697 809	5YR/4/2	80	381	9	1.71	36.5	1.0	297
27	697 808	5YR/4/2	170	358	7	2.68	34.5	2.1	189
28	696 806	10YR/3/4	50	366	12	0.58	27.6	2.6	190
29	721 790	7.5YR/4/0	150	152	2	0.17	17.9	0.8	361
S30	027 799	5YR/4/1	+	79	-	0.28	15.6	-	331
31	824 811	10YR/4/3	90	58	3	0.82	15.6	0.7	417
32	825 833	10YR/4/3	80	53	5	0.01	14.3	-	216
33	610 800	10YR/3/4	70	145	30	1.04	24.5	-	274
34	634 774	10YR/3/4	80	67	3	0.54	27.7	2.4	373
35	650 763	10YR/3/4	120	61	0	0.00	31.69	-	194
36	721 761	10YR/4/3	60	91	10	1.71	13.3	-	327
37	707 760	10YR/4/3	70	130	8	0.04	21.4	-	173
38	839 826	10YR/4/2	80	64	1	0.54	50.2	-	101
39	818 857	10YR/4/1	70	94	1	0.18	32.5	-	106
40	724 798	10YR/4/2	150	213	7	0.87	71.9	1.6	130
41	724 798	10YR/3/2	600	210	7	1.94	56.8	1.1	174
42	768 813	10YR/3/3	100	165	2	0.79	56.9	3.6	112
43	768 813	10YR/3/1	200	164	2	0.85	30.3	0.9	106
44	722 807	7.5YR/4/2	70	305	7	0.65	77.5	2.2	178
45	711 805	7.5YR/4/2	80	343	16	1.16	54.7	-	128
46	710 798	10YR/5/0	800	236	7	0.03	23.6	0.8	120
47	710 798	10YR/3/2	700	237	7	0.90	27.4	0.9	106
48	728 806	10YR/3/3	80	267	5	1.63	64.5	1.9	104

1	2		3	4	5	6	7	8	9	10
49	712	796	10YR/3/2	100	213	8	1.20	44.8	0.6	155
50	634	823	10YR/4/2	150	335	6	5.09	61.7	-	180
51	609	845	5YR/3/3	180	297	18	0.45	60.9	-	136
52	723	823	10YR/3/2	50	381	10	3.85	78.9	-	112
53	718	823	5YR/3/4	50	347	9	1.25	78.6	-	124
54	711	818	7.5YR/3/2	70	343	9	0.85	59.0	-	184
55	706	813	7.5YR/5/2	50	419	9	3.93	88.2	-	57
56	710	810	7.5YR/4/2	50	399	4	1.03	56.3	0.6	176
57	718	814	7.5YR/4/2	50	430	3	0.70	92.6	0.6	171
58	726	813	7.5YR/4/2	50	375	9	1.96	74.4	2.2	186
59	733	814	10YR/4/2	50	326	3	0.78	69.6	-	262
60	745	818	10YR/3/2	50	338	5	1.01	15.4	2.2	269
61	750	825	7.5YR/4/2	70	305	7	2.92	76.4	0.6	178
62	740	823	7.5YR/4/2	70	256	2	1.41	60.6	-	193
63	834	825	10YR/4/2	150	43	7	0.97	82.0	1.0	104
64(s)	836	834	-	-	43	-	1.81	75.0	-	192
65	816	848	10YR/2/1	150	101	4	0.11	62.7	-	101
S66	153	724	10YR/3/2	+	52	-	1.63	32.4	-	176
67	678	821	10YR/4/2	90	305	4	2.14	82.5	-	120
68	656	820	10YR/3/4	350	343	6	2.43	72.9	-	112
69	651	815	10YR/3/3	80	450	9	0.82	39.1	-	110
70	656	810	7.5YR/4/2	150	465	9	0.39	75.1	-	66
71	671	814	10YR/3/2	60	434	14	1.22	60.3	-	151
72	695	826	10YR/3/3	90	267	13	3.45	34.5	-	216
73	716	833	10YR/3/3	100	247	9	1.82	88.4	-	143
74	572	801	10YR/4/2	150	290	25	0.85	85.8	-	101
75	578	785	5YR/4/4	60	110	2	0.13	64.3	-	106
76	718	844	10YR/3/4	80	267	16	0.48	69.7	-	100

1	2		3	4	5	6	7	8	9	10
77	727	830	10YR/4/3	80	271	8	1.06	89.5	-	100
78	737	842	7.5YR/4/2	50	297	11	0.51	11.3	-	322
79	757	846	7.5YR/4/2	70	162	9	0.97	16.1	-	187
80(s)	748	838	-	-	247	-	1.69	51.8	-	216
81	754	841	7.5YR/4/2	100	206	7	0.91	21.4	-	242
82	767	840	7.5YR/3/2	100	177	3	3.86	62.1	-	118
83(s)	778	827	-	-	12	-	2.55	84.9	-	117
84	762	834	10YR/4/4	50	259	13	4.70	92.6	-	102
85	763	826	7.5YR/3/2	70	268	5	2.02	86.4	-	47
S86(s)	955	784	-	-	58	-	3.16	68.6	-	122
87	656	799	10YR/4/1	60	472	16	0.42	75.6	-	108
88	656	803	7.5YR/3/2	80	495	5	1.27	65.5	-	134
89	674	811	10YR/3/4	50	457	3	2.33	80.9	-	153
90	689	809	10YR/3/2	50	404	4	0.31	41.8	0.6	160
91	700	813	10YR/3/4	50	411	3	0.69	56.6	-	204
92	627	772	10YR/3/4	80	76	3	0.65	58.7	-	165
93	651	768	10YR/3/4	70	53	3	0.41	50.6	3.2	158
94(s)	743	781	-	-	61	-	0.16	48.4	-	101
95	686	792	10YR/3/3	70	274	13	0.14	2.94	-	165
96	680	794	7.5YR/3/2	100	366	18	1.60	97.8	1.8	225
98	703	791	7.5YR/4/2	80	221	7	0.52	52.2	1.9	214
99	666	769	7.5YR/4/2	60	61	1	0.20	53.2	1.8	164
100	685	773	10YR/4/3	70	69	8	0.10	32.4	-	143
101	748	811	5YR/3/4	60	267	8	1.97	70.4	0.9	111
102	752	803	5YR/4/1	150	152	7	0.88	38.8	0.4	257
103	776	799	10YR/4/2	200	107	0	0.25	33.0	0.6	158
104	778	801	10YR/4/3	80	122	6	0.16	41.5	-	160
105	782	812	10YR/3/3	90	122	2	0.32	28.9	-	194

1	2		3	4	5	6	7	8	9	10
106	797	798	10YR/3/4	90	84	5	0.44	30.8	-	249
107	811	810	7.5YR/3/2	150	76	2	0.35	56.6	-	174
108	785	847	10YR/3/4	60	175	5	20.2	28.6	-	345
109	796	834	10YR/3/3	70	91	13	1.25	52.9	-	219
110	778	827	5YR/3/2	250	146	2	1.28	78.5	-	100
111	699	785	10YR/4/3	80	145	7	0.10	61.5	1.0	102
112	720	784	10YR/4/4	60	76	4	8.3	64.5	-	311
113	735	788	10YR/4/4	70	99	8	0.07	39.3	-	110
114	754	788	10YR/4/2	80	91	11	1.27	25.1	-	213
115	752	771	10YR/4/3	100	99	6	0.09	45.3	-	171
116	795	760	10YR/4/2	80	114	9	0.02	30.1	-	100
117	811	774	10YR/3/2	60	107	2	0.29	27.4	-	118
S118	998	786	10YR/3/3	+	107		0.19	31.9	-	331
S119	972	796	10YR/3/4	+	78		0.25	61.2	-	175

S = sample in Secondary Study Area

(s) = sample in fluvioglacial sand

+ = depth of sample unknown

was not so oxidised that titanaugite would be too weathered for identification.

As has already been pointed out, titanaugite grains are more or less indistinguishable from non-titaniferous augite grains in most optical properties apart from colour in plane polarised light. Under crossed nicols, that is with both polarising prisms so positioned that their planes of vibration are at right angles to each other, the extinction angle and interference colours are similar. The crystal form, cleavage structure and relief of both minerals are also similar.

The colour of titanaugite however contrasts with the yellows, greens and browns of other varieties of augite. The general impression of the colour of the grains from essexite is purple (Griffiths,1939; Harker, 1960; Read,1962), although titanaugite has also been described as purplish brown (Hess,1949), mauve (Wells, 1956), violet and red (Milner,1962) and lavender (Krumbein & Pettijohn,1938). The mineral is slightly pleochroic (i.e. the colour changes as the mineral is rotated in plane polarised light) whereas in other varieties of augite pleochroism is weak or absent (Kerr,1959). This characteristic however was not used as a distinguishing feature owing to the possibility of incorrect identification. Zonal inclusions of small plagioclases in the essexite variety of titanaugite on the other hand did help to confirm identification in cases where they were present in the mineral grains (Hatch et al.,1961; Fig.7.2).

In order to help positive identification of the mineral a type slide of fresh titanaugite grains was prepared. A portion of a euhedral crystal of titanaugite was crushed and passed through 0.25mm and 0.125mm sieves. The grains remaining on the 0.125mm sieve were mounted on glass slides in Canada balsam as previously described. Where positive identification of a grain on a sample slide was difficult the type slide was placed over the sample slide and the objective focused on to the type slide.

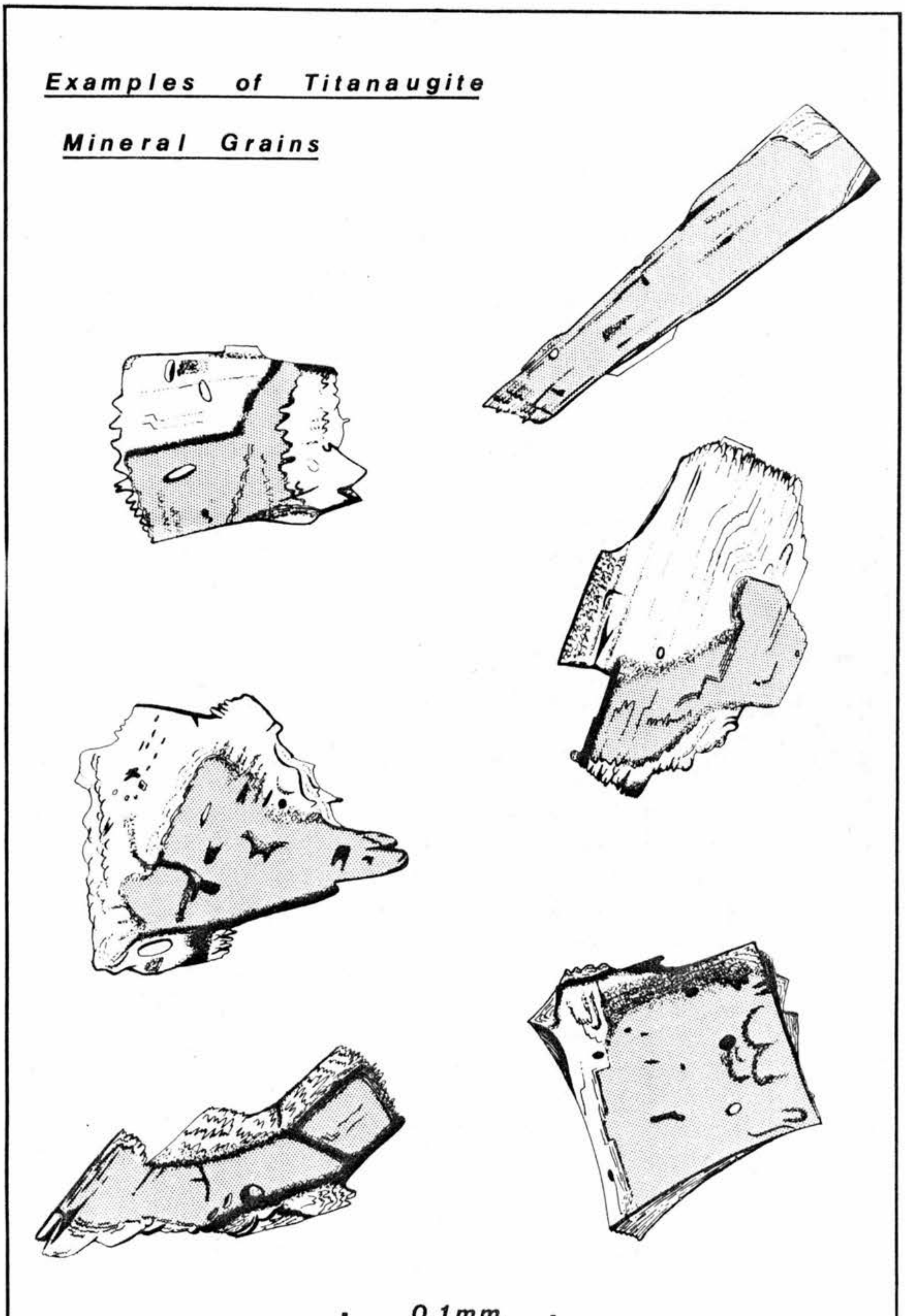


Figure 7.2

Results and discussion

The results of the 122 samples analysed are shown in Table 7.1. In addition to the National Grid Reference of the sample site, colour of the moist sample according to the Munsell Color Chart, number of non-opaque grains counted for each sample and percentage weight of heavy minerals, the other data given were calculated in the following manner. The percentage titanaugite is expressed as the percentage ratio of titanaugite grains to all non-opaque grains. (Opaque and non-opaque grains are conventionally counted separately.) The percentage opaque mineral grains was derived from a combination of the results of weighings during laboratory procedure and counts made on microscope slides. The weight of opaque minerals that had been magnetically removed from the heavy mineral sample prior to microscopic analysis was also calculated. To this was added the "estimated" weight of opaques within the non-magnetic fraction that was mounted on the slide. This estimated weight was calculated from the multiplication of the percentage ratio of opaque to non-opaque minerals counted on the slide by the weight of the non-magnetic heavy minerals. The percentage opaque mineral grains was then determined by calculating the percentage ratio of both weights of opaque grains to the total weight of the heavy minerals.

The slope of the ground surface in the vicinity of the sample is a simple measure based on the perpendicular distance between the two adjacent 25ft (7.6m) contours. The angle of slope was calculated by simple trigonometry and rounded to the nearest degree. The height (O.D.) in feet of each sample site was determined from interpolation between contours on 1:25,000 scale maps and converted to the nearest whole metre.

The results of the analyses of heavy minerals from different depths within till at the same site (samples 12A-12E, 13A & 13B, 40 & 41, 42 & 43 and 46 & 47) indicate that there is a tendency for titanaugite percentages to decrease with depth. At site 12 titanaugite percentages rise slightly from sample 12A to 12B but fall substantially towards the deepest sample (12E). At site 13 the titanaugite percentage is halved over a depth of 60cm. For samples 40 and 41 and 42 and 43 titanaugite percentages also decline according to the depth of the sample. At the site where samples 46 and 47 were taken, on the other hand, the titanaugite percentages are approximately equal. The overall tendency for titanaugite percentages to increase with decreasing depth is more probably a result of selective weathering of minerals rather than sequential glacial deposition. This point will be discussed later.

For the five fluvioglacial sand samples no titanaugite grains were identified within the heavy mineral fraction. This was probably mainly a result of the peripheral location of the sample sites with respect to the major axis of the essexite erratics train although it may also be a function of sorting during fluvioglacial transport.

In order to determine whether the factors of percentage titanaugite grains, percentage heavy mineral grains, percentage opaques, slope, height and depth were interrelated, a multiple regression analysis was carried out. The results of this analysis for all the till samples in the Main Study Area are shown in Table 7.2. Although sometimes the significance is high, the correlation coefficient indicates that the relationship is weak. The significant relationship between slope and height is readily accounted for since the highest sample sites also tend to be on the steepest slopes. The significant correlation between percentage opaques and percentage heavy minerals can be explained in that the opaque minerals comprise a large proportion of the heavy fraction in the majority of the samples. The significant correlations between the factors of percentage opaques and slope, and percentage opaques and height are a function of the greater degree of till weathering, and therefore the greater quantity of opaque minerals, with increasing height and steepness of the ground surface in the vicinity of a sample site.

The negative correlation between percentage titanaugite and height is not surprising in view of the juxtaposition of the erratics train and the topography of the area. However the significant correlation between percentage titanaugite and percentage heavy minerals is problematical. It may be that since intrusive igneous rocks provide the major quantities of opaque as well as non-opaque heavy mineral sand grains in the till, the large number of samples immediately down-ice of the essexite outcrops combine high titanaugite with high opaque percentages. The remaining samples with low titanaugite values, on the other hand, record a mixture of high and low opaque percentages.

<u>Table 7.2</u> <u>Multiple correlation of results from 113 heavy mineral samples from the Main Study Area</u>

	Percentage titanaugite	Percentage heavy mins.	Percentage opaques	Slope	Height
Percentage titanaugite	-				
Percentage heavy mins.	+0.16''	-			
Percentage opaques	N.S.	+0.16''	-		
Slope	N.S.	N.S.	+0.13'	-	
Height	-0.13	N.S.	+0.35'''	+0.25'''	-
Depth	N.S.	N.S.	N.S.	N.S.	N.S.

N.S. = not significant

' = significant at 90% level

'' = significant at 95% level

''' = significant at 99% level

In the same manner in which the wall stone data were treated in chapter 5, the percentage titanaugite data for till samples in the Main Study Area were subjected to two-dimensional interpolation by means of the SYMAP contour mapping computer program. Samples from fluvioglacial sands and those samples collected from the Secondary Study Area were excluded as were samples 50, 51, 74 and 75 from the Main Study Area. These last four samples have been omitted as no titanaugite grains were identified in their heavy mineral fractions and they are located at some distance from the main group of sample sites that already define the traceable limits of the dispersion of titanaugite grains.

In total, 101 data points were used in the production of the contour map shown in Fig.7.3. Sample 12C was used to represent the titanaugite percentage at site 12. For the remaining sites where more than one sample was collected, the uppermost sample was used in order that the depths of the samples at these sites should correspond as nearly as possible to the depths of the remaining sites.

A different border to that used in chapter 5 was placed around the data points to form a closely fitting polygon. The long axis of the area within the border was aligned in the same direction as the corresponding area used for the wall stone data.

The range of titanaugite percentages was divided in a geometric progression in a similar way to the wall stone data so that there was greater differentiation of shading at the lower end of the range of titanaugite percentages than at the higher end. Six levels of shading have been used to represent areas where titanaugite grains are interpolated as being present, and no shading represents areas that have been interpolated as devoid of titanaugite grains. A barrier to interpolation was imposed along a line immediately north-west of the essexite outcrops and runs in the same direction as the long axis of the area enclosed in the SYMAP border.

Fig.7.3 shows that titanaugite percentages decline rapidly in the first few kilometres down-ice of the outcrops; thereafter the decline is more gradual with titanaugite percentages not exceeding 2.5 except for an area represented by the second level of shading some 14km from the source. The width of the train of titanaugite grains appears to be greater immediately down-ice of the outcrops tapering in the direction of ice transport. The true lateral extent close to the outcrops is not as large as it is portrayed however, and this has resulted from the interpolation procedure of the SYMAP program. The wide spacing of nil data point values delimiting the southern border of the train of titanaugite grains (samples 92, 35 & 100) immediately down-ice of the essexite outcrops has merely resulted in enclaves of no shading surrounded by areas of the lowest shading level.

Apart from a small area immediately north-east of the non-porphyritic outcrop the analysis of the heavy minerals enabled the extent of the erratics train to be determined on the high parts of the Campsie Fells where analysis of essexite stones in the walls was not possible. Owing to the wide spacing of data points however, the location of the periphery of the shaded area representing

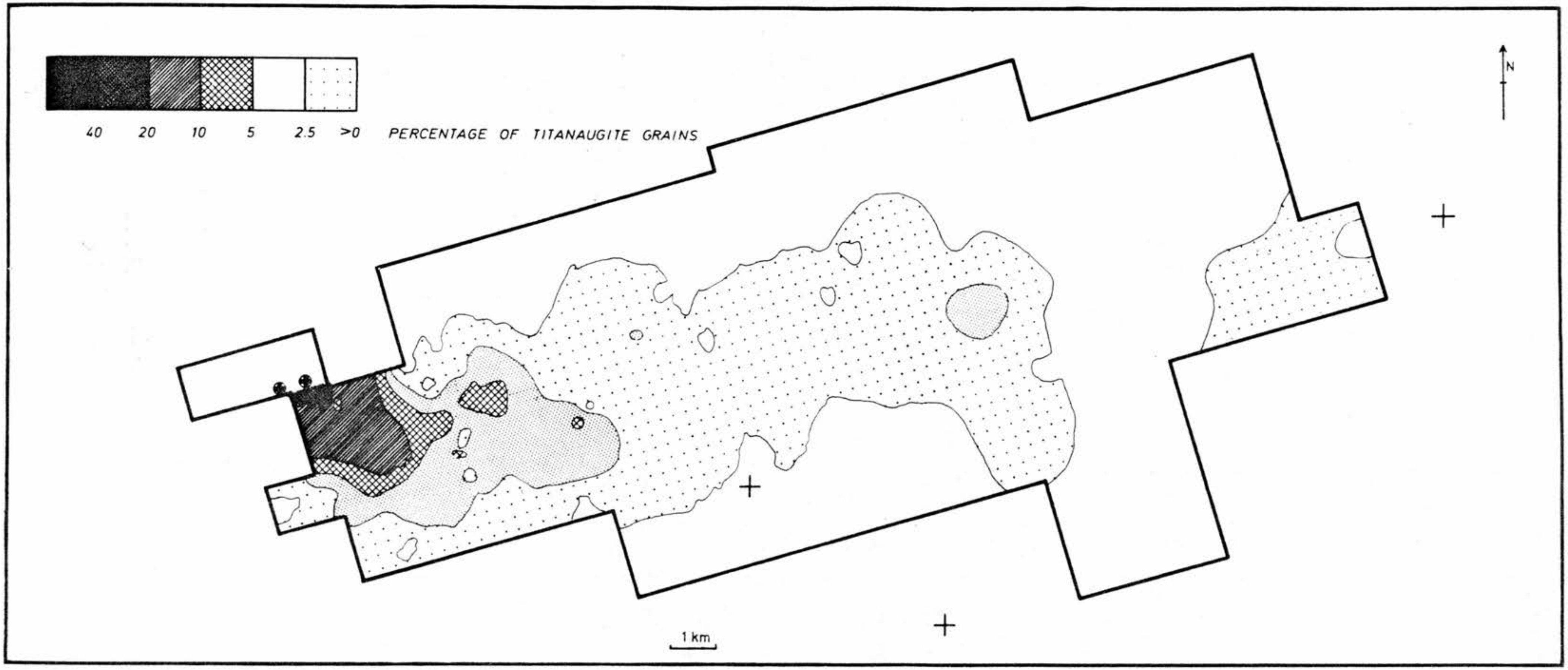


Figure 7.3

SYMAP of titanaugite percentages.

the extent of titanaugite grains is not reliable.

The SYMVU three-dimensional graphic displays of the data are shown in Figs 7.4 and 7.5. In Fig.7.4 the major axis of the train is evident, running slightly farther to the south than the alignment of the long axis of the SYMAP border. Since the absolute values are shown, the line of generally higher titanaugite percentages along the major axis is apparent as a series of humps, a detail that is not shown in the contour map. Fig.7.5 shows a trend of titanaugite percentage peaks that lies close to a curve described by a negative exponential function (see chapter 5). In the light of the poor results obtained for the wall stone data however, an equation was not calculated expressing the decline of percentage titanaugite grains with distance from the source.

The contour map of percentage titanaugite values resembles the contour maps of the wall stone data in terms of three common features. Firstly, the direction of transport is similar for both titanaugite grains and essexite stones. Neither of these two size grades of essexite material was found westwards of the outcrops. Secondly, the lateral extent of both size grades are broadly similar considering the limitations of the SYMAP interpolation procedure. Thirdly, the rates of decline of percentage titanaugite grains and the porphyritic essexite wall stones are similar in that both contour maps show a rapid decline in values close to the outcrop and a less steep decline east of a point c.6km down-ice of the outcrops.

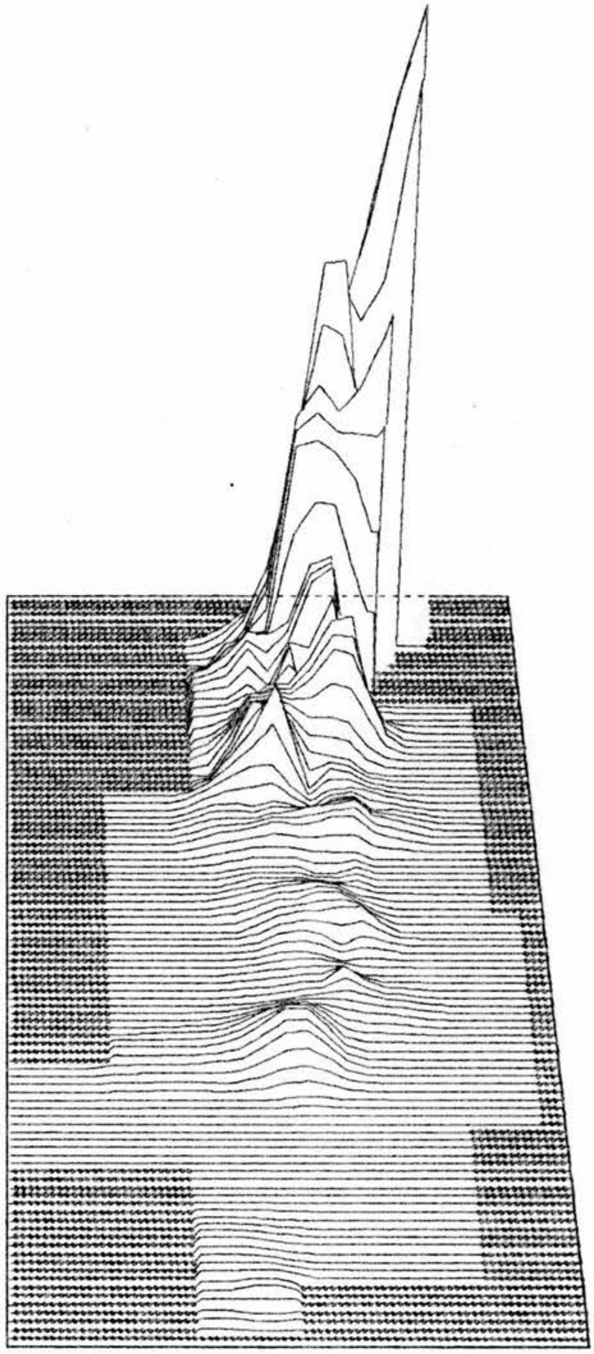
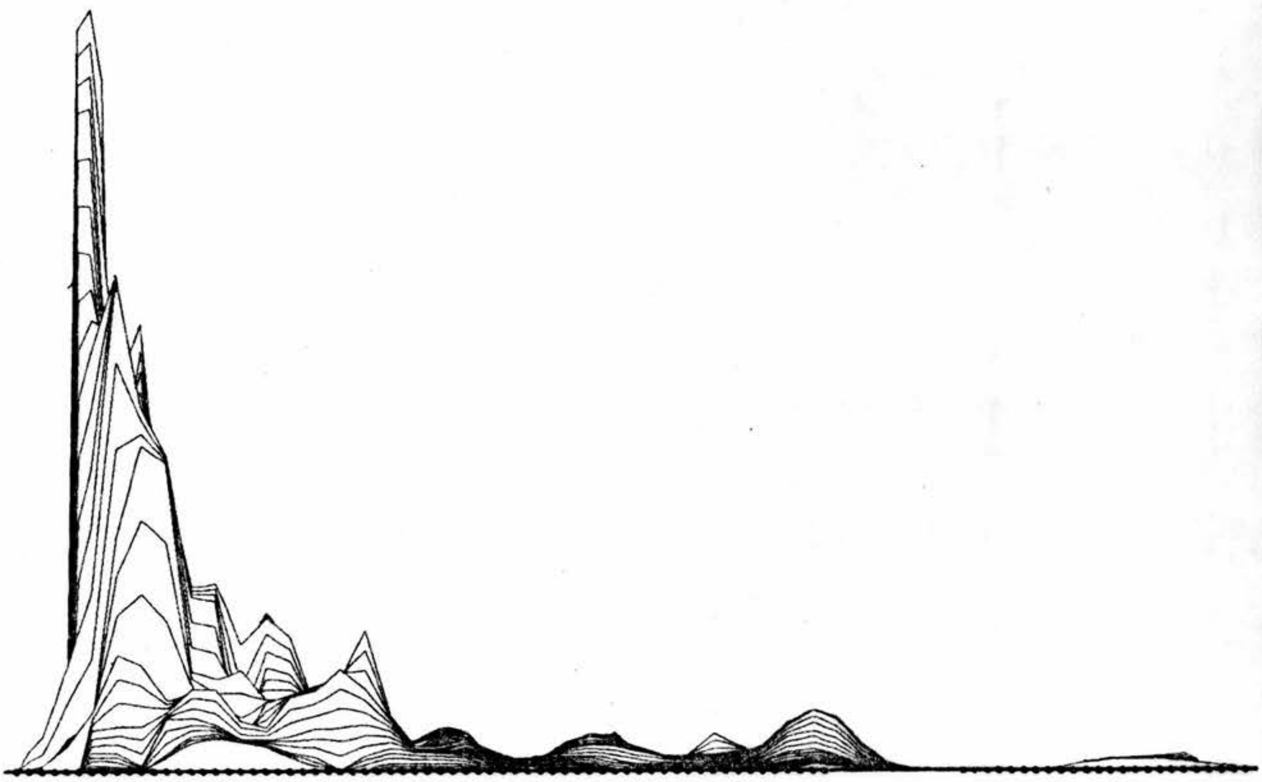


Figure 7.4

SYMVU of titanaugite percentages viewed from the east-north-east.

Figure 7.5

SYMVU of titanaugite percentages viewed from the south-south-east.



The clarity of the pattern shown in Fig.7.3 and its strong resemblance to the contour maps of the wall stone data indicates that any variation in the percentage of titanaugite grains in the samples as a result of different depths, and therefore different degrees of weathering, must be slight.

The similarity in the distribution patterns of the two size grades of essexite material is in contrast to the majority of literature concerning the distance of glacial transport of different size grades of material in till. Dreimanis and Vagners(1965,1969,1971), Krumbein (1933), Kruger(1937), Gravenor(1951,1957), Anderson(1957), Kauranne(1958), Bik(1966), Pettersson(1968) and Gillberg (1968a) amongst others supported the view that fine material in till undergoes a greater distance of travel than coarse material. This paradox may be explained in terms of the following reasons.

Firstly, it might be argued that the size grade analysed for its titanaugite content does not correspond to the terminal grade of that mineral; hence its scarcity at distances greater than 6km down-ice of the outcrops. Dreimanis and Vagners (1971), however, showed that the terminal grades of heavy minerals range from 0.25mm to 0.032mm, with major modes in the 0.25mm to 0.125mm and 0.062mm to 0.032mm grades. The size grade used in the present analysis therefore falls within the extreme limits, and in fact corresponds to one of the major modes. If the major mode of titanaugite were in the smaller size grade (0.062mm to 0.032mm), then a peak in the 0.25mm to 0.125mm size grade would still be expected as the mineral grains were gradually comminuted to finer terminal grade size fragments.

Secondly, there is a possibility that the influx of heavy minerals from other igneous sources might have led to a dilution of the titanaugite grains within the heavy mineral fraction. Smithson(1953) considered that the introduction of a small amount of heavy minerals could cause a disproportionately large change in the heavy mineral assemblage. For the dispersion of titanaugite grains however, a major influx of heavy minerals of sand size would not be introduced into the till until the Kilsyth area (c. 6km from the source) where a series of quartz dolerite outcrops is located (see chapter 3). The percentage of titanaugite grains is however already less than 2.5 at this point.

Thirdly, it is possible that although crushing of essexite stones has taken place during glacial transport, as results discussed in chapter 5 indicate, the inherent strength of the rock might give rise simply to the breaking up of single stones into a few pieces with little fine material produced (Holmes,1960). However Beaumont(1967) argued that crushing of coarse grained igneous rock fragments of less than 10cm in diameter gave rise to a breakdown into individual minerals. Since porphyritic essexite tends to become comminuted to fragments of this size or less as a result of the closely-spaced joints (see chapters 3 & 5), a large supply of mineral grains could be expected. Furthermore analysis of essexite material in the till samples described in chapter 4 indicated that many pebbles were of the non-porphyritic as well as porphyritic variety. Therefore the strength of the rock cannot be the reason for the low amounts of titanaugite in the till samples down-ice of the essexite outcrops.

Fourthly, it might be suggested that, since titanaugite is only one mineral within essexite and the essexite outcrops themselves are of limited areal extent, the low percentages of titanaugite could be expected. However the high percentages of titanaugite recorded for samples located within a short distance down-ice of the outcrops (samples 1, 15, 16, 17, 18, 19 and 20) appear to contradict this argument. Furthermore titanaugite in fact constitutes a large proportion of both varieties of essexite.

Fifthly, the views of Donovan and James(1967) and Shilts(1973b) might be chosen in preference to those of Dreimanis and Vagners(1971) <u>et al</u>. to explain the rapid decline in titanaugite percentages with distance from the source. These workers considered that the majority of the fine as well as the coarse till material undergoes short glacial transport. Donovan and James (1967) found that the larger erratics undergo the greatest distance of travel and Shilts(1973b) showed that the distribution patterns in till for the boulder and fine material from various sources in southeastern Quebec were similar.

On the other hand, if the views of Dreimanis and Vagners et al. are accepted, the rapid decline in titanaugite percentages may be explained in terms of different modes of transport by the glacier ice. This point has already been made in connection with the analysis of the content of essexite fragments in till in chapter 4. Subglacial transport of this material contrasting with an englacial transport for the large number of essexite stones now in the dry stone walls was one of the possible explanations given for the unexpectedly low amounts of essexite in the till down-ice of the source. The low amounts of titanaugite in the till appear to lend support to this view. Discussion of this matter will be continued in chapter 9.

Trend surface analysis

Using the same computer program that produced the trend surfaces of the wall stone data, first, second and third order trend surfaces of the titanaugite percentages were derived (Fig.7.6). The %RSS for each surface and the corresponding level of significance are given in Table 7.3. All three surfaces are significant at above the 99% level as revealed by tables based on F-ratios in Norcliffe(1969).

Table 7.3 Percent reduction in sum of squares and significance levels of trend surfaces of heavy mineral data

First order		quadratic	Second order		cubic	Third order	
%RSS	signif.	%RSS	%RSS	signif.	%RSS	%RSS	signif.
14.7	0.01	9.0	23.7	0.01	5.8	29.5	0.01

The first order trend surface shows a similar west-south-west to east-north-east alignment to the corresponding surface for porphyritic (E_A & E_N) stone data. As for the wall stone data the large contrast between high values immediately east of the outcrops and low values farther east has controlled the direction of the trend. The first order trend surface gives the highest %RSS of the three surfaces as for wall stone data.

The second order surface assumes a broad tongue form. The low %RSS attributable to the quadratic component compared to the linear component results in part from the large contrast in values for data points close to the essexite outcrops.

The third order surface is in a narrower tongue form not dissimilar to the trend surfaces of the wall stone data. The fact that the second and third order surfaces correspond more closely to the original titan-augite percentages than the same surfaces did to the wall stone data probably results from the more even distribution of the data points. The value for the nearest neighbour statistic of Clark and Evans(1954) for the 101 heavy mineral sample sites used in the trend surface analysis was 0.77 for the smallest rectangle enclosing the area within the SYMAP border, and 0.94 for the area within the border. These two results indicate that the distribution is not far from being random, which is represented by a value of 1. Thus the heavy mineral sample sites are very close to being randomly distrib-

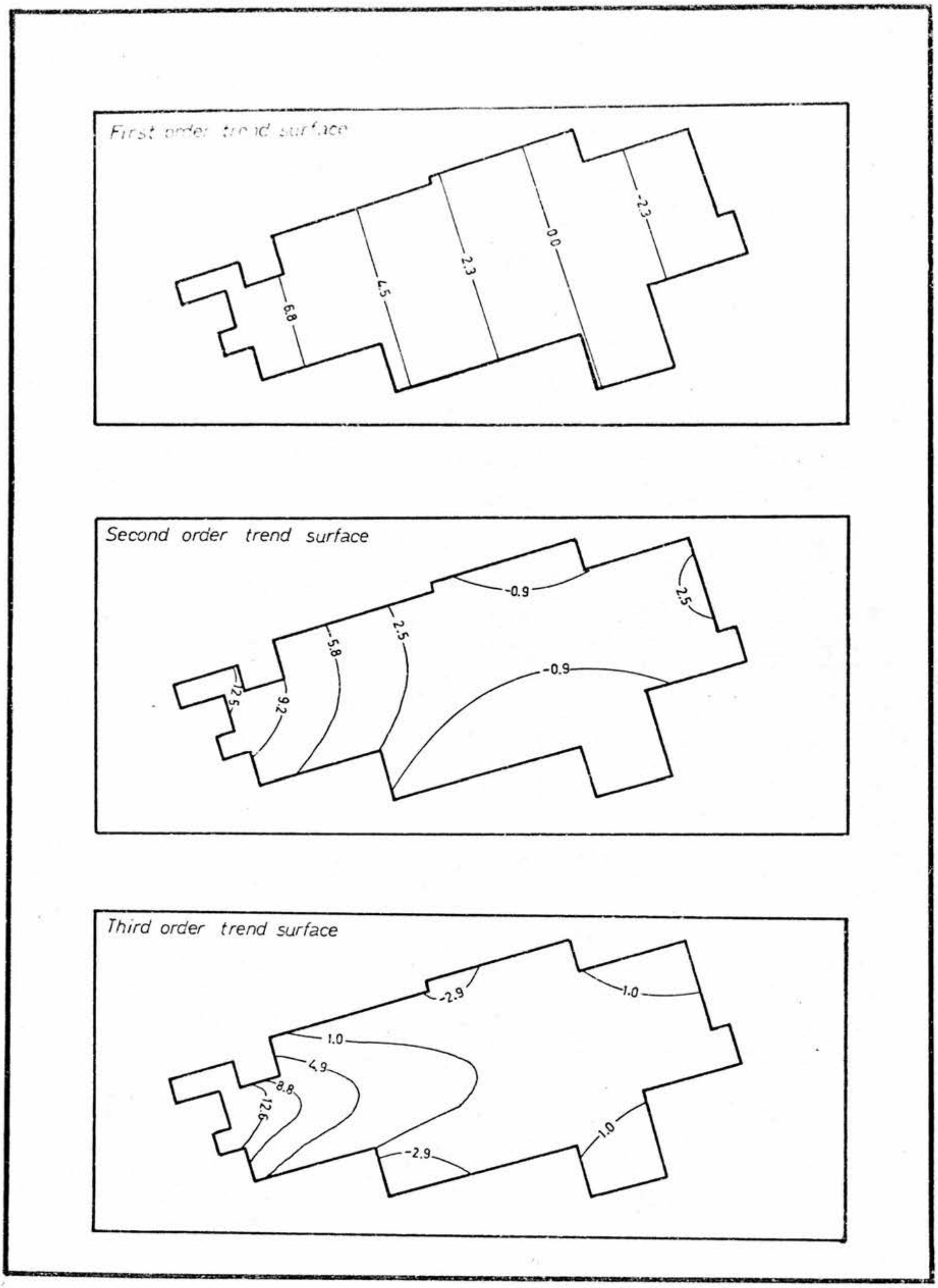


Figure 7.6

Trend surfaces of titanaugite percentages.

uted within the SYMAP border. Since a random or preferably, even distribution of data points is required for trend surface analysis to produce reliable results, the trend surfaces of the heavy mineral data can be regarded as of greater value than the trend surfaces of the wall stone data.

CHAPTER 8

EVIDENCE OF GLACIER ICE MOVEMENT IN THE MAIN STUDY AREA AND ITS RELATIONSHIP TO THE ESSEXITE ERRATICS TRAIN

> "The narrowed ends of the boulders... pointed one way, like index fingers" (Miller,1884,p.178)

The literature discussed in chapter 2 shows that an erratics train indicates the overall direction of former glacier ice movement in an area. Other ice direction indicators, such as striae, the long axes of ice-moulded features and the preferred orientations of till fabric studies on the other hand, reflect local variations in ice direction. The parallelism of striae, ice-moulded features and till-particle orientations has been demonstrated in a number of studies (e.g. Alden, 1905; Wright,1912; Wright,1957; Gravenor & Meneley,1958; Baranowski,1970; Harris,1972; Walker,1973).

An analysis of these three indicators of small-scale variations in ice direction was undertaken in the Main Study Area with the purpose of comparing the direction of ice movement shown by them with that of the essexite erratics train. It was hoped that such a comparison might help in the interpretation of the manner in which the essexite erratics had been distributed.

Till fabric analysis

Miller Snr.(1850) was probably the first to note that stones in till tend to lie with their long axes paralleling the direction of neighbouring striae. Miller Jnr. noted that the "longer axis of the stones is often directed in the line of glaciation" (Miller,1884, p.167). In North America Hind described the orientation of till stones in 1856 (Elson,1966). Bell(1888) observed a tendency for boulders on Swiss glaciers to assume a longtitudinal position with respect to ice flow. Upham (1891) described elongated stones in lodgement till with their long axes parallel to contiguous striae. The first systematic investigation of till fabrics was made by Richter(1932,1933,1936). He established quantitatively the relationship between preferred orientation and ice movement and also noted a secondary tendency for alignment of long axes transverse to flow.

The single most significant contribution to the study of till-particle orientation was made by Holmes(1941). He confirmed that stones align themselves either parallel or transverse to ice flow direction. He suggested that the former attitude resulted from pebbles being dragged along shear planes in basal ice layers and at the ice-till contact whilst orientation transverse to flow was a result of rolling into position by rotation about the longest axis during total immersion in ice. He also studied the effect of size, shape and roundness of the constituent stones on the orientation with respect to ice flow direction, concluding that small changes in these parameters had a profound effect on the orientation of the stones.

Harrison(1957b) noted angle of plunge or dip as well as azimuth direction of particle long axes. He found that there was a tendency for long axes to dip up-glacier and concluded that this had been a direct result of processes acting in the transporting medium. Wright (1957) agreed with this view, finding not only that preferred orientation of long axes paralleled the alignment of neighbouring drumlins, but also that the stones had an up-ice dip averaging 23^{o}.

In Britain the first important study of till fabrics was carried out by West and Donner(1956) on tills in East Anglia. Baden-Powell(1948) had postulated two separate directions of ice movement corresponding to Lowestoft and Gipping Advances on the basis of the lithology of the till matrix. West and Donner (1956) inferred the same directions of ice flow from the results of till fabrics.

Glen, Donner and West(1957) applied the work of Jeffery(1922) and Taylor(1923) on the theoretical behaviour of particles suspended in a viscous fluid to explain the alignment of particles in till. Taylor(1923) had shown that ellipses in a shearing waterglass medium quickly assume a position with the long axis parallel to flow but, after a long period, develop a transverse long axis orientation. Using this evidence Glen et al.(1957) suggested that particle orientation in till occurs by viscous flow in glacier ice.

Later work, however, revealed that orientation could also occur within lodgement till. MacClintock and Dreimanis(1964) showed that an ice sheet could cause re-orientation of particles in unfrozen, overridden deposits to a depth of 10.7m. Gravenor and Meneley(1958) considered that fabrics developed as a result of transport of subglacial till. Detailed studies of modern glacial sedimentation, such as the work by Boulton(1968,1970a, 1970b,1971), has led to other workers (e.g. Niewiarowski, 1969; Lindsay,1970; McKensie,1970; Drake,1971; Mark,1974) attempting to distinguish between fabrics produced by subglacial, englacial and supraglacial processes.

Since the early 1960's much attention has been turned to the problems of sampling. Kauranne(1960), Andrews and Smith(1966), Andrews and King(1968), Johansson(1968), and Young(1969) showed that considerable variation of preferred orientations occurs in till fabrics over short distances. The size of sample required to obtain a representative pattern of particle orientations has been studied by a number of workers (e.g. Harrison,1957b; Kauranne,1960; Andrews & Smith, 1966; Young,1969; Andrews & Smith,1970). The effect of size and shape of till particles on till fabric orientation has received greater attention in recent years following the early work by Holmes(1941), (e.g. Andrews & King,1968; Krüger,1970; Ramsden,1970; Drake, 1974).

The problem of operator variance in sampling till fabrics has been investigated during the last decade. Hill(1968) studied the results of a number of operators measuring the same artificial till fabric. He found that, although measurement errors on individual particles amounted to 30° or 40°, the fabric patterns obtained were similar. Krüger(1973) in a similar study observed that most errors resulted from inaccurate measurement of the orientation of particles with dips of 50° or more.

Statistical treatment of till fabrics has been the subject of considerable work. Two-dimensional methods for deriving preferred orientations have been in use since the early quantitative studies on till fabrics (e.g. Reiche,1938; Krumbein,1939; Curray,1956; Harrison,1957a; Kauranne,1960). With increasing interest in the analysis of particle dip following the work of Harrison(1957b) the development of methods for deriving a three-dimensional solution has taken place (e.g. Steinmetz,1962; Andrews & Shimizu,1966; Ramsden,1970; Mark,1971,1973,1974).

Methodology

In the Main Study Area twenty-five till fabric analyses were carried out. The locations of the sample sites of these till fabrics are shown in Fig.8.1. These sites were distributed as evenly as possible throughout the Main Study Area but Fig.8.1 indicates that the majority are clustered along the south- and south-east-facing scarp slope of the Campsie Fells and this reflects the availability of suitable till sections in the area.

Till is comparatively thick along the lower parts of the scarp slope of the Campsies and is accessible at a number of stream sections. On the higher and steeper parts of the Campsies, however, till is for the most part absent, thin or covered by peat deposits. In only a few localities do patches of thicker till exist, and these provided sites for samples 4, 21 and 24.

No till fabric analyses were possible along the Kelvin-Bonny Water valley or the Carron Valley owing to the occurrence of thick alluvial and fluvioglacial deposits. On the undulating ground east and north-east of Cumbernauld no suitable sites for till fabric analysis were found, and only the excavation of an oil-pipeline trench running north-south across the area east of Denny gave rise to the availability of suitable till sections in the north-eastern part of the Main Study Area.

At three sites, two till fabric analyses were made to determine if there were significant differences in the fabrics. Samples 18 and 22 are located a few kilometres west and north-west of the essexite outcrops and they were carried out to determine the direction of ice movement west of the outcrops.

Ideally the minimum depth for till fabric analysis should be 100-150cm. Below this depth postglacial disturbance of till particles as a result of, for example, frost action, soil creep and the action of tree roots is unlikely (Beaumont,1971). Some workers, however, have carried out till fabric analyses at shallower depths. Harris(1967) investigated till fabrics at depths of less

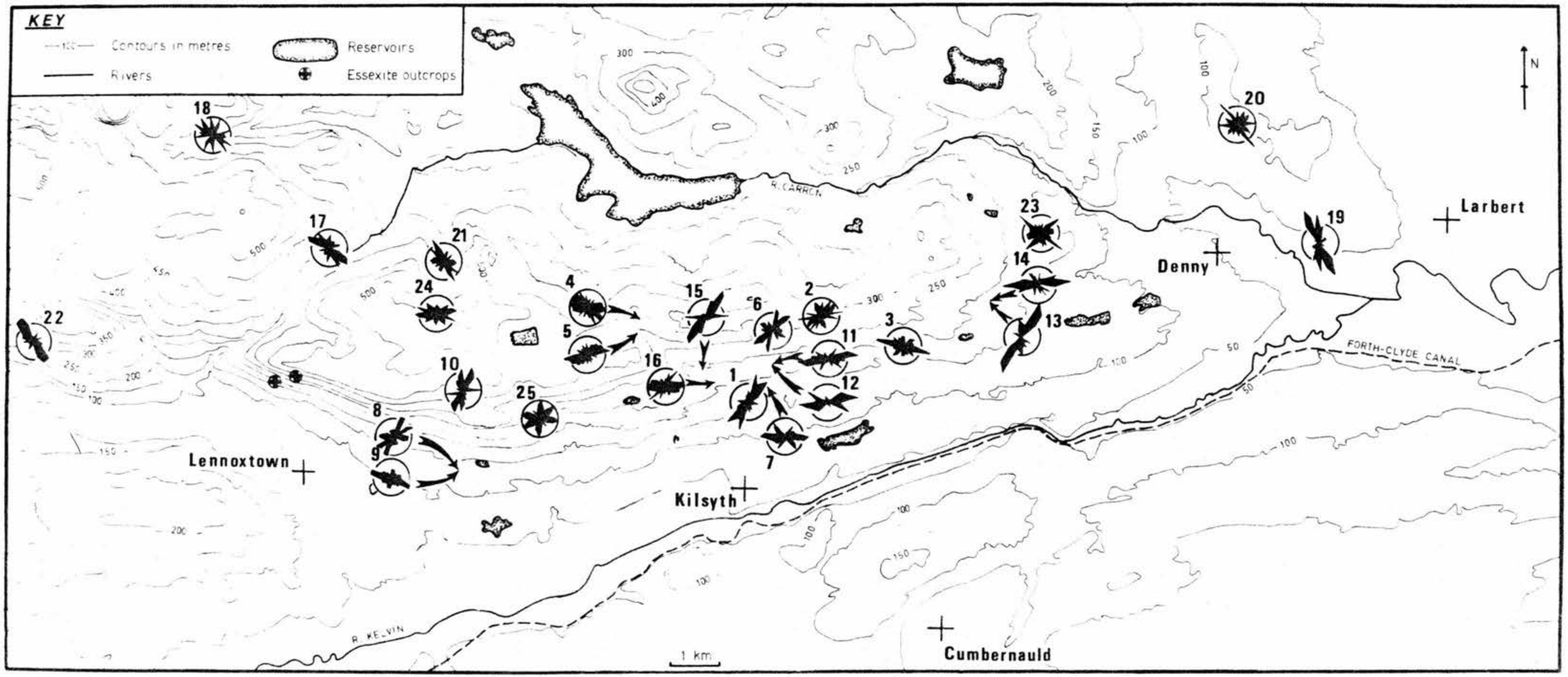


Figure 8.1

Location of till fabric sample sites with mirror image rose diagrams of particle orientations. Circles denote a frequency of 5 stones.

than 90cm, Järnefors(1952) at 50cm and Cowan(1968) at depths of 25 to 30cm. In the present analysis all till fabrics were taken at depths of greater than 100cm, except samples 5 and 10 which were sampled at depths of 90cm and 80cm respectively (Table 8.1).

Having selected a suitable site, a horizontal shelf c.30cm^2 was carefully excavated within fresh till by means of a mattock. A horizontal surface was used in preference to a vertical face since with the latter "there is a great temptation to select pebbles that are projecting out of the face" (Andrews,1971a,p.11). Other workers have also used a horizontal surface for this reason (e.g. Kauranne,1960; Andrews & King,1968; Kirby, 1969; Young,1969; Lineback,1971).

From this shelf, till matrix was carefully scraped away with a penknife to reveal the macro-particles. All particles were excavated and inspected to ascertain their suitability for inclusion in the till fabric sample. If two particles were touching they were rejected, as were all particles known to be in the vicinity of large boulders. Other workers have further selected or rejected particles for till fabric analysis on the basis of the a:b ratio of the particle axes. An a:b ratio of 3:2 is the most commonly-quoted minimum figure (e.g, Wright,1957; Burke, 1969b; Kirby,1969; Young,1969; Krüger,1970; Evenson,1971; Hill,1971; Mickelson,1971), although ratios of 2:1 (Andrews,1963; Beaumont,1971), 1.7:1 (Mickelson,1973; Drake,1971) and 1.3:1 (Ramsden,1970) have also been used. In the present analysis, however, the effect of shape on the orientation of particles was to be investigated and therefore particles were accepted if the direction of their long axis could be readily determined.

The size range of particles accepted for till fabric analysis varies considerably from worker to worker. Krüger(1970) and Mickelson(1971,1973) used particles with a long axis length of between 1 and 10cm, Järnefors(1952) and Young(1969) stipulated particles less than 10cm and Andrews(1963) used a range of particle sizes between 0.8 and 10cm. Andrews and Smith(1966) only investigated the long axes of particles larger than 1cm while Burke(1969) and Niewiarowski(1969) measured the orientations of particles larger than 1cm and less than 15cm. Ramsden(1970) studied particles down to 0.6cm in a few instances but usually concentrated on particles larger than 2.5cm. Kirby(1969) used a size range of 0.5 to 25cm with most particles between 2 and 3cm. Although in the present analysis no strictly defined size limits were adhered to, the size range of 1 to 15.7cm and an average of 3.1cm do not differ greatly from the corresponding values quoted by other workers.

A sample size of 50 particles was used for each of the twenty-five till fabric samples. This number of particles has been used by many other workers (e.g. Järnefors,1952; Hoppe,1952; West & Donner,1956; Wright, 1957; Norris,1962; Andrews,1963; Day,1971; Mickelson,1971; Cowan,1968), although 100 particles have been generally accepted as standard (e.g.Holmes,1941; Beaumont,1967; Scott & St.-Onge,1968; Penny & Catt,1967; Niewiarowski,1969;

Drake,1971,1974). The smaller sample size was chosen since the emphasis was on investigating the direction of ice movement rather than glacial processes and it was therefore "desirable to take a large number of samples with less observations per sample, rather than to increase the number of till-stones per sample" (Andrews,1971b, p.325).

The orientation and dip of each selected particle were both measured to the nearest 5^{o} using a Suunto compass/clinometer. Particles were rejected if the long axis was found to dip at an angle greater than 60^{o}. Some workers have also used this limit for measuring dip (e.g. Kirby,1969; Young,1969), others preferring different limits of, for example, 70^{o} (Hill,1971), 40^{o} (Krüger,1970) and 30^{o} (Johansson,1968). In the majority of studies the orientation of all particles has been analysed regardless of the angle of dip. Krüger(1973) in a laboratory experiment, however, found that accurate measurement of the orientation of particles with a dip of more than 50^{o} was difficult. In fact till particles are rarely so positioned that the dip of the long axis is much above 30^{o} and during the present analysis few particles had to be rejected as a result of an angle of dip that was too steep.

The long(a), intermediate(b) and short(c) axes were also measured for each particle to the nearest millimetre. This was carried out using a lidless wooden box c.25cm long, from which one end board and one side board had been removed. The bottom and remaining side board were covered in millimetre graph paper with centimetre numbering and protected by a clear plastic sheet (Matisto, 1961). Each particle was placed on the bottom board with one end of its long axis touching the end board. The lengths of the three axes were then read off the graph paper with the aid of a second, small, rigid plastic box which was moved along the board until it touched the required point on the particle. Not only was this method of obtaining the values for the three axes of a particle more accurate than simply reading off the lengths by eye from the graph paper but it was also more rapid.

Although a pair of calipers with a vernier scale allowing accuracy to 0.1mm was tried, it was found to have three major disadvantages compared to the measuring box. Firstly, in a laboratory experiment comparing the time taken to measure the three axes of 50 particles of pebble size, measurement with the calipers took almost twice as long as with the measuring box. Secondly, with calipers it is not possible to ensure that all three axes are mutually orthogonal. On the other hand, this can be achieved using the measuring box without moving the particle. Thirdly, with larger particles particularly, the two extreme points of a particle axis may be some distance apart in a direction perpendicular to the axis being measured. Using calipers difficulty arises in spanning this distance whilst still maintaining the correct line of measurement. With the measuring box, however, the plastic box can be placed at the required point on the particle without changing the alignment of the axis being measured.

The values of orientation, dip and the three axes were regarded for each particle on a prepared plotting form and subsequently plotted on to a conventional polar equidistant projection. This procedure ensures greater objectivity of particle selection and is preferable to either direct plotting on a polar net (Harrison, 1957a) or the use of a till fabric rack (MacClintock, 1959).

The till at each till fabric site was designated either weathered or unweathered and noted accordingly. Weathered till was recognised by its brown colour as a result of oxidation and generally loose texture compared to unweathered till which was usually tenacious, grey (with the exception of the Campsie Fells where it was reddish) and fissile. Occasionally this distinction was not so clear and although the till was evidently oxidised it was tough and retained a fissile structure. Such till was nonetheless recorded as weathered. On the other hand, the till from which sample 10 was taken was oxidised, and therefore regarded as weathered, but it was so stony that it had little in common texturally with the more clayey tills encountered elsewhere.

Results and discussion

The till fabric data for each site were plotted on equidistant projections (Figs 8.2-8.8) with 10^{o} allowed for each orientation measurement as a correction for magnetic variation west of true north. Orientation is represented by the circumferential scale and dip by the radial scale. Each particle is represented by a dot and where more than one particle occurs in the same position a proportionally larger dot is used according to the scale in Fig.8.2. The perpendicular lines intersecting at the centre of each polar net represent the north-south and east-west ordinates. The dots representing particles with horizontal dip were distributed as symmetrically as possible on either side of the projection.

The stippled, mirror-image rose shape superimposed on each of the polar nets gives a rapid visual impression of the azimuth directions of the particle long axes. The observations have been grouped in $18 \times 10^{\circ}$ units in the sequence $2\frac{1}{2}^{\circ}$-$11\frac{1}{2}^{\circ}$, $12\frac{1}{2}^{\circ}$-$21\frac{1}{2}^{\circ}$ etc. The addition of $2\frac{1}{2}^{\circ}$ to units in the sequence 0-9°, 10-19° etc. was carried out since orientations were recorded to the nearest 5° and the introduction of a systematic error was thus avoided (Kirby,1969). Observations up to 180° were allotted to the appropriate 10° grouping whilst for those between 180° and 360°, 180° was subtracted and the residual value allotted to the appropriate 10° grouping. The frequency for each grouping was then plotted on the polar nets such that the outer circle represents a frequency of 9 observations. A mirror-image of this 180° distribution was then drawn in the other hemisphere. Smaller versions of these diagrams are shown in Fig.8.1.

Around the periphery of each polar net the orientation of the section from which the till fabric was sampled is shown. This is included to show that by using a horizontal shelf the preferred orientation of the till fabric bears no relationship to the section orientation.

The direction and angle of slope obtained from 1:10,560 scale maps for the ground surface in the vicinity of each of the till fabric sites are shown in Table 8.1. A correspondence between preferred orientation of particles and direction of slope may indicate a secondary downslope movement as a result of solifluction or slumping of till and is therefore of no value in interpreting former directions of ice movement. Sometimes a downslope alignment of till particles may simply indicate a coincidence of glacial movement and slope direction. The directions of the preferred orientations of samples 22, 18, 17 and 10 correspond broadly to the direction of slope in the immediate vicinity. Of these, however, only the preferred orientation of sample 10 shows a large divergence from known ice movements in the Main Study Area (see chapter 3).

Statistical analysis

Although the preferred orientation of some samples can be estimated from the mirror-image diagrams, in most samples there is clearly a need for an objective statistical method of obtaining this direction. Many methods, both two-dimensional and three-dimensional, exist for analysing data with a circular or spherical distribution (see Steinmetz,1962), but since the majority of workers use only one method for analysing their

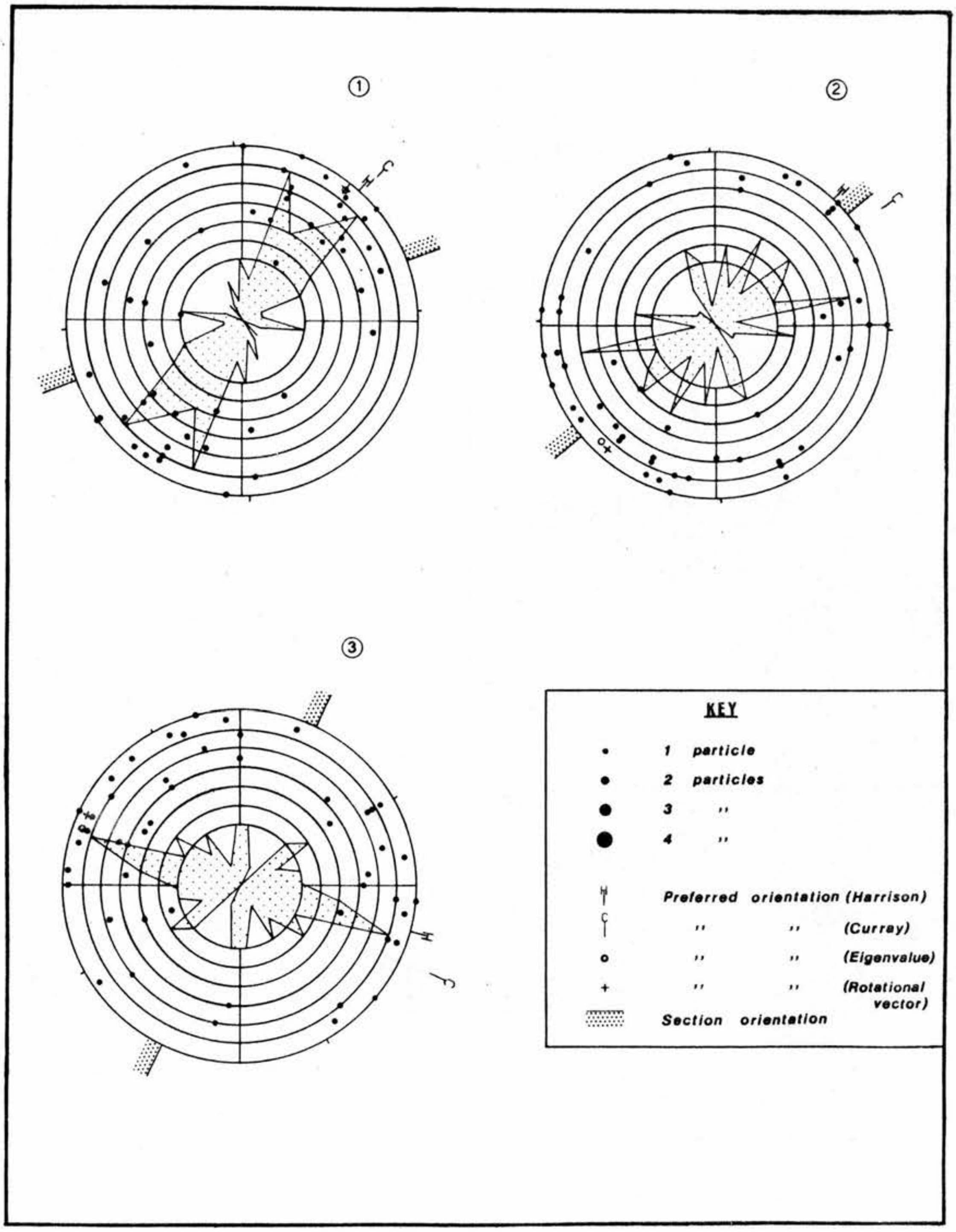


Figure 8.2

Till fabric samples 1-3 and key.

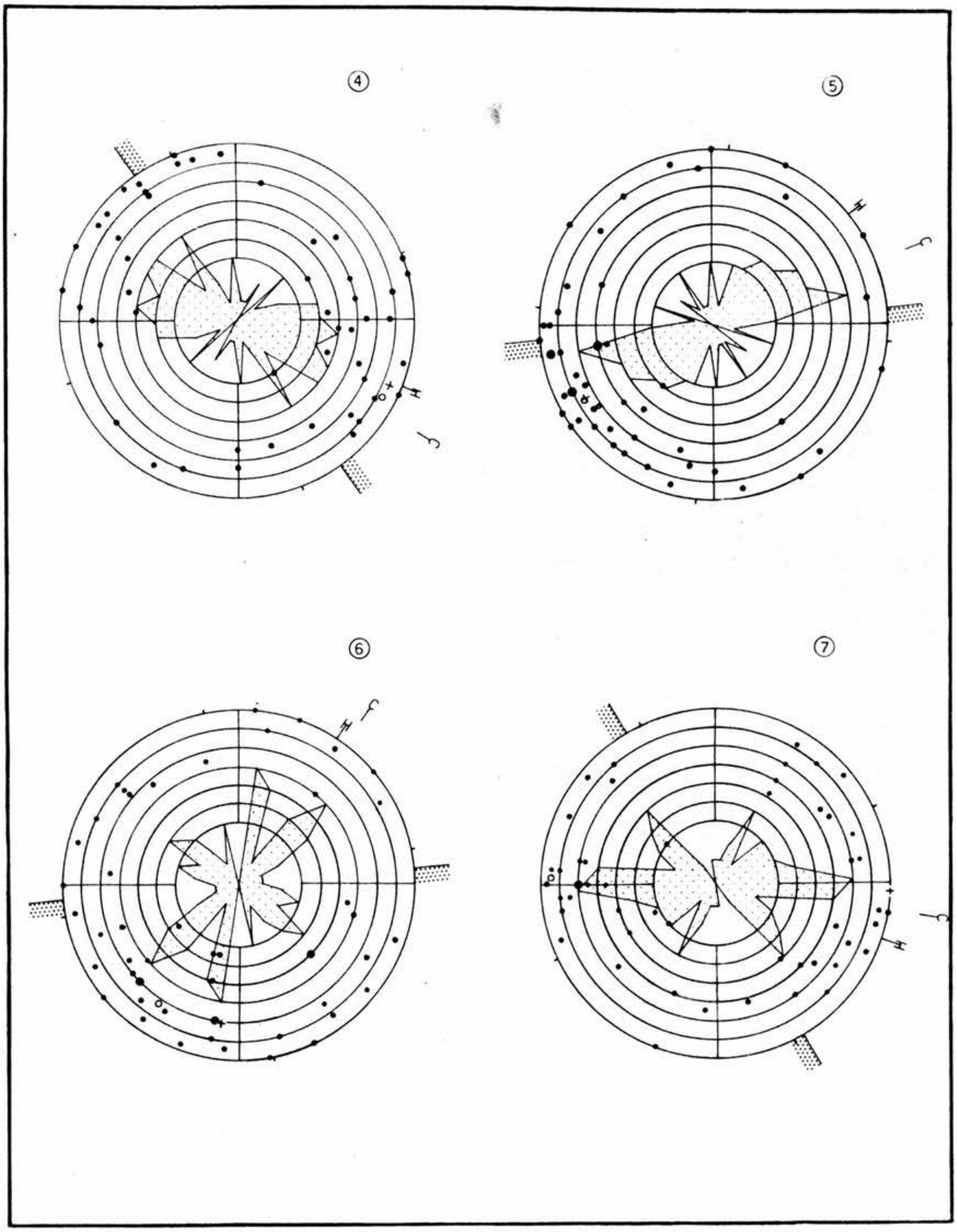


Figure 8.3

Till fabric samples 4-7.

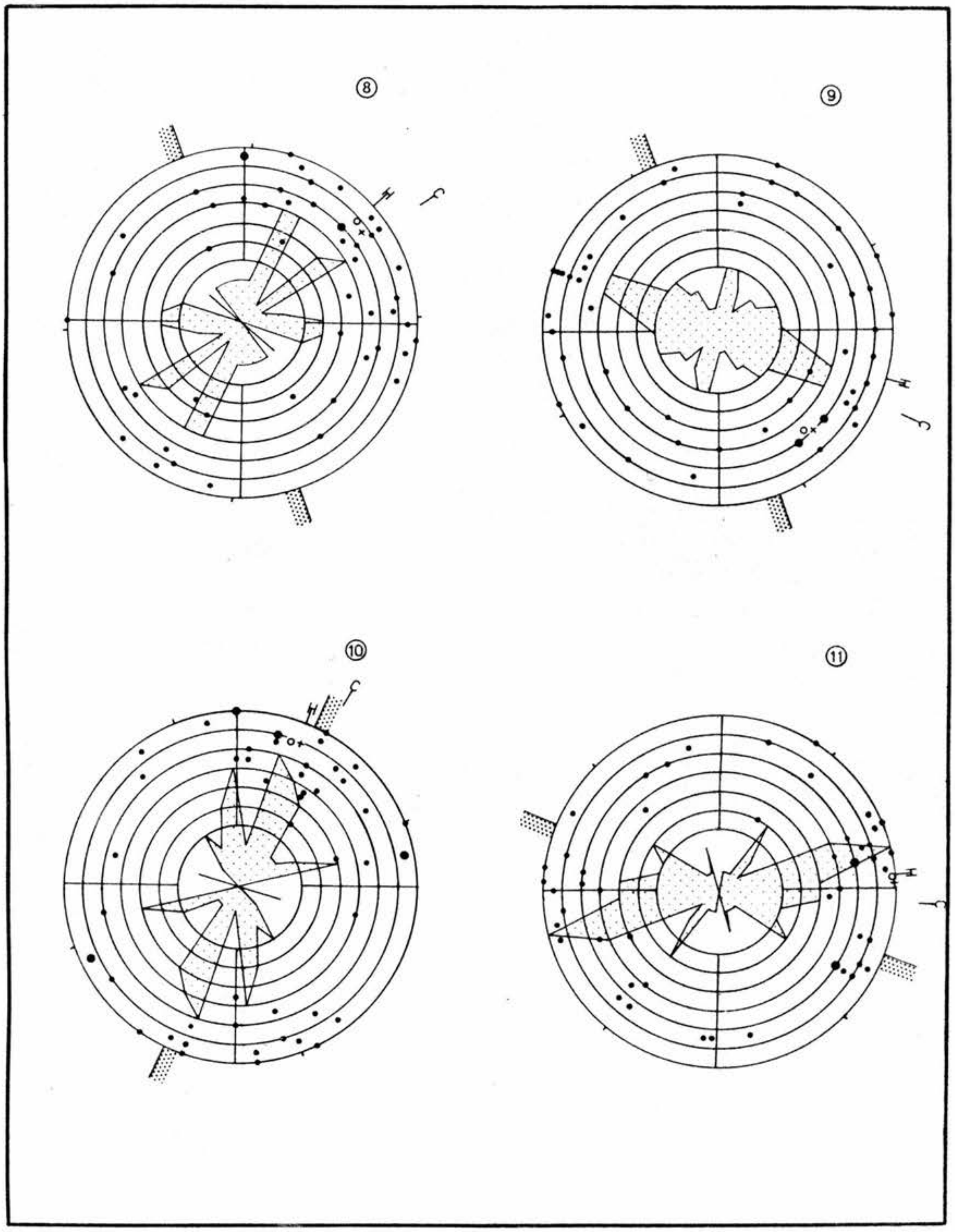


Figure 8.4

Till fabric samples 8-11.

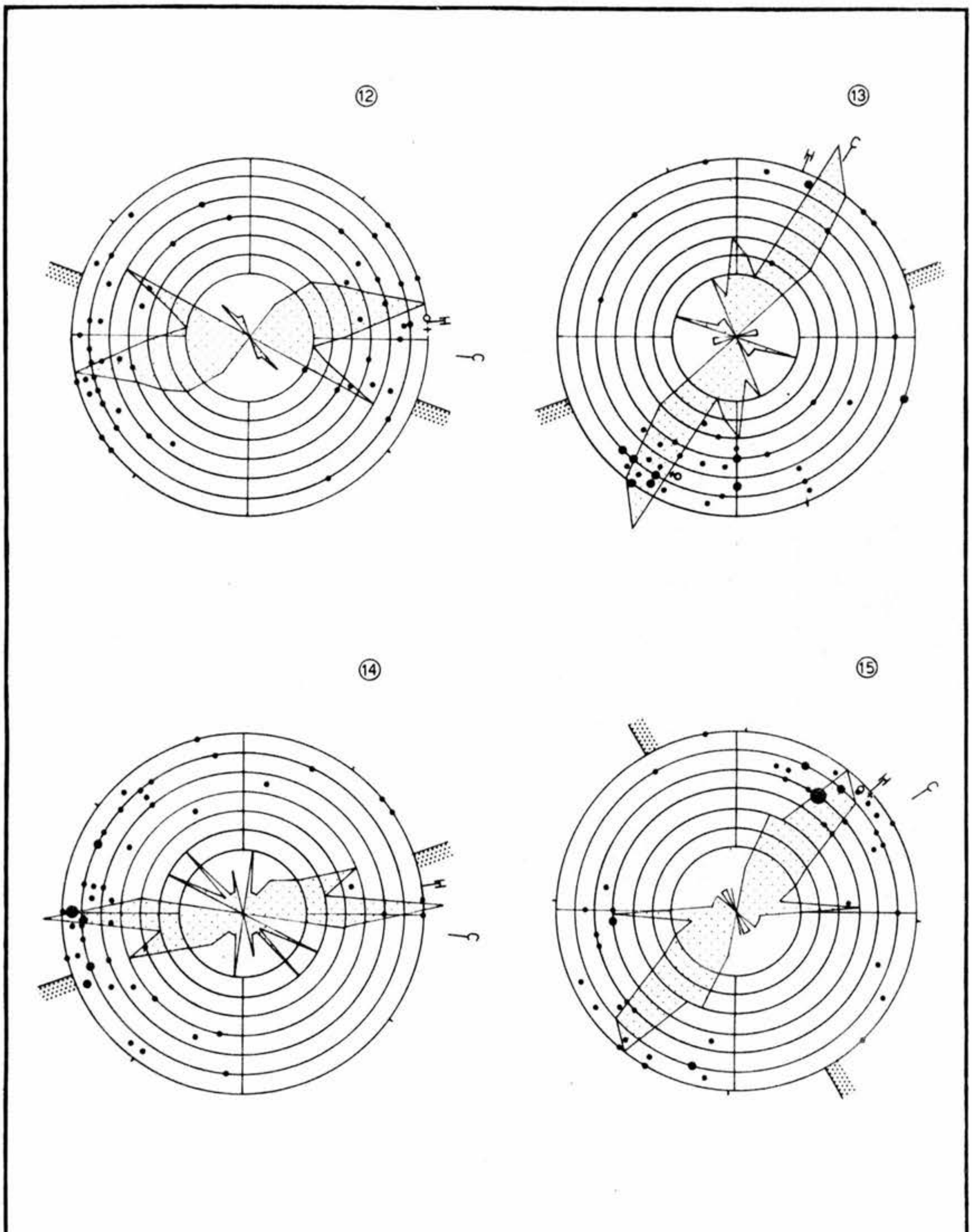


Figure 8.5

Till fabric samples 16-19.

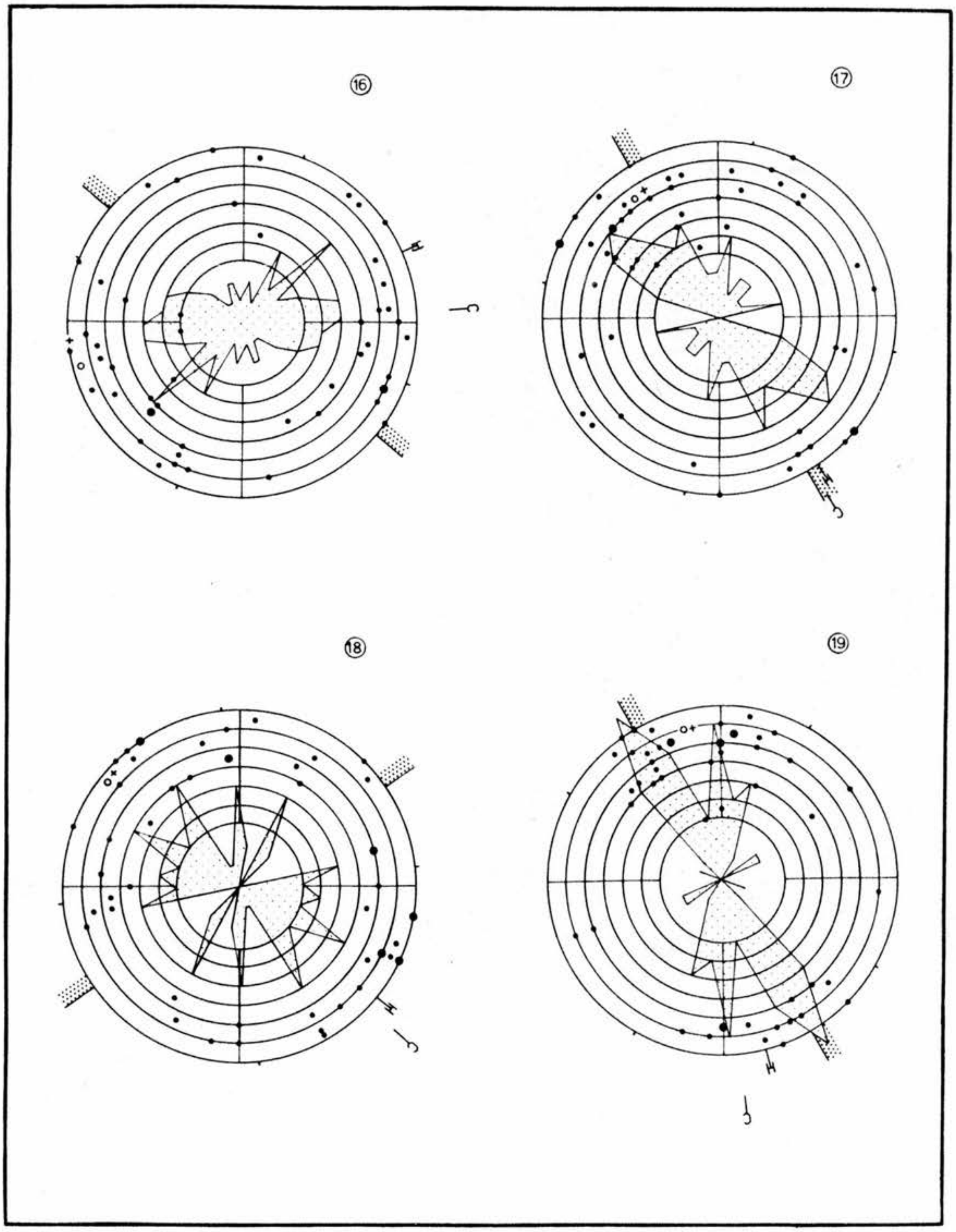


Figure 8.6

Till fabric samples 16-19.

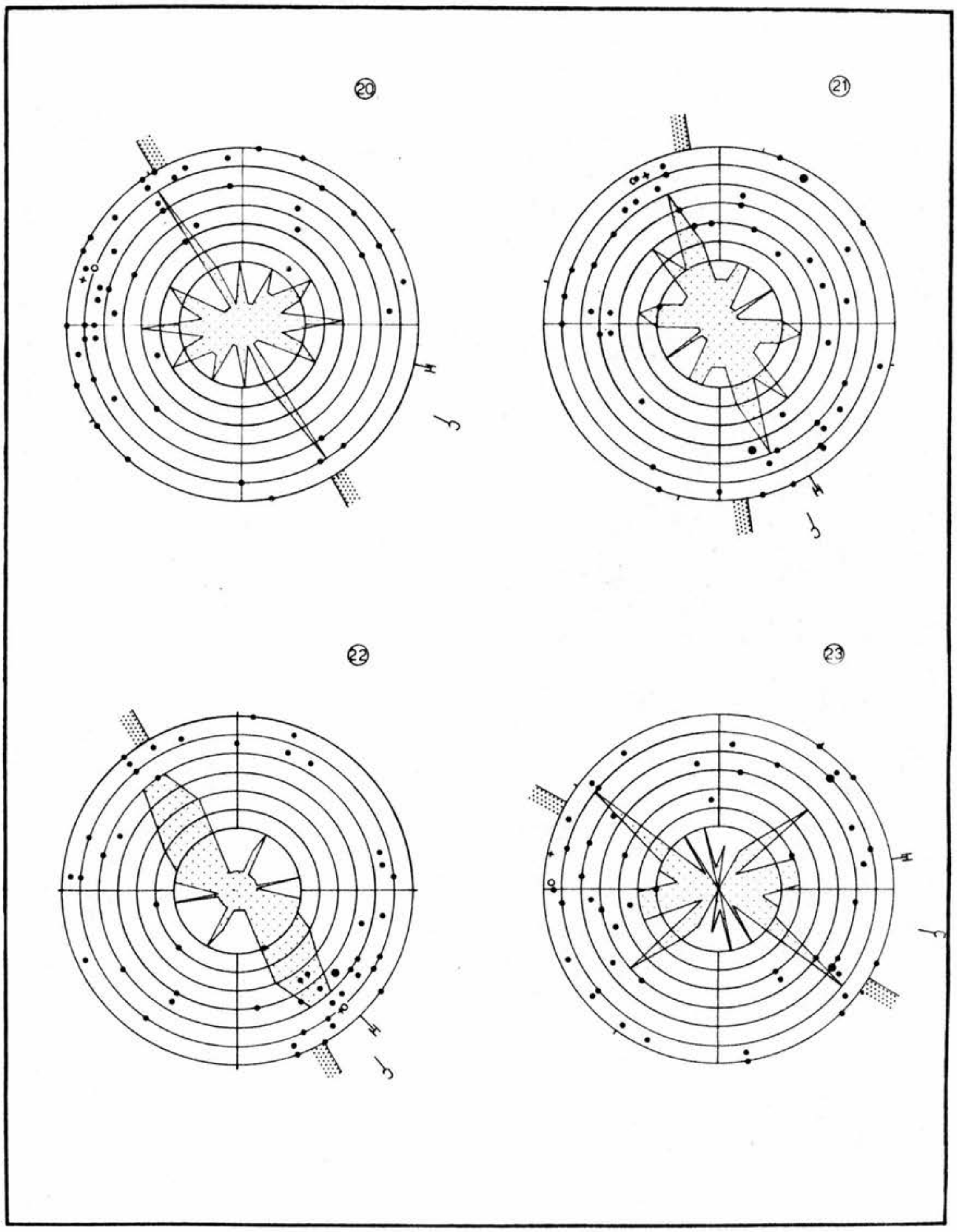


Figure 8.7

Till fabric samples 20-23.

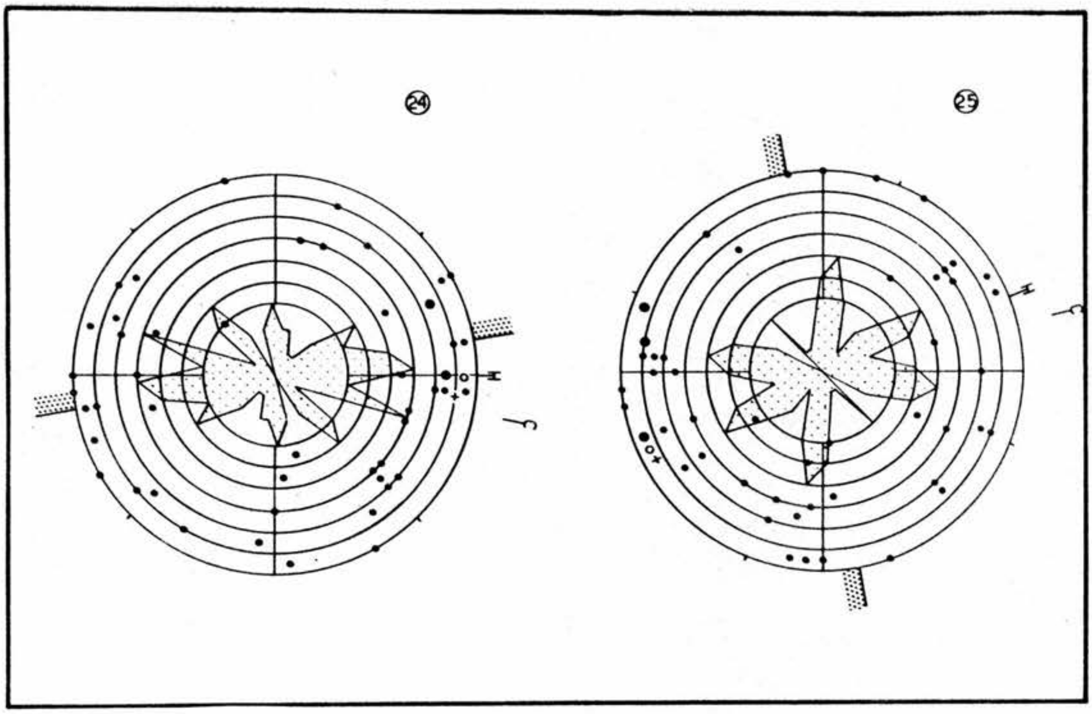


Figure 8.8

Till fabric samples 24 & 25.

Table 8.1 Till fabric data

Sample no.14	till type 13	Grid ref.12	depth (cm)11	section orient'n 10	slope (direction & angle) 9	vector summation 8 (pref. orien)	Tukey chi-square (pref orien.) 7	Rotational6 vector (pref. orien) or.	Rotational6 vector dip	Eigenvalue5 (pref. orien) or.	Eigenvalue5 dip	vector summation (strength)4 %	Tukey chi-square (strength)3	Rotational vector (strength)2	Eigenvalue (strength)1
1	W	721 790	150	70°	X	43°	52°	48	5	48	4	52^{+++}	+++	+++	+++
2	W	735 808	100	50°	SSE 3°	55°	53°	51	-5	234	6	29^{++}	+	+++	+++
3	U/W	751 804	280	25°	S 13°	115°	115°	125	-4	300	6	31^{++}	+++	+++	+++
4	U/W	697 808	150	145°	SSE 7°	122°	123°	123	6	127	7	34^{+++}	+++	+++	+++
5	W	696 806	90	85°	N 13°	68°	62°	250	14	249	13	33^{+++}	+	+++	+++
6	W	723 806	120	85°	SE 6°	37°	44°	198	19	223	17	13NS	NS	+++	+++
7	U/W	721 794	200	150°	E 2°	99°	119°	101	0	282	5	38^{+++}	NS	+++	+++
8	W	661 778	130	160°	SSE 3°	55°	57°	62	14	57	12	26^{++}	++	+++	+++
9	U/W	661 778	170	160°	SSE 3°	115°	116°	327	-20	150	23	27^{++}	+	NS	+++
10	W	661 794	80	155°	SSE 5°	31°	32°	34	11	30	12	41^{+++}	+++	+++	+++
11	U/W	724 798	150	110°	SSE 5°	94°	94°	97	1	95	2	45^{+++}	+++	+++	+++
12	U/W	724 798	600	110°	SSE 5°	94°	94°	97	0	93	0	57^{+++}	+++	+++	+++
13	U/W	768 813	200	70°	X	32°	32°	34	-14	212	14	52^{+++}	+++	+++	+++

14	13	12	11	10	9	8	7	6	5	4	3	2	1
14	W	768 813	100	70°	X	95°	91°	97 -11	277 11	41^{+++}	++	+++	+++
15	U/W	710 798	300	150°	SSW 6°	57°	57°	58 1	55 3	55^{+++}	+++	+++	+++
16	W	712 796	150	130°	SSE 12°	87°	76°	83 -1	264 4	28^{++}	NS	+++	+++
17	U/W	633 822	150	80°	SE 7°	149°	157°	159 -14	334 16	33^{+++}	+++	+++	+++
18	U/W	611 845	180	55°	SE 25°	133°	139°	142 -3	318 3	27^{++}	++	+++	+++
19	U/W	834 825	150	155°	SSW 2°	174°	175°	359 11	356 11	56^{+++}	+++	+++	+++
20	U/W	817 848	150	180°	S 4°	115°	113°	116 -5	301 9	13NS	NS	+++	+++
21	U/W	657 819	350	35°	SSW 7°	155°	159°	163 -6	339 5	21^{+}	+	+++	+++
22	U/W	572 801	150	150°	SSE 25°	141°	145°	149 9	147 9	38^{+++}	+++	+++	+++
23	U/W	778 827	300	60°	NE 2°	102°	91°	102 -2	282 4	22^{++}	+	+++	+++
24	U/W	656 810	100	260°	SW 6°	102°	100°	107 10	101 6	29^{++}	++	+++	+++
25	U/W	676 789	400	170°	SE 13°	77°	78°	72 -6	256 5	19^{+}	NS	+++	+++

U/W = unweathered

W = weathered

X = horizontal

NS = not significant
+ = significant at 90% level
++ = significant at 95% level
+++ = significant at 99% level

data there is little opportunity for comparing the results of different methods. In the present study, however, the 25 till fabrics have been subjected to analysis by four methods: the commonly-used two-dimensional methods of Curray(1956) and Harrison(1957a) and the three-dimensional methods of Andrews and Shimizu (1966) and Mark(1973).

Two major problems arise from the statistical analysis of till fabrics. Firstly the circular or spherical (if a three-dimensional solution is required) distribution means that the data have no natural point of origin. Secondly the bi- or multi-modal nature of many till fabrics creates problems when deriving a mean direction.

Some early two-dimensional methods were dependent on the chosen origin (e.g. Reiche,1938; Krumbein, 1939). However the vector summation method of Curray (1956) is independent of origin and treats the data in their original circular form (Krüger,1970). The method described by Harrison(1957a) is based on work by Tukey (1954) who used a combination of vector summation and chi-square, and is superior to the simple chi-square of Kauranne(1960). Both the vector summation and Tukey chi-square methods give a mean direction and a measure of statistical significance. The data are tested against a model of a random distribution in the former, and a uniform distribution in the latter method. In both methods the data have been reduced to a distribution in one hemisphere prior to analysis. (Although the method described by Harrison(1957a) has provision for treating the data in a circular form, a sample size of 100 is required to carry this out for data grouped in 10° units.)

Andrews and Shimizu(1966) employed an adaptation of Watson and Irving's(1957) vector procedure for calculating descriptive techniques to analyse three-dimensional orientations with the aid of a computer. They argued that the conventional horizontal reference plane was not necessarily the most appropriate for treating till fabrics. With successive trials they found that a rotation of the reference plane through 90° on an east-west axis produced the highest vector magnitude (i.e. highest degree of clustering). Andrews and King(1968) used a modified version of this method allowing the axis of rotation to pass through the area of minimum observations which they considered was the "best" compromise. Mark(1971) modified the method further so that the computer program calculated the maximum vector magnitude for a series of rotations. The data are analysed on one hemisphere and, since vectors have a "sense" (i.e. a directed orientation) as well as an orientation and magnitude, particles dipping below the horizontal in the other hemisphere must be regarded as pointing above the horizontal in the hemisphere being considered (Mark,1971). The computer program also gives values for a parameter "CHI-SQ." which allows determination of whether a sample is significantly non-random at a given probability level, and a parameter "k" which indicates whether the sample approximates a spherical normal distribution.

Ramsden(1970) criticised this procedure and Mark (1973,1974) pointed out an error in the significance test associated with the rotational vector technique and suggested an alternative approach to analysing till fabrics, using eigenvalues. The computer output for this technique gives the calculated azimuth and dip of the largest, intermediate and smallest eigenvector, the largest of these being regarded as the preferred orientation of the data. The level of significance based on randomness of direction can also be determined from the computer output using tables in Anderson and Stephens(1971).

The preferred orientations of all four methods and dips of the three-dimensional methods are shown in Figs 8.2-8.8 and in Table 8.1. Where the mirror-image diagram indicates a strong unimodal distribution (e.g. sample 1; Fig.8.2) the preferred orientation of the four methods corresponds closely. On the other hand, where the distribution is multi-modal (e.g. samples 6, 16, 20 & 23; Figs 8.3, 8.6 & 8.7) or bi-modal (e.g. sample 9; Fig.8.4) the preferred orientations diverge to a greater extent.

The levels of significance attached to the preferred orientations of the till fabrics do not correspond closely for the four methods. The two-dimensional methods show the highest agreement but frequently indicate different levels of significance. As regards the three-dimensional methods, all the samples with the exception of sample 9 are significantly non-random according to the rotational vector procedure and significantly non-uniform according to the eigenvalue method. There is clearly more discrepancy in this parameter between the four methods than there is in the determination of preferred orientation. This lack of agreement may be a result of the nature of the tests employed. Steinmetz(1962) argued that a comparison of the orientation data with a random or uniform distribution is a weak and non-sensitive test because orientation measurements are made for the very reason that an investigator expects his observations to be clustered. As a result he advocates testing distributions against a perfectly-oriented model.

Comparing the relative merits of the four methods, the three-dimensional techniques seem to offer nothing more than can be deduced from the polar nets or from the results of the two-dimensional techniques, and can give rise to misleading results. The following points outline the drawbacks associated with the three-dimensional methods.

(i) Both three-dimensional techniques assume a spherical normal distribution. As has already been mentioned however, a till fabric frequently possesses a bi-modal distribution with a primary mode representing particle long axes aligned in the direction of ice movement and a secondary mode corresponding to particles aligned transverse to this direction. For bi-modal and multi-modal distributions a "mean" vector will be produced between the two modes, as has occurred with samples 6 and 9 (Figs 8.3 & 8.4). Andrews and Shimizu(1966) attempted to overcome this problem by cutting out the transverse mode from the analysis, but this is clearly a highly subjective and therefore unsatisfactory procedure. Although a similar problem arises from using the two-dimensional methods, the less complex situation means that erroneous results can be easily detected.

(ii) The fact that the particle axes are all placed in one hemisphere prior to analysis by the rotational vector procedure means that a clustering of the points is bound to occur. The test for randomness of directions based on the length of the resultant vector is therefore invalid (Ramsden,1970).

(iii) Both three-dimensional methods have been used in a situation for which they are not designed. This is also true for the two-dimensional methods, but not so detrimental, since the relatively straightforward calculations involved mean that any inherent faults can be quickly diagnosed and taken into account during interpretation. For three-dimensional methods, with a more complex situation this is difficult.

(iv) In the present analysis, particles with a dip exceeding 60° have been omitted from the analysis and thus a small proportion of the sample population has not been represented.

(v) The orientation data are measured to the nearest 5° for both azimuth direction and dip. Errors are involved in extracting and replacing particles prior to measurement, estimating the position of the long axis, aligning the compass with this estimated position, reading the scale and errors can result from mental and physical tiredness (Hill,1968; Krüger,1970; Ramsden,1970). The application of sophisticated three-dimensional techniques to data that are approximate is unwarranted. Furthermore the apparent precision it imparts to the result is likely to lead to over-interpretation of the data (Kirby,1969).

For illustrating the preferred orientations of till fabrics in the present analysis the Tukey chi-square method has been used (Fig.8.9). There is little to choose between this method and that of Curray(1956), except that the former has the advantage that it can also be used for determining the preferred orientation on 360° as well as 180° distributions. There is in general a closer correspondence between the alignment of other ice direction indicators and the preferred orientations of till fabrics from unweathered till than from weathered till. Samples 1, 2, 5, 6 and 10 (from weathered till) appear to diverge significantly from the general alignment of striae in the vicinity. Two striking departures in the direction of preferred orientation of unweathered till fabrics (samples 16 & 20) can be explained in terms of the multi-modal character of the distribution pattern (Figs 8.6 & 8.7). However, many other unweathered till fabrics have given rise to preferred orientations that match the directions of striae in the immediate neighbourhood fairly closely (e.g. samples 18, 21, 23, 24 & 25).

The fact that there is a difference in the correspondence between direction of ice movement and weathered and unweathered till fabrics suggests that there has been some degree of postglacial action affecting the alignment of particles due to the shallow depth of the weathered samples. Straw(1968) criticised Harris(1967) for sampling till-particle orientations at depths of less than 90cm and regarded the results as suspect since the particles could have been subjected to reorientation by every day processes such as pedogenesis, mass movement, frost penetration and biotic agencies. On the other hand, the divergence and weak orientation strength may reflect for some samples an ablation origin (Niewiarowski,1969; Drake,1971).

The size of sample considered necessary for a reliable picture of the alignment of particles in till varies from worker to worker. A few researchers, rather than rely on precedent, have investigated the problem of a suitable sample size. Kauranne(1960) found little difference in the mean direction given by sample sizes of 25, 50, 100, 200 and 500 particles but noted a large difference in the significance attached to each sample size and recommended that 300 to 400 measurements should be carried out. Harrison(1957b) measured 410 particles and concluded that any randomly chosen three increments of 25 consecutive measurements were sufficient to give the direction of the preferred orientation. Andrews and Smith(1966) showed that there was little difference in the confidence cone around the preferred orientation with increasing sample size. Andrews and Smith(1970) considered that 10 to 25 particles might be enough to show the mean direction. Beaumont(1967) measured 100 particles but felt that 25 particles gave an approximate indication of where the preferred orientation lies. Young(1969) found that for till fabrics with a clear orientation pattern the measurement of 25, 50 or 100 particles gave virtually no difference in the direction of the preferred orientation although strength values varied. Sometimes the first 5 or 10 particles gave a good approximation of the alignment found where 100 particles were used.

In order to investigate the effect of size of sample on the direction and strength of the preferred orientation of till fabrics in the present analysis two samples of high strength, two of moderate and two of low strength were selected from the till fabrics. Using the vector summation method of Curray(1956) the samples were recalculated from the first 5, 10 and 25 particles measured. The results indicate that with 25 particles a good approximation of the preferred orientation found for 50 particles can be obtained for the moderate and high strength samples, but for one of the low strength samples (sample 20) there is a large divergence (Table 8.2). Values of strength increase with the halving of sample size to 25 for low strength fabrics whilst for moderate and high strength fabrics values either fall or, for sample 3, increase only slightly. With decreasing sample size however a greater strength value is required before the orientation can be regarded as significant, and therefore an apparently high strength value combined with a small sample size does not necessarily imply a significantly orientated fabric.

Table 8.2 <u>The variation in preferred orientation and orientation strength with different sample sizes</u>

Strength	sample no.	50 particles or.	50 particles str.	25 particles or.	25 particles str.	10 particles or.	10 particles str.	5 particles or.	5 particles str.
Low	25	77°	19.0%	86°	34.8%	78°	35.7%	71°	38.6%
	20	115°	12.8%	163°	20.7%	170°	24.8%	163°	16.1%
Moderate	16	87°	28.4%	90°	24.3%	65°	17.9%	60°	26.6%
	4	122°	34.0%	142°	32.0%	122°	28.4%	157°	20.0%
High	11	94°	44.7%	97°	25.8%	115°	49.4%	107°	26.9%
	3	115°	30.7%	117°	31.4%	124°	42.9%	125°	26.6%

When 5 and 10 particles are used the difference between the three types of fabrics is accentuated. The maximum divergence of preferred orientation with 5 or 10 particles in high strength samples from the value obtained for 50 particles is 21°, in moderate strength samples 35°, and in low strength samples 48°.

These results corroborate those obtained by Young(1969) in a similar study of the effect of sample size on the strength and direction of preferred orientations of till fabrics. He found that a good approximation of the alignment with 100 particles could be obtained for 4 out of 6 weak, moderate and high strength samples using the first 5 or 10 particles. In the present analysis 3 out of 6 samples give similar preferred orientations for 5 or 10 as for 50 particles (samples 3, 11 & 25). It is significant that 2 of these 3 samples are in the high strength category.

From this analysis it may be argued that if only an approximation of till fabric orientation is required, the measurement of 10 particles will suffice, provided that there is a strong preferred orientation. Using a series of such analyses over a till section the degree of variation of alignment of till particles, and therefore the reliability of a single main analysis, can by determined.

Dip analysis

The dip values for all the till fabric samples are shown in histogram form in Fig.8.10. There is a concentration of dip measurements in the low value classes with the mode occuring four times in the 0-5° class, nine times in the 5-10° class and eight times in the 10-15° class, which accounts for 21 out of the 25 samples. Mean values of dip range from 12.5° to 20.7° and the mean value of dip for all the samples is 16.3°. This compares with mean values of 7° obtained by Krüger(1970), 11° by Holmes(1941) and Young(1969), 14° by West and Donner(1956), 15° by Burke(1969b)and 23° by Wright(1957).

To determine whether particles transverse to the preferred orientation are more steeply dipping than those parallel to it, each till fabric was divided into major and minor quadrants based on the Tukey chi-square preferred orientation values. The four barbs on the outer circle of each till fabric sample in Figs 8.2 to 8.8 denote the limits of these quadrants.

A total of 357 out of 1250 particles measured lie in the minor quadrant. The overall mean value for dip is 17.1° compared with 16.0° for the 893 particles in the major quadrant. When the particles are subdivided into weathered and unweathered categories, the mean dip of the 123 minor quadrant particles is 15.3° compared with 15.8° for the 242 major quadrant particles from weathered till, and the mean dip of the 234 minor quadrant particles from unweathered till is 18.0° compared with 16.1° for the 651 major quadrant particles. There appears to be a lower mean value of dip for the unweathered major quadrant particles compared with the minor quadrant particles, which suggests that the processes responsible for orienting particles transverse to the direction of ice movement may also cause them to be more steeply dipping. However, for only one sample (sample 9) is there a marked transverse mode and therefore the majority of the minor quadrant particles measured are somewhere between the two positions (i.e. parallel to ice movement and perpendicular to it).

A number of workers including Harrison(1957b), Wright(1957), Krüger(1970) and McKensie(1970) have found a preferred up-ice dip of till particles. Krüger (1970), however, pointed out that reference to the horizontal plane when considering preferred dip can be misleading and that reference to the subglacial slope should be made. Analysis of up-ice dip was not carried out for the till fabrics from the Main Study Area due to the difficulty of determining the appropriate reference plane.

The relationship of shape and size of till particles to preferred orientation

Holmes(1938,1941) maintained that size, shape and roundness of particles affected the long axis orientation in relation to ice flow direction. Streamlined particles tended to show parallel orientation whilst asymmetrical particles tended to deviate from this direction. Increased size of the long axis also tended to give rise to parallel orientation and greater elongation led to a transverse orientation of the particles.

Andrews and King(1968) analysed the effect of size and shape on particle orientation in till. They found that "the elongated and rather smaller stones tend to show stronger preferred orientation than the larger and more rounded stones" (Andrews & King,1968,p.452).

Krüger(1970), like Holmes(1941), found that streamlined particles show a strong preference for parallel orientation with ice flow direction. In contrast to Holmes(1941) however, he found that greater elongation of particles gives rise to parallel rather than transverse orientation. He also suggested that long axis orientation parallel to ice flow tends to decrease with increasing roundness.

Ramsden(1970) investigated a:b ratios of particles giving the most reliable estimate of ice flow direction and concluded that a:b ratios of 1.3:1 or more give the most reliable indication of former ice direction. He also considered that "larger pebbles do display a far smaller amount of scatter than do smaller ones" (Ramsden, 1970,p.109).

Drake(1974) investigated the shape of particles according to Zingg's(1935) definitions (Fig.4.7) in relation to direction of ice movement. He found that rods and blades showed strong parallelism to ice flow direction and that the fabrics of spheres and discs were weak. In contrast to the work of Holmes(1941), he found that the transverse alignment was a product neither of extreme rods nor blades, but of particles close to the common intersection of the four Zingg shape classes.

To investigate the relationship between shape and preferred orientation in the present analysis, the Zingg shapes for the 1,250 till particles measured and the deviation of each long axis orientation from the preferred orientation of the sample according to the Tukey chi-square method were calculated. As ice flow direction varies over the Main Study Area it was not possible to determine the divergence of long axis orientation from this parameter. Table 8.3a shows the deviations of all particles measured and the deviations of particles from unweathered till only. Table 8.3b shows the mean deviations of the particles classified as spheres from unweathered till in Table 8.3a, and of the 81 randomly-chosen discs , blades and rods from unweathered till. The results do not indicate, as might be expected, that spheres and discs are more weakly oriented with respect to ice direction than blades and rods. Table 8.3b suggests the opposite relationship, i.e. that spheres and discs are more reliable indicators of preferred orientation.

Table 8.3 The mean deviations of spheres, discs, blades and rods from preferred orientation

	SPHERES		DISCS		BLADES		RODS	
	N	Mean dev.	N	Mean dev.	N	Mean dev.	N	Mean dev.
(a) unweath. till	81	33.2°	106	30.6°	219	31.1°	444	32.5°
unweath. + weath. till	181	34.4°	195	31.5°	267	31.8°	607	34.0°
(b) unweath. till	81	33.2°	81	29.4°	81	30.6°	81	35.8°

As a further investigation of the dependence of orientation on particle shape, regression analyses were carried out of preferred orientation against size (a-axis length of the particle), b/a ratio, c/b ratio and Krumbein sphericity for the 850 particles from unweathered till. In the light of previous work, a significant correlation between preferred orientation and the b/a ratio might be expected. However, all the results were statistically insignificant except for the regression of preferred orientation on c/b ratio, which gave a weak correlation coefficient of +0.075 that was nevertheless significant at the 95% level. This suggests that the less oblate the particle, the more likely it is to show orientation parallel to the preferred orientation of the till fabric. The very weak relationship indicated by the correlation coefficient, however, means that little or no reliability should be placed on this result.

If it is accepted that the more elongated till particles tend to lie with their long axes parallel to ice movement, the contradictory results obtained in the present analysis can be explained by one, or a combination of the following reasons. Firstly, the choice of particles for measurement was made on the basis of whether the long axis could be easily determined. Fig.8.11 indicates that selected particles are clustered close to the intersection of the four Zingg shape classes. Analysis of the relationship of particle shape to deviation from the preferred orientation might not be expected therefore to yield significant results, since the particles have a narrow range of shapes. Secondly, the preferred orientation of the sample is not necessarily equivalent to ice direction. Thirdly, the factors of shape that particularly affect alignment of till particles may not have been measured. Holmes(1941) maintained that small changes in, for instance, roundness and surface form could significantly alter the orientation of till particles.

Striae and ice-moulded features

The majority of the striae shown in Fig.8.9 have been derived from 1:10,560 scale Geological Survey maps, whilst the remaining ones were found during fieldwork (Plate 11). Although the processes responsible for the formation of striae are understood, those forming the flutes, drumlins and crag-and-tails comprising ice-moulded features are points of conjecture (See Russell,1895; Alden, 1905,1911; Dyson,1952; Gravenor,1953; Hoppe & Schytt,1953; Kupsch,1955; Gravenor & Meneley,1958; Lemke,1958; Schytt, 1959; Smalley & Unwin,1968; Baranowski,1970; Glückert,1973; Shaw & Freschauf,1973). The accepted view is that the depositional forms were produced during the later stages of occupation by active ice since any alteration in ice flow direction would quickly remould the features (Wright, 1912; Hughes,1964).

In the Main Study Area, dissection of some ice-moulded forms by meltwater and postglacial streams has meant that the true alignment of individual features is difficult to determine even though the overall direction of a group of features is clear. Therefore to avoid erroneous results only the long axes of the clearer examples of ice-moulded features were determined and located on 1:25,000 scale maps.

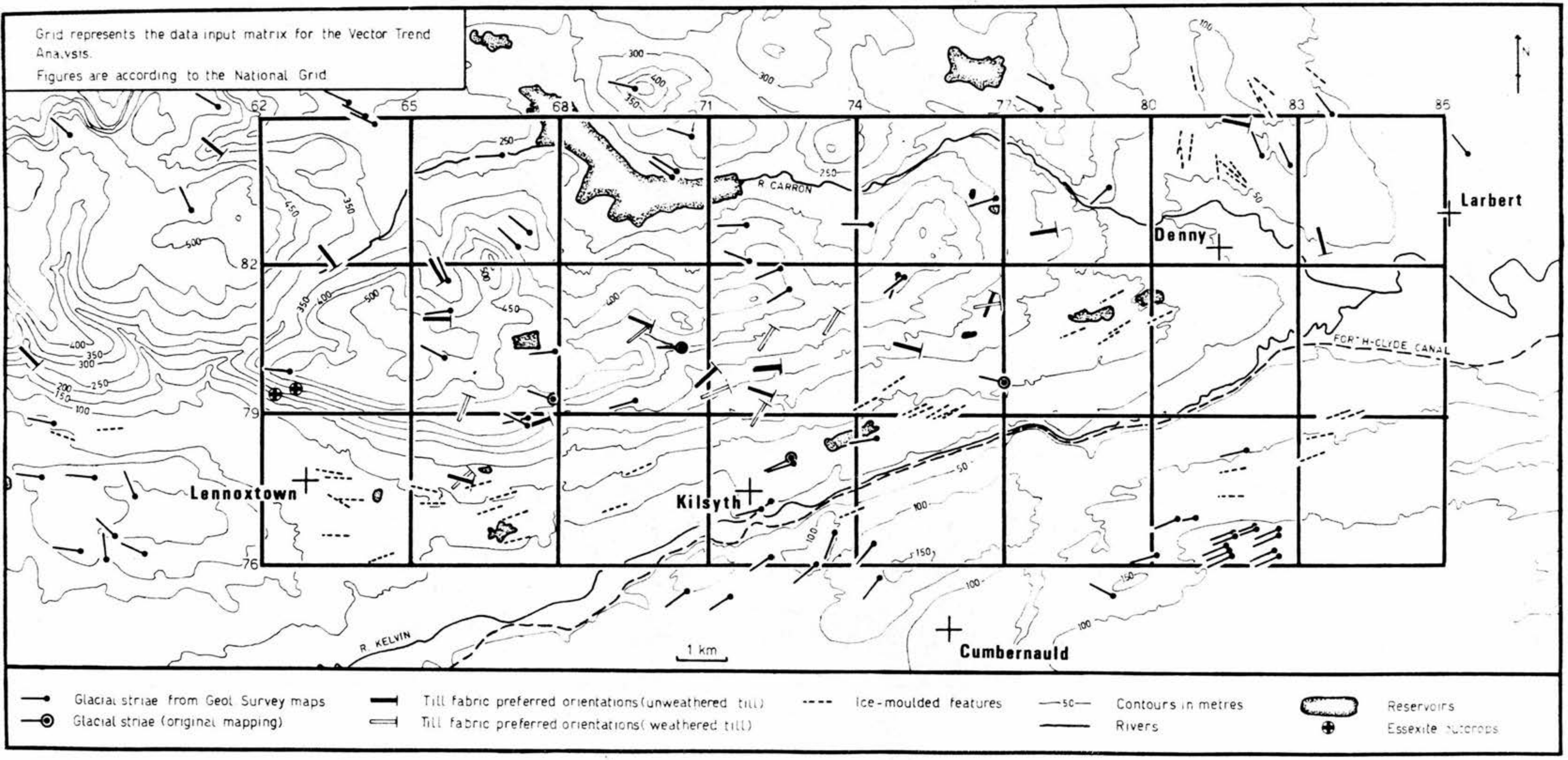
Vector trend analysis of the ice direction indicators

Although a general impression of glacier ice flow direction can be gained from Fig.8.9, no direct comparison with the essexite erratics train is possible. It was considered desirable therefore to derive a regional trend of the directional data. The application of a straightforward trend surface technique is not feasible when dealing with azimuth directions due to the circular form of the distribution. However, Fox(1967) and Roberts and Mark (1970) have developed computer programs based on orthogonal polynomial trend surface techniques specifically for use with directional data, a method known as vector trend analysis.

The computer program used in the present analysis is a slightly modified version of the one given by Fox (1967). It is limited to gridded data so that non-gridded data must be grouped into cells prior to analysis, with a maximum of 8 rows and 8 columns of cells. For each cell a direction cosine is determined according to methods discussed in Steinmetz(1962). Polynomial coefficients are used to compute trend values for each grid cell and trend surfaces up to the quintic can be produced. The program gives the vector mean azimuth for each cell, the percent reduction in the sum of squares (%RSS) of each trend surface and the Z-squared array.

The Main Study Area was divided into grid cells to prepare the data for computer analysis. Following experimentation, the grid cell pattern shown in Fig.8.9 was selected using 3 x 3km squares based on the Ordnance Survey National Grid. This was found to be the best configuration of grid cells that included at least one ice direction indicator in each cell while not exceeding 8 cells in an east-west direction.

All the alignment data for striae and ice-moulded



<u>Figure 8.9</u>

Ice direction indicators and grid for vector trend analysis.

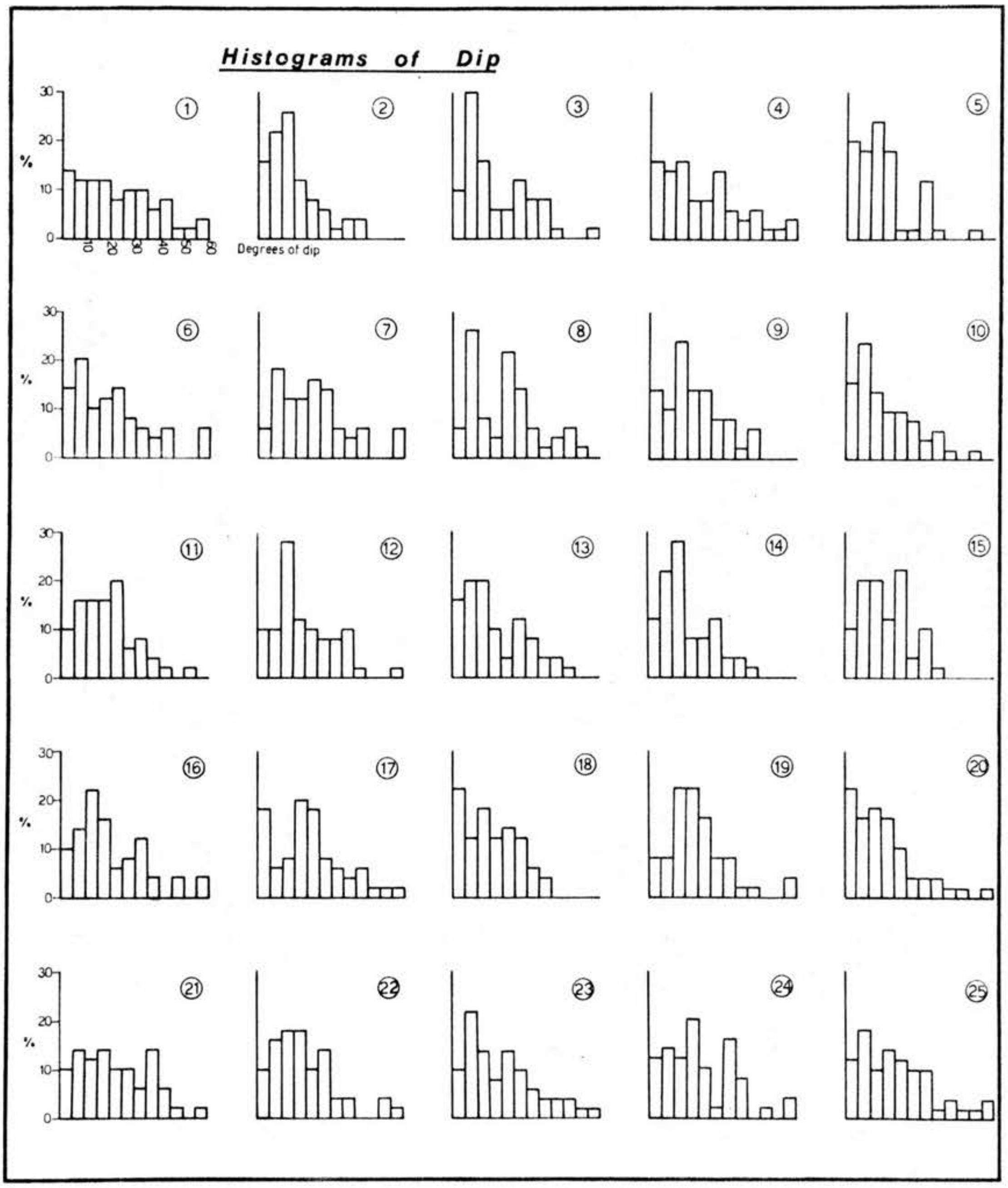

Histograms of Dip
30
20
%
10
0
10
20
30
40
50
60
Degrees of dip
1
2
3
4
5
6
7
8
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Figure 8.10

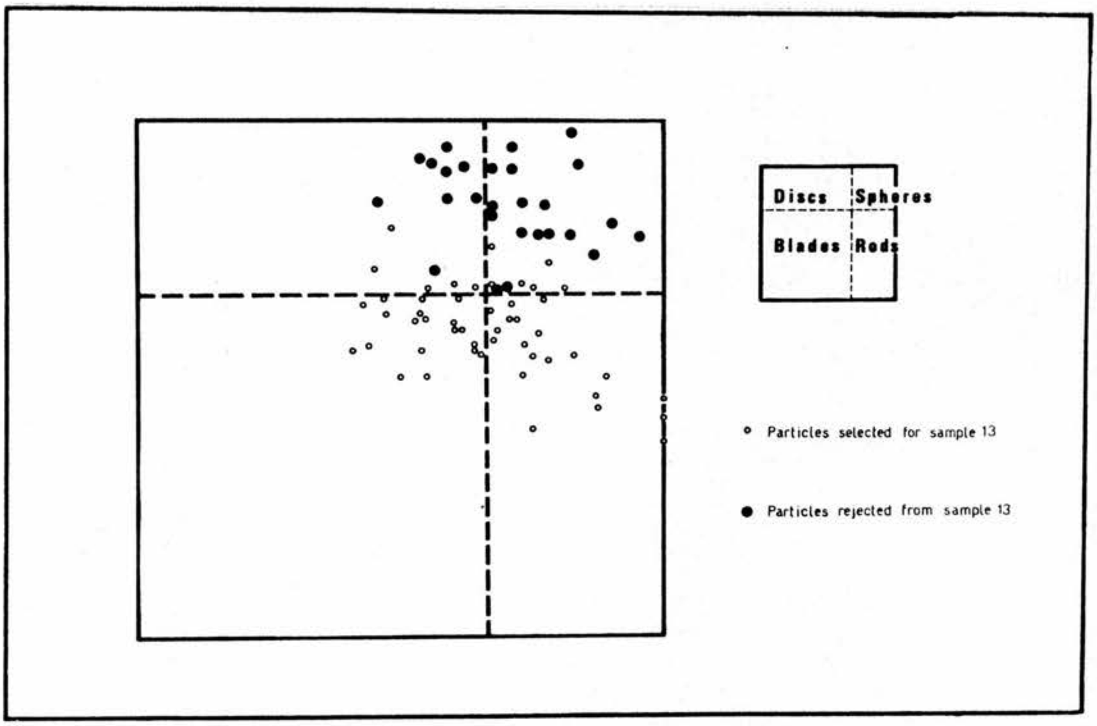

Figure 8.11

Particles chosen and rejected from the analysis of till fabric sample 13.

features were included but only the preferred orientations of till fabrics from unweathered till with a significant orientation at above the 90% level (Tukey chi-square method) were used. This meant that out of the 17 unweathered till fabrics, 3 (samples 7,20 & 25) were excluded from the vector trend analysis. Trend surfaces that included all the unweathered till fabrics differed only slightly from those shown in Figs 8.12 and 8.13.

Fig.8.12 shows vector mean azimuth directions for each cell and first, second and third order trend surfaces. The line of the major axis of the essexite erratics train drawn from the contour map of porphyritic plus non-porphyritic (E_A) values (Fig.5.5) is also shown for comparison. The %RSS for the trend surfaces are shown in Table 8.4.

Table 8.4 Percentage reduction in sum of squares for vector trend analysis (8 x 3 grid cells)

1st.Order	Quadratic	2nd.Order	Cubic	3rd.Order
15.1	22.2	37.2	29.1	66.1

The map of vector mean azimuths (Fig.8.12a) indicates a general west-east trend of ice movement in the area. Within this overall flow there are a number of deviations. The arrows in the two top row, north-west grid cells are directed towards the south-east compared with a west-east direction in the two rows of grid cells between Lennoxtown and Kilsyth. In the rows of grid cells running east from Kilsyth to Denny the vector mean azimuths indicate a divergence of ice flow to the north-east and south-west around the higher parts of the Campsie Fells. In the top two row cells between Denny and Larbert, however, there is a marked clockwise rotation of vector mean azimuths towards the south-east and south-south-east.

The first order trend surface (Fig.8.12b) reflects the underlying west-east alignment of the data over the Main Study Area with a slight anti-clockwise shift of the trends in each cell from west to east. The low %RSS (15.1) shows that there is a large amount of variation not accounted for by this trend surface. The map of residuals from this surface (Fig.8.13a) shows that the greater part of the variation is accounted for by the north-west and north-east corners of the grid indicated by a strong positive (i.e. clockwise) deviation.

The second order trend surface (Fig.8.12c) shows a more complex pattern than Fig.8.12b. The trend follows a sinuous course from west to east. Arrows in the cells farthest west point south-east. Near Kilsyth they are directed north of east, in the two top row cells between Denny and Larbert they are directed south-east and east-south-east and in the two cells in the lowest row they point east-north-east. If a comparison of the course of these arrows is made with that of the major axis of the erratics train there is a striking correspondence. The higher %RSS (37.2) of the second order surface indicates that the quadratic component adds considerably to the explanation given by the linear component. The residuals

(Fig.8.13b) indicate large positive deviations in the north-east corner and in the central two cells of the grid corresponding to the divergence of ice around the higher parts of the Campsie Fells.

The third order trend surface (Fig.8.12d) reveals a slightly more intricate sinuous pattern than the second order surface. The addition of 29.1 by the cubic component to the %RSS of the third order surface means that it accounts for 66.1% of the variation in the original data. The arrows in the north-west and north-east corners of the grid are turned farther clockwise than in the second order surface, thus reflecting more closely the alignment of the vector mean azimuths (Fig.8.12a) for these areas. In the central four columns of cells the arrows rotate gradually in an anti-clockwise direction from west to east, reflecting the influence of the Campsie Fells in controlling the direction of ice flow. The residuals of this surface (Fig.8.13c) indicate that the only major deviations of the vector mean azimuths from the third order surface correspond to the directions in the central two cells.

Since there is such a close correspondence between the second and third order surfaces and the alignment of the major axis of the erratics train it seems reasonable to infer that the essexite erratics have been transported by the same glacier ice that produced the striae, ice-moulded features and preferred orientation of till particles. Furthermore the striae, ice-moulded features and till fabrics have almost certainly resulted from the movement of the last ice to be active within the area (i.e.

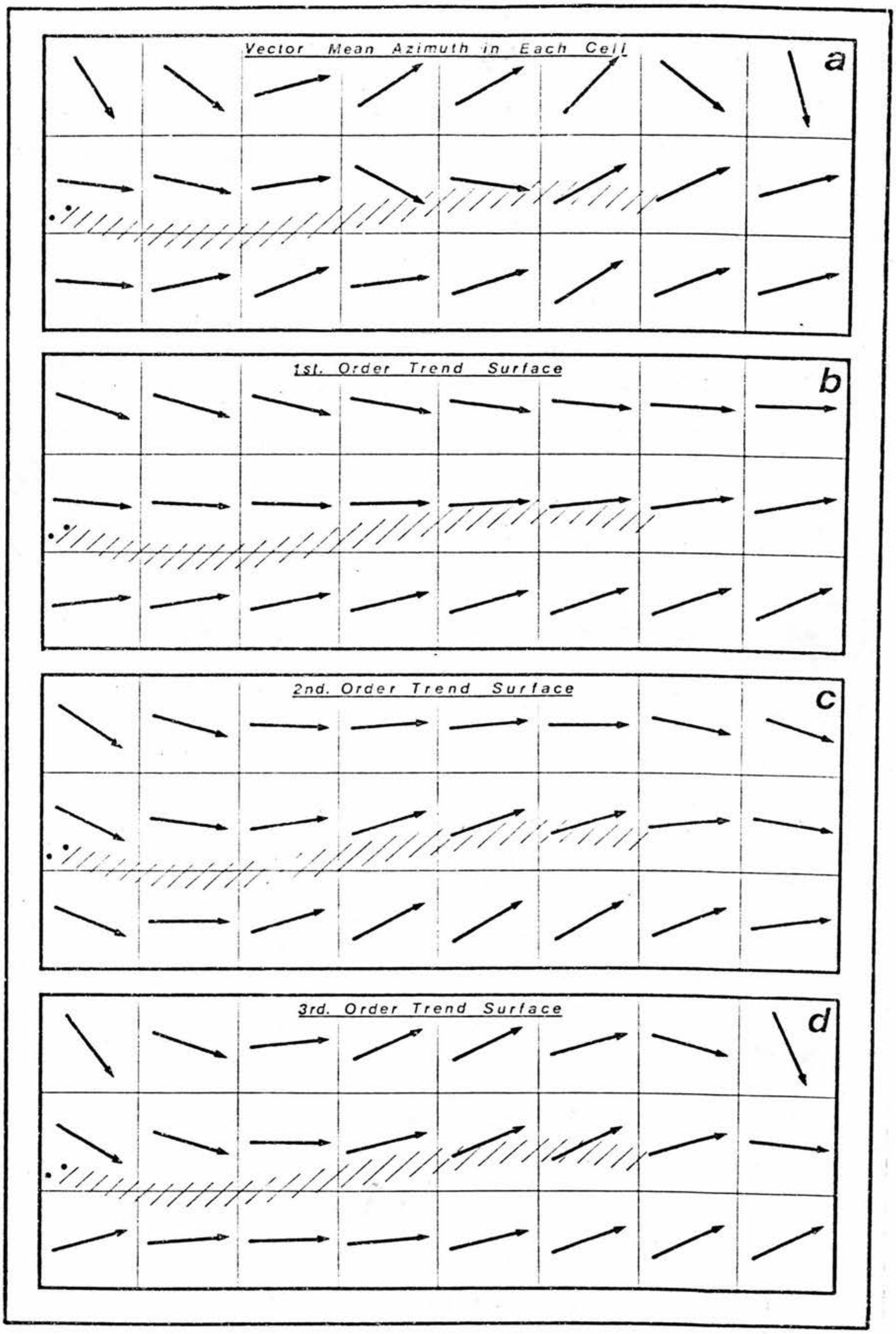

Figure 8.12

Vector trend surfaces (8 x 3 grid).

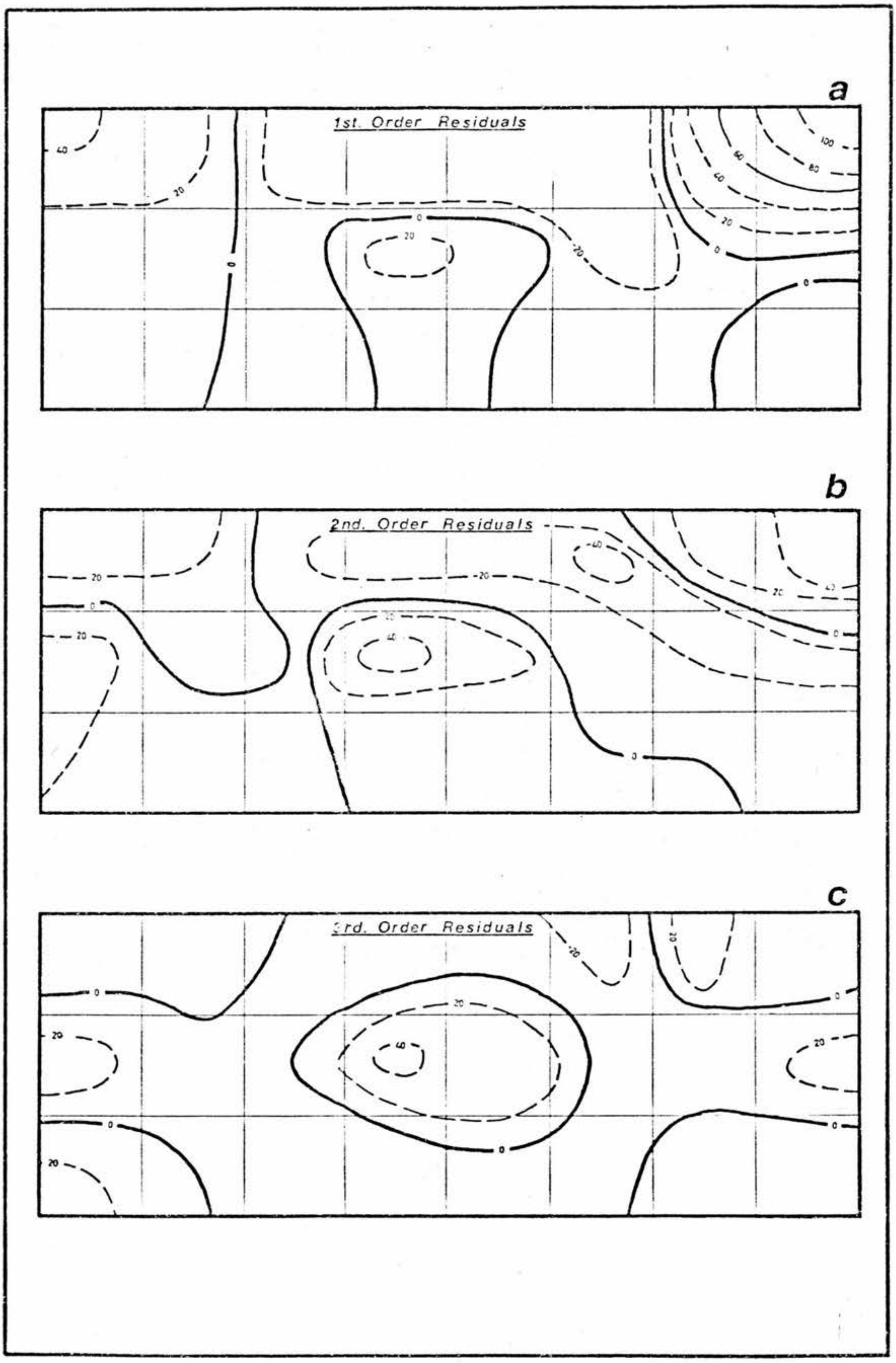

Figure 8.13

Vector trend surface residuals (8 x 3 grid).

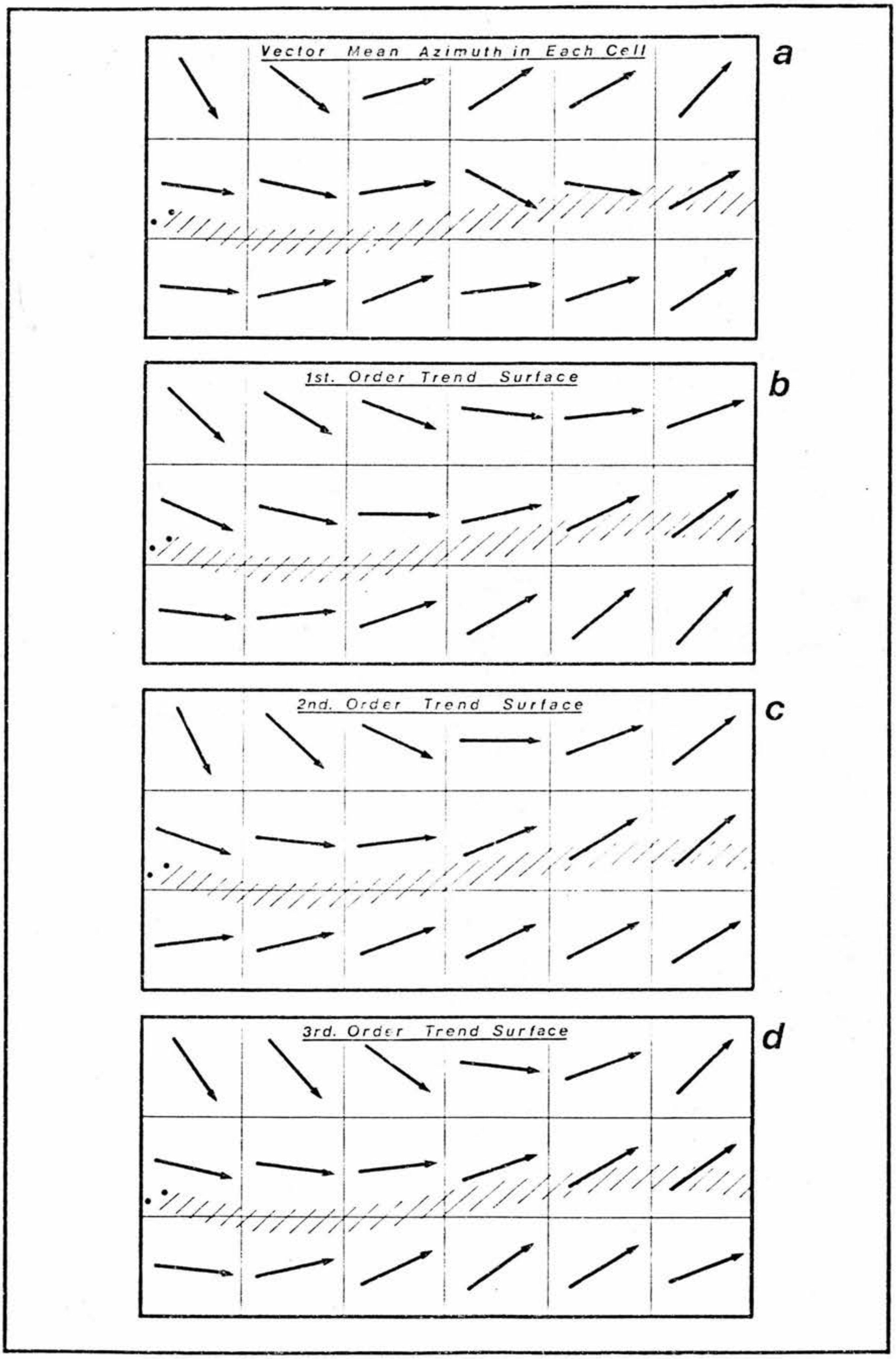

Figure 8.14

Vector trend surfaces (6 x 3 grid).

the latter stages of the Devensian glaciation). Therefore the formation of the erratics train can also be assigned to this time.

From the second and third order vector trend surfaces and from what is otherwise known of ice movements in the Main Study Area (see chapter 3), it seems that the interaction of two major ice streams occurred in the Denny area. One stream moved south-east and east from the Highland edge across the area gradually turning towards the north-east along the Kelvin-Bonny Water valley, the other moving south-east from Stirling towards Denny and Falkirk. In order to analyse the direction of movement of the ice that transported the erratics train, the last two columns of cells were excluded from the trend surface analysis, since these cells reflect the movement of ice flowing south-east from the Stirling area.

The vector mean azimuth directions for each cell (Fig.8.14a) show a strong anti-clockwise rotation for the columns in a west-east direction. The high %RSS (74.2) for the first order surface indicates this strong trend (Table 8.5; Fig.8.14b).

Table 8.5 Percent reduction in sum of squares for vector trend analysis (6 x 3 grid cells)

1st Order	Quadratic	2nd. Order	Cubic	3rd. Order
74.2	16.5	90.7	6.6	97.3

The quadratic component explains a further 16.5% of the variation in the data making a total of 90.7 %RSS for the third order surface. The cubic component explains 6.6% of the variation so that the third order surface leaves only 2.7% of the variation of the original data unexplained.

The higher %RSS of the 6 x 3 grid compared with the 8 x 3 grid is a result of the omission of data refecting the movement of ice from the Stirling area leading to a better approximation by the trend surfaces. The arrows at the eastern end of the 6 x 3 grid however, deviate more from the line of the major axis of the erratics train than the arrows at the corresponding points in the trend surfaces based on the 8 x 3 grid. This supports the view that the alignment of the erratics train represents the overall direction of ice movement since the ice stream moving south-east from the Stirling area is clearly an important factor.

CHAPTER 9

FORMATION OF THE ERRATICS TRAIN

> "though the passage from cause to effect involves no special logical problem, the reverse process does" (Skellam,1953)

This chapter deals with the possible glacial processes responsible for forming the Lennoxtown essexite erratics train in the light of the evidence from the present investigation. The following eight points summarise the most important pieces of evidence.

(i) Essexite erratics have been carried obliquely up the steep south-facing scarp of the Campsie Fells from the outcrops (c. 120-290m O.D.) to an altitude of 417m at a point north of Brown Hill some 3.5km down-ice of the outcrops. There appears to be little or no variation in the maximum altitude to which porphyritic and non-porphyritic stones were carried, despite a difference in the altitude of the two outcrops.

(ii) Both porphyritic and non-porphyritic stones have undergone crushing and,to a lesser extent, abrasion during glacial transport. Crushing is indicated by the rapid disappearance of porphyritic stones and by the reduction in the size of non-porphyritic stones in the dry stone walls down-ice of the outcrops (see chapter 5). The initial increase in the roundness of essexite erratics from both outcrops and lack of a trend in this index beyond 5-10km in the down-ice direction suggests that abrasion has taken place, but that it is of secondary importance to crushing (see chapter 6).

(iii) Bedrock fragments of both varieties of essexite and titanaugite mineral grains rapidly become scarce in the till down-ice of the source. On the other hand, non-porphyritic essexite stones are still common in the dry stone walls along the major axis of the erratics train for up to 20km from the outcrop.

(iv) Although the majority of the lower till-covered, south-facing slopes of the Campsie Fells in the Main Study Area have been subject to ploughing so that the topmost layers of deposits have been disturbed, in a few locations the original sequence remains undisturbed. This sequence is well displayed at the site of till fabric samples 11 and 12 (GR 724 798; Plate 12) , where a layer, no more than 50cm thick consisting mainly of boulders and cobbles with intervening pebbles and gravel, overlies thick deposits of clayey till. A similar sequence of deposits was found at the site where till fabric sample 16 was taken. Here a thin mantle of stones rests upon oxidised clayey till that merges into unweathered till at depth.

(v) The individual fans of erratics from both outcrops are distributed in a similar fashion, except that the limits of the fan of non-porphyritic stones (Fig.5.6) extend slightly beyond those of the fan of porphyritic stones.

(vi) The width of the erratics train, as for many erratics trains described in the literature, tends to increase with distance from the outcrops. Immediately down-ice of the source the train is narrow (though the exact limit of the northern boundary was indefinable due to the lack of suitable walls); near Cumbernauld it is more than 9km wide and near Edinburgh it is about 20km broad. In the Main Study Area the essexite erratics have been spread from the outcrops in an arc extending through 44°.

A comparison of the essexite erratics train as revealed by the present investigation with the map given by Peach(1909; Fig.3.2) is shown in Fig.9.1. Using the evidence of Peach(1909), many have cited the Lennoxtown essexite erratics train as an example of a narrow, linear erratics train reflecting a consistent direction of glacier ice movement. The present investigation indicates, however, that Peach(1909) only mapped the extent of the major axis of the train in the Main Study Area. It is clear therefore that an explanation of the formation of the erratics train must account for a considerable degree of lateral spreading of the essexite erratics.

(vii) The major axis of the erratics train is closer to the northern than to the southern periphery. This is particularly well illustrated at a distance of some 12km from the outcrops. At this point the northern limit of the train is <u>c</u>.3km from the major axis, whereas the southern limit is more than 6km from the major axis. The abundance of analysed walls north of the major axis of the train at this distance from the source makes it likely that a tolerably accurate definition of the northern limit has been achieved. On the other hand, the lack of suitable

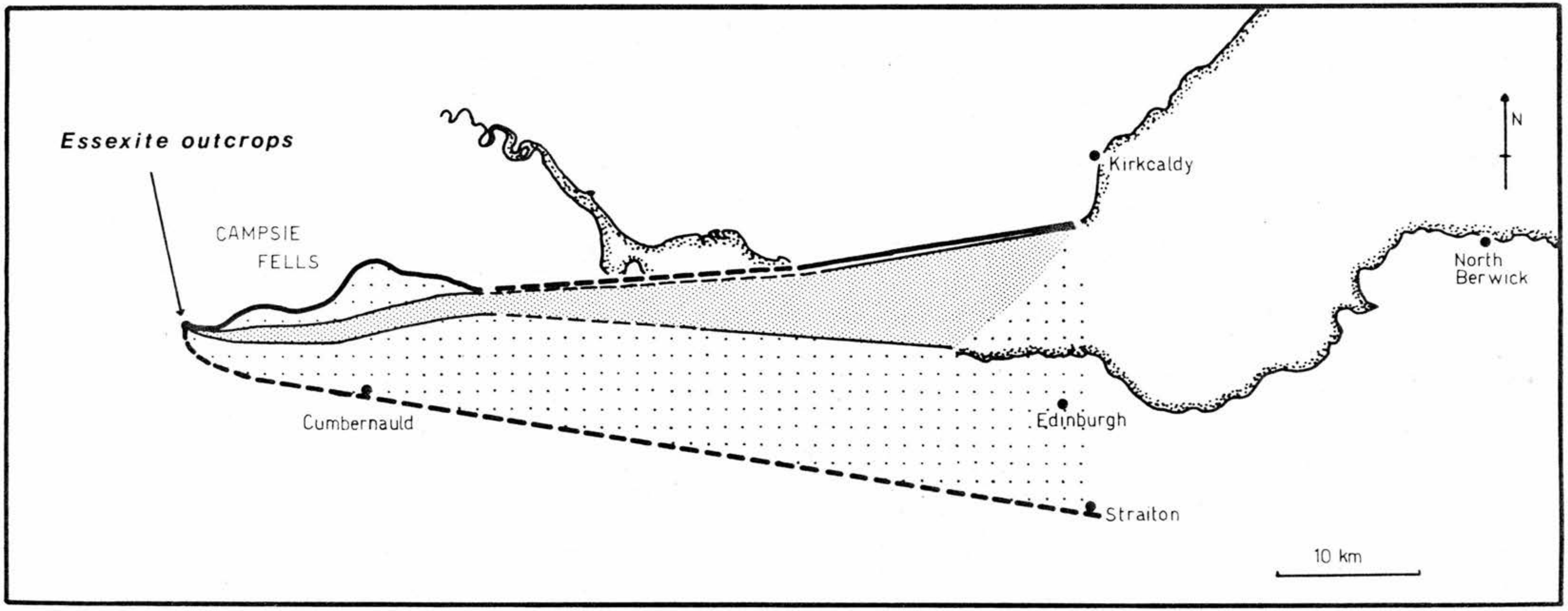

Figure 9.1

Comparison between the extent of the Lennoxtown essexite erratics train according to Peach (dense shading) and the present analysis (light shading).

walls to define the southern limit means that the difference in the distances between the two limits and the major axis may be even more marked than is indicated by the present investigation.

(viii) The alignment of the major axis of the erratics train corresponds closely with the overall directions shown by small-scale indicators of ice movement (i.e. striae, ice-moulded features and the preferred orientations of till particles). Since these indicators denote glacier ice movement during the last stages of active ice in the area it seems reasonable to infer that the erratics train was also formed at this time. The curvilinear course of the major axis immediately down-ice of the outcrops (Fig.5.5) and the increasing northerly component in the alignment of the ice direction indicators suggest that the direction of glacier ice movement was greatly influenced by the steep scarp face of the Campsie Fells.

Using the evidence outlined in these eight points it is proposed to show that the essexite stones found in the walls were mainly carried within the lower layers of ice, distributed in a fan as a result of deflection around subglacial obstacles and subsequently deposited as an ablation mantle. The essexite material in the till, on the other hand, is regarded as having been transported at the base of the ice.

At this point it is useful to clarify the contrasting characteristics of material deposited by lodgement and by ablation. Lodgement till is transported and deposited from the undersurface of the glacier ice.

Crushing and abrasion of the particles are intense. Ablation till, on the other hand, is deposited from material "in transport within or upon the terminal area of a shrinking glacier" (Flint,1957,p.122), has a characteristically loose texture and usually lacks a preferred orientation of particles (Ogilvie,1904; Drake,1971). It is derived chiefly from debris transported in the lower layers of ice, usually no more than a few metres thick, and from material on the upper surface of the ice. Since ablation till consists of the load at the time of ice sheet decay, it is usually thin.

The present investigation indicates an ablation origin for the majority of the essexite stones in the dry stone walls. The "ablation theory" readily accounts for the transport of essexite stones obliquely up the steep scarp slope of the Campsie Fells. The steepness of the slope seems to exclude the possibility of the transport of essexite stones at the bedrock-ice interface. Neither does it appear feasible that upward transport could have occurred as a result of shear plane movement within the glacier ice. It has been argued that such movement takes place mainly as a result of active ice overriding stagnant ice (Worcester,1939; Rich,1943; Clayton & Freers,1967; Parizek,1969) or as a result of ice being forced to rise over a topographic obstruction. Parizek(1969) maintained that dead ice could survive beneath thick ablation deposits in upland areas and that active ice on lower ground would override this stagnant ice dragging basal debris up along shear planes. This seems an unlikely explanation of the upward transport of essexite stones; although there is evidence for some ablation material on the Campsie Fells, it is relatively thin (Thompson,1968) and therefore unlikely to have reduced ablation to any great extent. As regards shear plane formation having taken place as a result of ice rising over a major relief feature, it is not difficult to envisage this having occurred where an obstruction lay perpendicular to the path of ice flow. However where, as for the Campsie Fells down-ice of the outcrops, the angle between the alignment of the feature and that of ice movement was small, it seems more reasonable to assume that ice would simply have been deflected. Further evidence, to be discussed later in this chapter, contradicts the idea of essexite stones having been carried up into the glacier ice beyond the bottom layers and therefore movement of the essexite stones along shear planes does not seem feasible.

Opinions differ as to whether crushing and abrasion are important processes in an englacial environment. Upham(1896) noted that englacial material was generally less abraded than subglacial material. Gry(1974) considers that the long transport undergone by some erratics has resulted from their being rapidly crushed at the base of the glacier ice to a size determined by the jointing characteristics of the rock, and thereafter being carried higher up into the ice where crushing was less intense. Henderson regarded ablation material as having "been transported gently with little grinding and crushing" (1972,p.57). On the other hand, Dreimanis and Vagners

(1969,1971) maintained that particles in an englacial position still undergo comminution, though to a lesser extent than in a subglacial position. Lister(1958) considered that the gradually decreasing size of material upwards through the Admiralty Gletscher in Greenland was indicative of englacial crushing of material. The evidence of both crushing and abrasion on essexite stones in the walls does not therefore rule out the idea of their being transported in an englacial position.

The contrast between the small amounts of essexite material in the clayey till and the relative abundance of non-porphyritic essexite stones in the walls down-ice of the outcrops is compatible with the ablation theory. Dreimanis(1958) found that surface ore erratics from Steep Rock appeared to be equally abundant 13-15km as 0.6-2.5km down-ice of the source, but pebbles in the till decreased rapidly in numbers. Dreimanis and Vagners(1969) noted that ablation debris often contains a greater proportion of material that has undergone long transport than lodgement material. It is suggested therefore that the difference in the abundance of essexite material in the walls and in the till can be attributed to an englacial transport for the majority of the wall stones compared to a transport at the base of the glacier ice and subsequent deposition by lodgement for the essexite erratics found in the clayey till.

Further evidence of an englacial transport for the wall stones is given by the narrow layer of stones overlying till in a few undisturbed localities. Flint

(1957) regarded similar layers of coarse material as lag concentrates, formed by sheetwash or deflation of a till surface. Frost-heaving of till stones has also been suggested as a possible cause of such layers. In the Main Study Area, however, frost-heaving does not account for the layer of stones since the underlying till, though often showing signs of weathering in the form of oxidation, nevertheless retains its fissile structure. Furthermore, the stone mantle cannot simply represent a residual layer of material derived from widespread removal of till because it consists of many large stones of a size that are apparently uncommon in the underlying till. Shilts(1973b) used similar evidence to support the idea of an ablation origin for a "boulder mantle" deposited as a result of the Lennoxville glaciation in southeastern Quebec.

To invoke an ablation origin for the essexite stones now in the walls, it is clear that the ablation mantle must have formerly been more widespread than it is today. Unfortunately the disturbance of the superficial deposits by man has meant that no confirmation of this is possible from field evidence. Nevertheless the observations of others suggests that the idea of a widespread cover of loose surface stones is not without some support. On a journey through this part of Scotland in 1784, Faujas St. Fond remarked on the great abundance of surface boulders (ref. in Geikie(ed.),1907). Nimmo(1880) and Milne-Home(1913) made similar observations at various locations in the Main Study Area. In recent literature concerned with aspects of the glacial geomorphology of the area the idea of an ablation origin for deposits is recurrent. Thompson(1968) considered that the lack of dry stone walls together with the presence of loose, angular stones on the Campsies, contrasting with the many dry stone walls and paucity of surface stones on the lower slopes was evidence for ablation moraine. Burke(1969b) frequently encountered an upper layer of sandy clay with stones in exposures in till in the Secondary Study Area, and discussed the possiblity of an ablation origin. Sissons (1968,1969) was also in favour of an ablation origin for till in an area to the north-west of Glasgow and in the vicinity of Grangemouth.

Attention is now turned to the problem of an explanation accounting for the lateral spreading of erratics with distance from the outcrops. This will be dealt with by considering separately each of the major theories outlined in chapter 2 and determining to what extent the evidence derived from the present investigation is explained.

Since the essexite erratics appear to have been distributed during the last phase of active ice in the area, the erratics train could not have been formed by ice flowing in different directions during separate glaciations (cf. Buell,1878; Petersen,1899; Ramsay, 1912; Hausen,1914; Hyvarinen et al.,1973) or during the same glaciation (cf. Milthers,1913; Hucke,1937; Edelman,1951; Gillberg,1965). A further argument against the idea of two glaciations being responsible for the spreading of the essexite stones is that the speed of weathering of the basic igneous essexite fragments would be too rapid

(Hyyppä,1948). Furthermore no evidence exists for ice flow in a direction other than that shown in Fig.3.7.

The idea, put forward by Sauramo(1924), that fans of erratics can be formed by fluctuations in the direction of ice movement towards a retreating ice margin does not account for the gradually broadening fan of the essexite erratics train, since the small changes in the direction of ice flow would redistribute erratics close to the outcrops to the same extent as erratics some distance down-ice of them. Had this been the chief way in which the essexite erratics had been spread, one may imagine that the erratics train would have consisted of a narrow, constant-width belt comprising a strong concentration of stones, flanked on both sides by narrow strips where the number of stones rapidly decreased in a direction away from the central belt.

The hypothesis invoking meltwater as the main agent responsible for spreading erratics into a fan shape is unable to account for the lateral spread of essexite stones for three major reasons. Firstly, the meltwater channels that have been mapped in the Main Study Area are parallel or sub-parallel to the direction of ice movement (Sissons,1963; Thompson,1968) and for this reason it seems unlikely that they could have been responsible for the considerable lateral dispersion of essexite erratics indicated by the present investigation. Secondly, as for the previous hypothesis, meltwater action would be equally effective in spreading erratics near their source as at some distance from it, thus tending to lead to a narrow belt rather than a broadening fan. Thirdly, the fact that erratics have been carried northwards away from the major axis of the train in an uphill direction also tends to argue against the idea of meltwater redistribution.

The hypothesis put forward by Teumer(1927; Fig. 2.7) of a wandering centre of ice motion causing the fan shape of erratics trains does not seem to be applicable as an explanation accounting for the essexite erratics train for two reasons. Firstly, the main centre of ice sheet flow in Scotland appears to have been the Rannoch Basin. No evidence exists to indicate that the centre shifted to any great extent and even if there had been a change in its position, it seems unlikely that such a movement could bring about a change of 44° in the direction of ice movement to form the Lennoxtown essexite erratics train at a distance of several tens of kilometres. Secondly, all of the erratics trains that have been carefully mapped show broadly the same pattern, with a major axis representing a high concentration of erratics flanked by areas of gradually decreasing erratic concentration in a direction away from the major axis. As is shown by the SYMAP contour maps, the Lennoxtown essexite erratics train is no exception in this respect. For this pattern to be formed, Teumer(1927) envisaged the centre of motion following a complex, specific course. Such a change in the centre of ice motion, however, would clearly not lead to all erratics trains having the same pattern with a major axis flanked by peripheral areas of low concentrations of erratics. This hypothesis can therefore be rejected since it can only account for the formation of one erratics train distributed as a result of ice flowing from a centre of motion, whereas in fact several typical erratics trains have often been mapped radiating from the the same centre (e.g. Hausen,1914).

The hypothesis that an erratics train forms as a result of ice movement controlled by major topographic features (e.g. Perry,1870; Saksela,1949) does account for one of the observed features of the Lennoxtown essexite erratics train. The curving course of the major axis immediately east of the outcrops is shown in all the SYMAP contour maps of the wall data given in chapter 5 and by the contour map of titanaugite percentages in chapter 7. It corresponds to the alignment of the scarp slope of the Campsie Fells in this area and, since the striae and ice-moulded features (Fig.8.9) also show this curving course, it seems reasonable to infer that the scarp slope of the Campsies caused the ice stream flowing through Strathblane to diverge around it. However, whilst a major relief feature might divert the direction of ice flow, which is shown in the distribution pattern of erratics, it cannot account for the rapid widening of an erratics train from its source.

On the other hand, the theory put forward by Lundqvist(1935; Fig.2.4) appears to be attractive since it accounts for many features of the Lennoxtown essexite erratics train. There is one drawback to his theory, however, and this is the proposal that during glacier thinning, ice would be forced to flow around hill masses thus spreading the erratics. For the essexite erratics train the greatest amount of lateral spreading has taken place to the south of the major axis where the hill masses are small. It seems improbable that ice would continue to be active whilst sufficiently thin to flow around such hill masses, and would more likely have stagnated.

If, however, Lundqvist's concept of thin ice flowing around hill masses is replaced by one where the basal layers of relatively thick, active ice are diverted in a similar manner around subglacial obstructions, then the lateral spreading of the essexite erratics can be explained. Large-scale divergence of ice, like that indicated by the radial alignment of drumlins in the Wadena drumlin field (Wright,1957), cannot be accepted as explaining the essexite erratics train because the striae and ice-moulded features indicate a parallel direction of ice movement down-ice of the essexite outcrops. On the other hand, divergence of ice flow around small-scale subglacial obstructions, as has been indicated by, for example, the alignment of striae on roches moutonnées, can account for the lateral spreading of erratics. The concept is well known (e.g. Demorest,1938; Edelman,1949; Kupsch,1955; Weertman,1957; Fig.2.3) in terms of bedrock obstructions but only recently has firm evidence come to light to establish that the same process of divergence takes place around drumlins (e.g. Savage,1968; Walker,1973).

Down-ice of the essexite outcrops the lower slopes of the south-facing scarp of the Campsie Fells are mantled in thick deposits of glacial drift (Fig.3.8) and much of this material has been moulded by the ice into drumlins or drumlinoid features. South of the Kelvin-Bonny Water valley there are a number of upstanding outcrops of quartz dolerite as well as ice-moulded forms in drift. There is therefore a sufficiently large number of subglacial obstructions to produce a high degree of lateral spreading of essexite erratics south of the major axis of the erratics train. However on ascending the steep, south-facing scarp slope of the Campsies the thickness of the drift decreases rapidly and for the first 3km or so down-ice of the essexite outcrops the scarp presents an almost uninterrupted smooth face rising some 400m above the Kelvin River.

With respect to this description of the down-ice area of the essexite outcrops, the major axis of the erratics train more or less follows the dividing line between the thick deposits of glacial drift to the south and glacial deposits that are either thin or absent to the north. The lateral spreading to the south of the major axis appears to have taken place for essexite material within the till as well as for the essexite stones now found in the walls. Since the essexite material in the till is regarded as having been transported at the base of the ice, there is no difficulty in invoking the divergence process to explain its distribution in a direction away from the major axis of the erratics train. However for the essexite stones in the walls, a difficulty arises since other evidence indicates that the majority of these erratics have been transported englacially. If these stones were carried to high levels in the ice then the divergence of the basal layers of ice would have had little or no effect in distributing them in a direction at variance to the alignment of the major axis of the train. It is proposed therefore that these stones underwent englacial transport in the lower layers of ice so that they were diverted around subglacial obstacles as a result of plastic deformation of the ice in which they were embedded.

The more limited nature of the lateral spreading of essexite erratics to the north of the major axis can be explained in terms of the paucity of suitable subglacial obstacles. From the contour map showing the distribution of wall stones of both types of essexite (Fig.5.5), it is clear that the areas of shading representing a marked northward extension of the traceable limits of the erratics train correspond to the locations where interruptions in the smooth face of the Campsies occur. For example, where the alignment of the scarp slope of the Campsies changes direction from east-south-east to east-north-east, the ice-moulded rock knoll, known as Brown Hill, stands out from the main mass of the Campsie lavas. Here, to judge from the contour map (Fig.5.5), part of the ice stream flowing along the scarp slope became diverted northwards on to Plea Muir. From the evidence of both titanaugite percentages and wall stone data, this body of ice did not succeed in flowing into the Carron Valley but instead followed the course of Birken Burn rejoining the main ice stream that flowed along the southern scarp of the Campsies between Laird's Hill and Garrel Hill (Fig.3.6).

Between Garrel Hill and Tomtain, where the Campsies once more present an uninterrupted high barrier, the essexite-bearing ice stream appears to have been confined to the southern slopes since neither essexite stones nor titan-augite grains were found to the north of these hills. Between Tomtain and Denny Muir, however, the expanse of high ground of the Campsies narrows and falls in height by almost 150m before rising again by 50m on Denny Muir. This decline in the height of the ridge separating the Carron and Bonny Water valleys appears to have been sufficient to allow an incursion of the ice stream flowing along the southern slopes of the Campsies into the Carron Valley. This is indicated by the existence of essexite stones in the dry stone walls on Denny Muir and as far north as the outwash terraces of the Carron Valley.

It appears therefore that the major element in the topography (i.e. the Campsie Fells , and in particular the southern scarp slope) has been important in controlling the extent to which the essexite erratics were spread laterally from the direction of ice movement. The minor elements, such as drumlins and rock knolls, on the other hand, seem to have been instrumental in actually causing the lateral spreading by divergence of the lower layers of ice around them. The effects of divergence of the ice in spreading essexite erratics a further c.1km and c.2km away from the major axis at Brown Hill and Denny Muir respectively gives credence to the idea that the far more extensive lateral spreading of essexite erratics south of the major axis could have taken place as a result of plastic deformation of the ice around a series of sub-glacial obstacles.

Furthermore the fact that the ice stream flowing along the Kelvin-Bonny Water valley was apparently able to move on to the Campsie Fells and into the Carron Valley supports the view expressed earlier in this chapter and elsewhere that the formation of the erratics train in the Main Study Area took place during the last stages of active ice. At this time the ice on the higher parts of the Campsies would have begun to stagnate whilst ice in the intervening valleys would still have been active and therefore capable of flowing on to the higher ground where the nature of the relief permitted. It is suggested that Brown Hill and the low col between Tomtain and Denny Muir offered the necessary interruptions in the smooth steep face of the Campsies to allow ice carrying essexite erratics to diverge northwards on to the higher ground.

The amount of removal of essexite represented by the essexite stones measured

Many workers, on observing a large number of sizable erratics down-ice of an outcrop, have often remarked on the considerable depth of removal of bedrock that these rock fragments must represent. For example Peach, noting the number of essexite boulders down-ice of the Lennoxtown outcrops, maintained that "considering the number of boulders observed, and the fact that these must of necessity be merely a small proportion of the total number derived from the intrusion, the result is somewhat surprising. If this may be taken as an indication of the transport of material throughout the whole Strathblane Valley, the amount of modification which the valley has undergone at the hands of ice must have been very considerable" (Peach,1909,p.31).

In the present analysis, with many large erratics in the sample of 2,352 stones measured (Plate 4), one might also be of the opinion that these stones must represent a considerable amount of removal of essexite bedrock. However, the total removal of the porphyritic and non-porphyritic outcrops represented by these stones amounts to only 0.02mm and 0.29mm respectively. This was calculated by summing the MPV values for all the porphyritic (665) and non-porphyritic (1687) stones measured. Thus despite the impression given by large numbers of visible erratics that this material alone indicates considerable bedrock removal, it has been shown here that when subjected to accurate measurement the results illustrate that the material in fact represents only a very small amount of bedrock erosion.

C H A P T E R 10

CONCLUSIONS

Five questions were posed at the beginning of this investigation. These concerned (i) the distribution patterns of essexite fragments from both essexite outcrops, (ii) the changes in the size and morphometric properties of essexite stones as a result of glacial and fluvioglacial transport and beach processes, (iii) the distribution pattern of titanaugite sand grains, (iv) the pattern of ice movement shown by striae, ice-moulded features and till-particle preferred orientations and (v) the formation of the erratics train.

(i) Two methods of determining the distribution pattern of essexite fragments in the vicinity of the outcrops were used. One, undertaken following a pilot study, involved calculating the percentage weight of essexite fragments (2-16mm) in samples of till both up- and down-ice of the essexite outcrops. The analysis revealed that essexite fragments were absent in the till samples up-ice of the outcrops and scarce in the till down-ice of them even where sampling sites were located close to the outcrops.

Using the dry stone walls in the vicinity of the essexite outcrops as random samples of the larger glacially transported essexite fragments, the distribution of essexite erratics was traced for c.20km from the outcrops. The SYMAP contour maps of the distribution patterns of porphy-riti ritic and non-porphyritic erratics (Figs 5.9 & 5.10) indicate the familiar erratics train pattern with the concentration of stones gradually decreasing in the direction of ice movement and decreasing more rapidly in a direction perpendicular to this. The major axes (i.e. the areas representing high concentrations of essexite stones) of the distributions for porphyritic and non-porphyritic stones follow a curvilinear course immediately down-ice of the outcrops which corresponds to the alignment of the steep scarp face of the Campsie Fells at this point. This is interpreted as indicating that the glacier ice distributing the erratics was deflected by the scarp face of the Campsies. The distribution of non-porphyritic stones indicated that there is a marked asymmetry in the erratics train with the major axis closer to the northern than to the southern periphery. The data obtained for the dispersion of porphyritic stones are inadequate to confirm the asymmetry for this variety of essexite.

Apart from these similarities there is one major contrast between the two distribution patterns, namely that the porphyritic essexite stones become scarce in the walls far more rapidly in a direction down-ice of the outcrops than do the non-porphyritic stones. The rapid decline in the numbers of porphyritic stones is attributed to the close spacing of the bedrock joints (Plate 1), which meant that these stones were quickly crushed down during glacial transport to a size that was too small to be useful in wall-building. The joints in the non-porphyritic variety of essexite, on the other hand, are more widely spaced (Plate 2) so that glacially crushed, joint-controlled blocks of essexite were sufficiently large to be included in the walls.

(ii) The changes in the size and morphometric properties of essexite stones during transport in various environments has shown that different processes act in the glacial, fluvioglacial and beach environments and are reflected in the results obtained from the measurement of these properties. Crushing in the glacial environment is indicated by a steady decline in the trend of the mean values of E_A for non-porphyritic stones in the walls with distance from the outcrop. The decline in the proportion of non-porphyritic wall stones recording short lengths between parallel joints with distance from the source suggested that crushing is concentrated on smaller fragments during glacial transport.

Abrasion during glacial transport has been shown to be a subsidiary, but active process affecting essexite stones by the increase in their roundness over the first 5-10km of travel from the outcrops. Beyond this, however, roundness fails to show a clear tendency either to rise or fall and this has been interpreted as being further evidence that crushing occurs during glacial transport, since the latter will tend to produce angular fragments.

Abrasion has been shown to be the most important process acting in the fluvioglacial environment by the higher value for mean roundness compared with that for glacial stones. The mean size of fluvioglacial stones was also found to be considerably smaller than of glacial stones and this has been attributed to the restriction in the size of particles imposed by the competence of the meltwater streams, a constraint that does not apply to glacially transported stones.

From the results of roundness obtained for essexite stones found on modern beaches of the Forth it has been concluded that abrasion is also the major process taking place in the beach environment. The size of beach stones is smaller than fluvioglacially and glacially transported stones. This has mainly been attributed to the greater degree of sorting that the beach stones have undergone compared with fluvioglacial ones which have been subject to less sorting, and with glacial ones which have undergone no sorting.

By plotting the mean values of several morphometric indices for different size grades of glacial, fluvioglacial and beach stones (Fig.6.4), it has been found that the areas enclosing size grade means for fluvioglacial stones overlap both with areas containing means for glacial and beach stones.

When the data were subjected to multiple discriminant analysis (Figs 6.6-6.9) the centroids for glacial and beach stones of both varieties of essexite were farthest apart, indicating that they were most distinctive whilst the fluvioglacial centroids were inbetween the centroids for the other two categories, showing that fluvioglacial stones had characteristics in common with glacial and beach ones. A gradual decrease in the distance between the centroids of the two essexite varieties within the same category has been noted from the glacial centroids which are farthest apart, to fluvioglacial centroids which are nearer, to beach centroids which are closest together. This has been interpreted as indicating the nature of processes acting in the different environments. During glacial transport the dominant process was crushing which would tend to accentuate the contrast in the size of the porphyritic and non-porphyritic joint-controlled blocks. On the other hand, the dominance of abrasion and the sorting action occurring in both the fluvioglacial and beach environments would tend to lead to fragments of a similar size being found in the same deposit. Using only the morphometric indices (Fig.6.8; Table 6.8), roundness accounted for most of the dispersion and, since the centroids for each variety of essexite are closer to the centroids of the other variety within the same category than to centroids in any other categories, it has been concluded that roundness is the most sensitive index differentiating between processes acting in the glacial, fluvioglacial and beach environments. Shape and size indices, on the other hand, tend to accentuate lithological contrasts rather than differences in processes. From the correlation coefficients derived from the correlation matrices based on the size and morphometric indices, it is suggested that, apart from R (roundness), the other important measures are MPV (maximum projection volume) or MPA (maximum projection area) and S (sphericity) or F (flatness).

An experimental abrasion test of various shapes and sizes of essexite particles indicates that asymmetrical particles are most susceptible to chipping, that large particles become rounded more rapidly than small particles, and that roundness for all particles increases rapidly at first and then more slowly with time.

A uniaxial compressive strength test revealed that essexite is a rock of moderately high strength with mean values of 1497 kg/cm^2 for the porphyritic and 1470 kg/cm^2 for the non-porphyritic variety. Bulk density values of 3.05 gm/cc for porphyritic and 3.06 gm/cc for non-porphyritic essexite are in accord with this. These results substantiate the idea that the essexite stones have been subject to crushing mainly along the bedrock joints during glacial transport.

(iii) The analysis of the distribution pattern of titanaugite sand grains in the till in the vicinity of the outcrops showed, like that of the distribution of essexite fragments in the till, that they are absent in the till up-ice of the outcrops and become rapidly scarce in a direction down-ice of the outcrops. The SYMAP contour map of the number of titanaugite grains expressed as a percentage of the non-opaque heavy mineral fraction (Fig.7.3) reveals a similar direction of transport to that of essexite stones in the walls and a rapid rate of dilution with distance from the outcrops in a down-ice direction.

(iv) The till-particle preferred orientations, striae and long axis alignment of ice-moulded features in the area up to 20km down-ice of the essexite outcrops show a similar trend to the alignment of the major axis of the erratics train when the directional data are analysed using a vector trend surface technique. This correspondence has been interpreted as indicating that the erratics train was formed by the same ice that gave rise to the striae and ice-moulded features and, since these normally reflect the direction of movement of the last active ice in an area, the distribution of the erratics has also been assigned to this time.

(v) The formation of the erratics train has been considered in terms of two related problems; the means of transport and the manner in which the erratics were spread into a fan. In chapter 9 it was concluded that the scarcity of the essexite fragments and the unexpectedly rapid decline in the percentage of titanaugite grains are indicative of a transport at the base of the ice sheets. From the evidence of the abundance of non-porphyritic stones along the major axis of the erratics train up to 20km from the source, the rapid upward transport of stones of both essexite varieties on to the Campsies and the existence of a thin layer of coarse debris overlying clayey till in certain undisturbed locations, it has been postulated that the majority of the essexite stones now in the walls were transported englacially and subsequently deposited as part of a thin ablation mantle. The dispersion of essexite erratics in a direction at variance to the alignment of the major axis has been attributed to the divergent flow of basal ice around subglacial obstacles. The levels at which the erratics were carried within the glacier ice must therefore have been restricted to the lower layers in order that the observed considerable lateral spreading could have taken place. The contrast in the extent of spreading north and south of the major axis appears to be a result of the lack of subglacial obstacles combined with the obstructing nature of the steep slope of the Campsies to the north compared to the south where subglacial obstacles in the form of drumlins and bedrock knolls are frequent and the general relief is uninhibiting to ice movement. Only at two points where the smooth steep face of the Campsies is interrupted has the ice carrying the essexite erratics been able to diverge northwards. The extent to which this ice was able to spread northwards at these locations suggests that there was little resistance to movement in this direction from other ice on the Gampsies. It is suggested therefore that the ice sheet was wasting at the time so that ice was thin or stagnant on the Campsies but active on the lower ground.

Apart from the conclusions already mentioned that are of general interest, a number of other points have emerged from this investigation that are relevant to the study of glacial and fluvioglacial processes.

Firstly, the short distance over which essexite erratic material becomes scarce within the till together with the evidence of its rapid fanning down-ice of the source helps to explain the local origin of the majority of till particles.

Secondly, if it is accepted that essexite erratics underwent lateral spreading as a result of divergence of the basal layers of glacier ice around subglacial obstacles, then the extent to which the erratics have been spread in directions at variance to that of major ice flow bears witness to the considerable plasticity of the bottom layers of an ice sheet.

Thirdly, the close correspondence between the roundness characteristics of the fluvioglacial and beach essexite stones supports the view expressed by King and Buckley(1968), amongst others, that the meltwater environment is extremely effective in rounding particles since the essexite stones in the meltwater streams would have undergone fluvioglacial processes for a relatively short period compared to the time the beach stones have been subjected to beach processes.

Fourthly, from the evidence already outlined it appears that crushing and abrasion do affect particles in englacial transport, crushing being indicated by the decline in the mean E_A values for non-porphyritic stones in the walls with distance from the source (Fig.5.25) and abrasion being shown by an increase in the roundness of essexite stones over the first 5-10km of transport down-ice of the outcrops.

Methods and techniques

This investigation has relied to a large extent on the use of a variety of techniques in the field and in analysis of the results. A fewremarks will now be made on the usefulness of these techniques.

Firstly, this investigation has highlighted the problems associated with attempting to trace an erratics train by analysing samples of till for their content of erratic material. The problems include the arbitrary decision of the size of samples, how large samples should be close to the periphery of the train and how to remove the erratic fragments from the rest of the till sample.

Secondly, the "wall-mapping" technique employed for tracing the erratics train proved to be extremely valuable. There seems to be little advantage, if only the distribution pattern of erratics is required, in deriving values of E_A and it is suggested that E_N should be used to measure the concentration of erratics at a point because it can be more rapidly determined in the field.

Thirdly, the till-particle orientations were a useful adjunct to the data otherwise available in the form of striae and ice-moulded features on the direction of ice movement in the Main Study Area. However, from the variability of the preferred orientations of the till particles in the present investigation it is apparent that they should be used in conjunction with other evidence of ice movement rather than be relied upon for deriving ice flow directions on their own.

Fourthly, the two instruments used in the measurement of the a, b and c axes (pp. 132 & 227) and the templates of radii for measuring the minimum radius of curvature on essexite stones proved to be extremely useful in determining these parameters with speed and accuracy. However, a more robust material for construction, such as a light metal alloy, would be preferable to the materials used for the instruments in the present investigation.

Much use has been made in the analysis of the results in this investigation of computer-based statistical techniques. The SYMAP contour interpolation technique proved to be invaluable in deriving an objective representation of the wall data and the titanaugite percentages. There was one drawback and this was the problem associated with the uneven spacing of the data points such that the relative size of an area representing a certain level of shading depended as much on the spacing of the neighbouring points as on their values. The SYMVU three-dimensional plots were useful from an illustrative rather than an analytical viewpoint.

Trend surface analysis has been applied to the wall data, titanaugite percentages and the directional data (i.e. striae, ice-moulded features and till-particle preferred orientations). For the wall data and titanaugite percentages, the technique has been considered unsuitable due to the problems associated with the elongate shape of the area analysed, the large number of data points, their uneven distribution and the large variation in their values over short distances. It has been concluded that the greater flexibility of the SYMAP technique gives a better representation of the form of the erratics train. For the directional data, on the other hand, vector trend analysis proved to be very useful in deriving the regional trends in the direction of ice movement.

The three-dimensional statistical techniques devised by Andrews and Shimizu(1966) and Mark(1973) for deriving preferred orientations and dips of till particles have been regarded as unsuitable. It has been concluded that these techniques tend to lead to "over-analysis" of the data and that the two-dimensional techniques of, for example, Harrison(1957a) and Curray(1956) are to be preferred.

On the other hand, multiple discriminant analysis was a considerable aid in analysing and illustrating differences between glacially and fluvioglacially transported essexite stones and stones that had undergone beach processes.

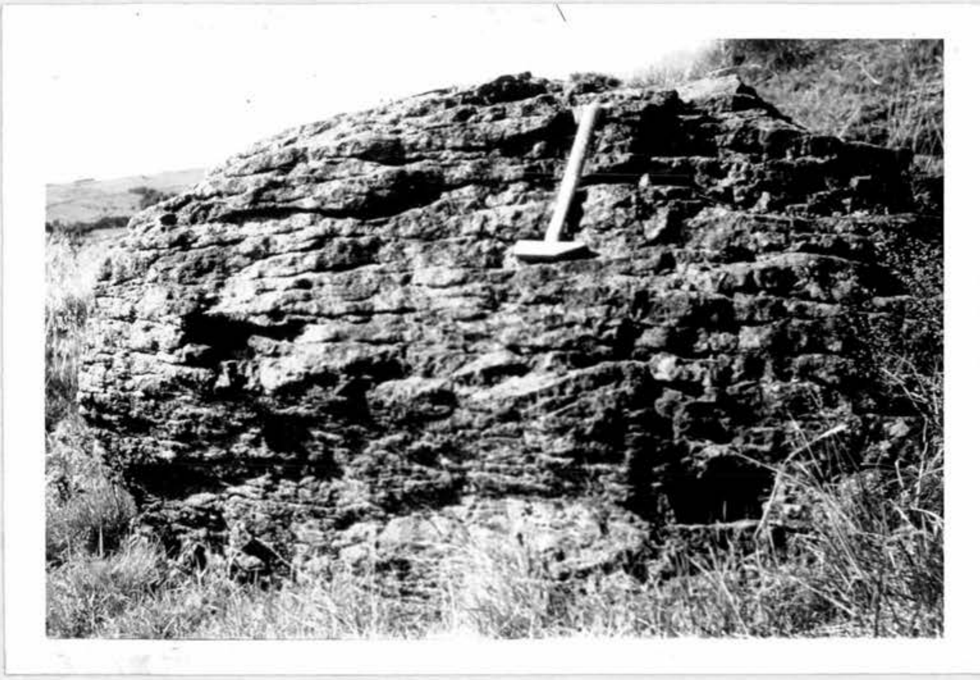

Plate 1

Porphyritic essexite outcrop

Plate 2

Non-porphyritic essexite outcrop

Plate 3

Stones removed from the surface of a field after ploughing in the Main Study Area

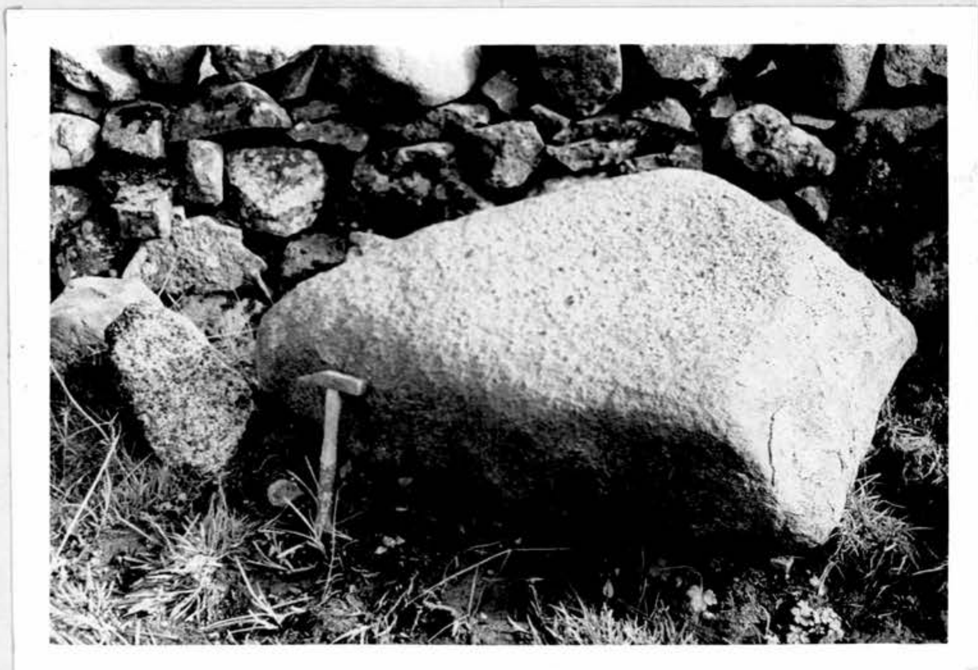

Plate 4

A large non-porphyritic essexite erratic (right) and porphyritic essexite erratic (left) (GR 678 787)

Plate 5

A non-porphyritic essexite erratic from fluvioglacial deposits near Bonnybridge (GR 817 800) being measured

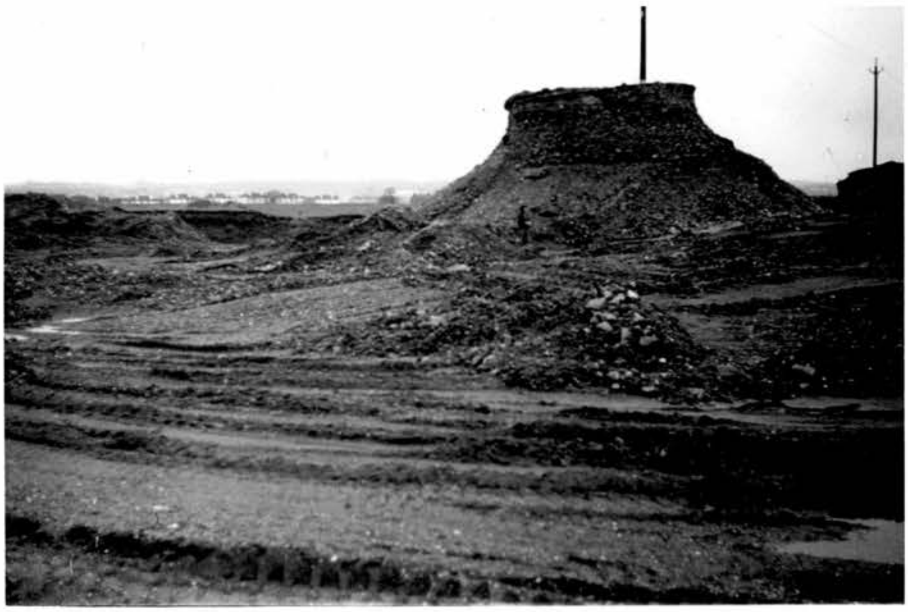

Plate 6

Commercial gravel pit in fluvioglacial deposits near Bonnybridge (GR 814 802)

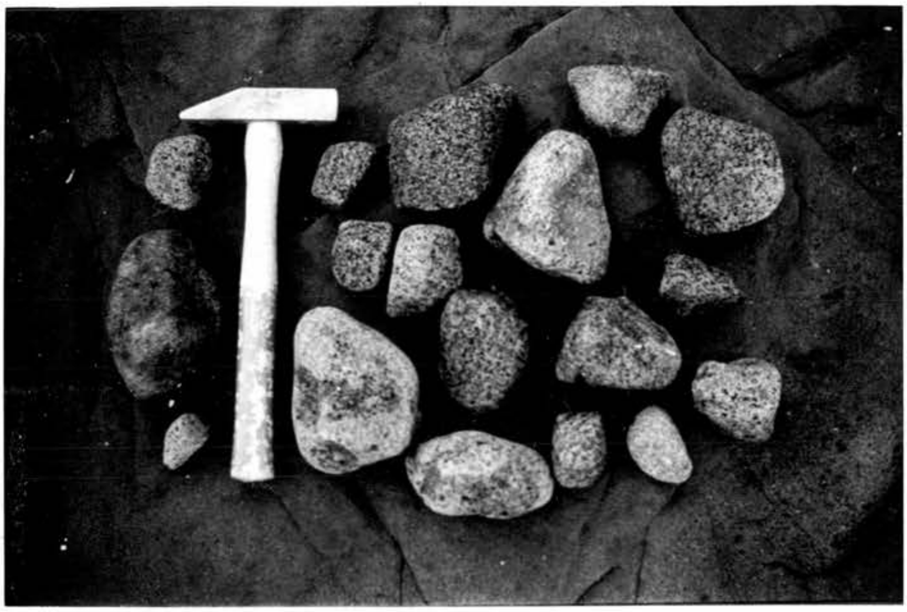

Plate 7

Typical porphyritic (left) and non-porphyritic (right) essexite erratics from the beaches of the south side of the Firth of Forth

Plate 8

An unusually large non-porphyritic essexite erratic found on the foreshore of the Firth of Forth, near South Queensferry

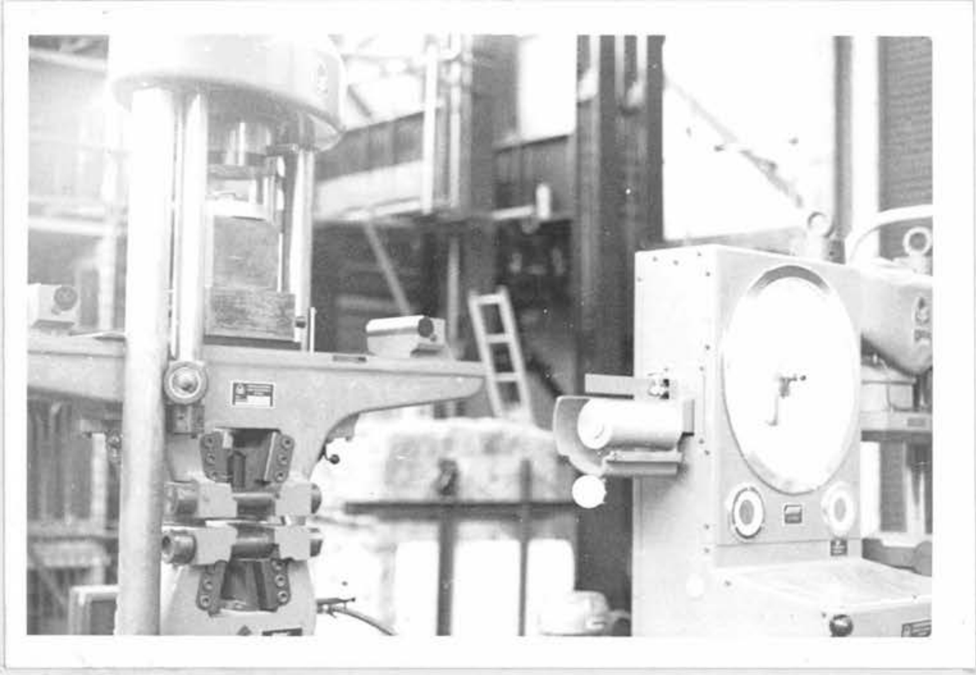

Plate 9

Losenhausen apparatus used for determining the compressive strength of essexite

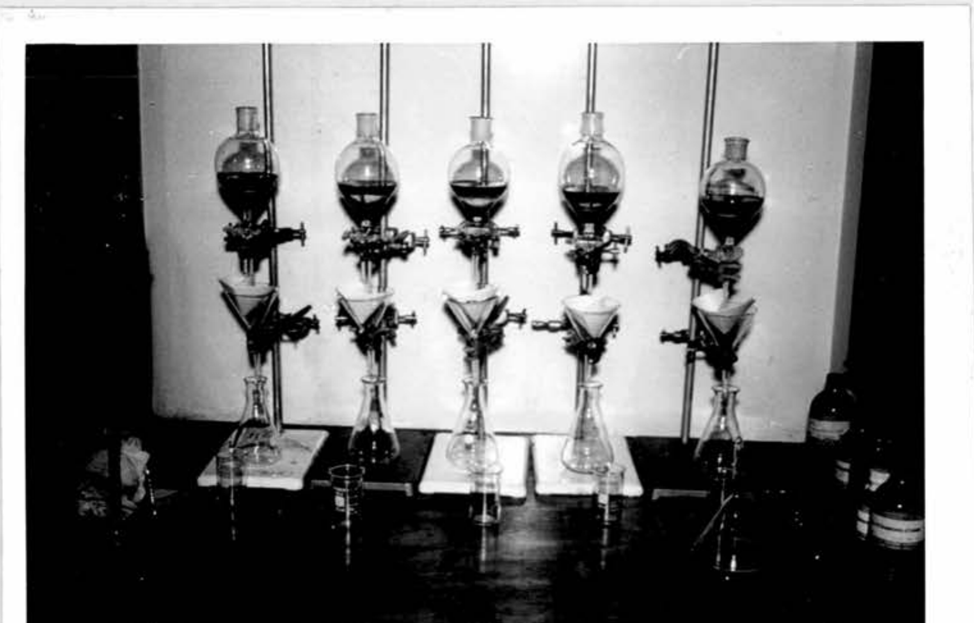

Plate 10

Apparatus for separating heavy mineral sand grains

Plate 11

Striae on the Campsie Fells (GR 703 808). Their direction is indicated by the alignment of the hammer shaft

Plate 12

Ablation mantle overlying thick deposits of clayey till (GR 724 799)

Plate 13

Blocks, triangular blocks and blades prior to experimental abrasion. Scale is 10cm in length

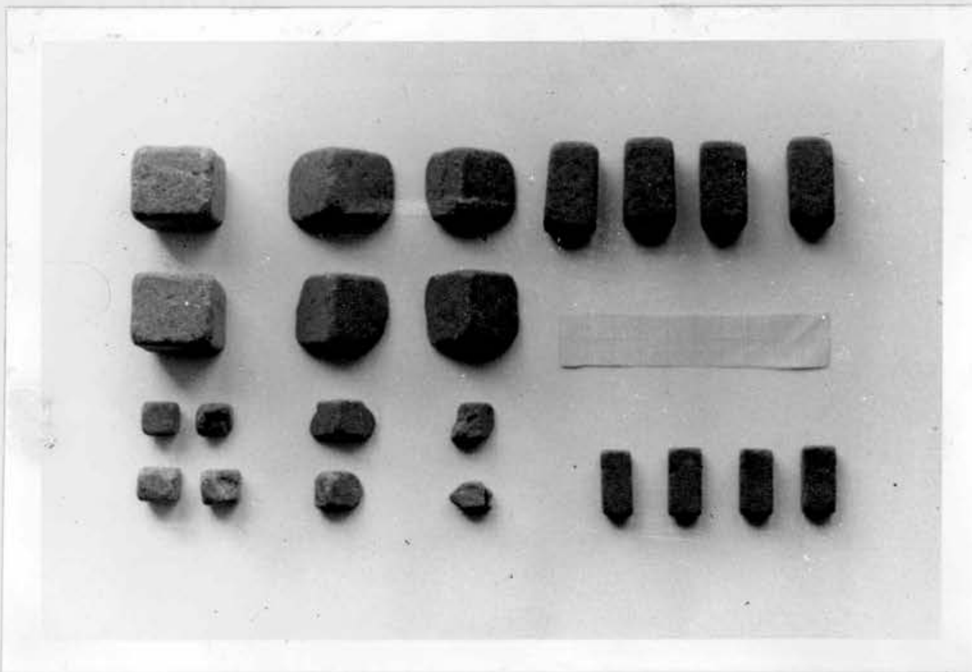

Plate 14

Blocks, triangular blocks and blades after 64 hrs of experimental abrasion. Scale is 10cm in length

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