

A quantitative analysis of some fluvioglacial
deposits from east-central Scotland

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DECLARATION

I hereby declare that this thesis,
entitled "A quantitative analysis of some
fluvioglacial deposits from east-central
Scotland", has been composed by myself
from my original work



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SUMMARY

The thesis attempts to differentiate between environments of deposition within different types of fluvioglacial deposits by the use of quantitative analytical techniques developed chiefly in fluvial transport studies. A number of type examples of fluvioglacial features are studied. Before discussion of field and laboratory data is undertaken, the basic procedures for obtaining the raw data are laid down. The main techniques involved are mechanical grain size analysis of representative field samples and the determination of pebble morphology statistics of an unbiased selection of pebbles from each suitable field sample. A case study of one particular feature is followed by summaries of the two sets of results. These sets of results are then compared with each other with respect to degree of information given, and are subsequently related to sequences of deposition as suggested by field observation. It is concluded that short-range variations within fluvioglacial deposits are not measurable with acceptable degrees of certainty, but that the application of techniques used in the thesis to larger depositional suites would add substantially to an understanding of both varying environmental conditions of fluvioglacial deposition and sequences of deglaciation.

CHAPTER 1. INTRODUCTION

The main theme of this study is the quantitative analysis of fluvio-glacial deposits. While many studies of environment of deposition in fluvial, marine and aeolian geomorphology have been published, virtually no work of a quantitative nature has been published on fluvio-glacial deposition. Occasional quantitative comparisons with glacial till are cited but stratified drift is seldom included in any general analysis or discussion.

OBJECTIVES OF THESIS

The first objective is to attempt to differentiate between environments of fluvio-glacial deposition by applying various quantitative techniques of sediment analysis. A subsidiary objective is the evaluation of the quantitative techniques themselves in terms of the usefulness of the information they yield concerning fluvio-glacial deposition. The main techniques used are mechanical analysis of field samples and pebble morphology techniques. These methods need no elaboration here as they are discussed in subsequent chapters.

It was decided to restrict the thesis to "type" stratified drift features, or at least to those features whose origin and relations with Pleistocene ice movements were fairly clear. A basic division into proglacial outwash, ice-contact kame, and englacial or subglacial esker deposition was employed initially. Time did not permit a comparison with associated tills.

It was further decided to concentrate on the gravel fractions of the field samples. This was done for a number of reasons:- firstly, gravels are easier to work with in the laboratory than sands; secondly, relatively little special equipment is needed to obtain the basic pebble morphology statistics; thirdly, for any study of short-distance changes gravels are more suitable than sands in that they are more rapidly modified by transport.

THE NATURE OF FLUVIOGLACIAL DEPOSITION

In any individual area, fluvio-glacial depositional features seen at the present time relate to the last glacial phase in that area, the final ice dissolution. This implies ice which is in decay and is stagnant, or nearly so. Depositional features of earlier decay phases are not visible in the landscape as these would have been overridden by, or more probably incorporated within, the succeeding ice advance.

As decaying ice was involved, seasonal flow of meltwaters would have been initiated. Large amounts of meltwater would have been available for both deposition and erosion. The immense size of some glacial meltwater channels testifies to the strength and volume of flow. The deposits associated with this flow of meltwaters can be classed in three groups. Firstly, deposits, such as eskers, were laid down under pressure either englacially or sub-glacially. Secondly, deposits were laid down amid the dead-ice terminal zone. Ice-contact faces commonly resulted. Delta bedding

occurred, as a result of water ponded due partly to the high englacial water table present from time to time. Kame and kettle topography of irregular mounds and hollows frequently resulted. Thirdly, proglacial outwash deposition took place.

Comparisons of these methods of deposition with the fluvial environment may not be strictly valid, except possibly in the case of proglacial deposition. Proglacial rivers in many cases resembled braided stream networks. Otherwise, fluvioglacial landforms typically show a chaotic style of deposition. Beds which are sequential in a vertical direction were not necessarily consecutive in time of deposition. A large range of material sizes is typically present at any given exposure, indicating a very poor degree of sorting among the deposits at any one site in most cases. Large-scale slumping of beds due to ice-contact deformation further confuses the bedding sequence. A major problem in an analysis of these deposits is the relation between the large within-site variation and the relatively small between-site variation. The application of methods of analysis tested and proved in the fluvial environment provides, at the very least, a basis for further investigation of the differences in environment of deposition of the various types of fluvioglacial landform.

DESCRIPTION OF FEATURES STUDIED

As has been stated, type examples of fluvioglacial features have been studied. Suitable definitions of these features may be

found in R. F. Flint's "Glacial and Pleistocene Geology" (Flint, 1957). Problems do still exist, however, as to the exact formation of some types of kame- and esker-like features, and the exact relationships, and indeed boundaries, between till and stratified drift are not always unequivocal.

Features were identified initially on aerial photographs (loaned by the Air Photographs Library of the Scottish Development Department) and traced on to 1:25000 maps using a Zeiss Aero-Sketchmaster. These crude maps served merely to locate possible sampling sites, such as active or abandoned commercial excavations and riverbank cuts, and were not supplemented except in one instance by accurate ground mapping of features. General observation at each sample site was deemed sufficient to establish basic depositional relationships with adjacent deposits. The thesis does not aim at a comprehensive deglaciation description of each suite of deposits examined.

Samples were taken from deposits in the Midlothian basin area, from the Eddleston valley to the south of this basin, from the area of east-central Lanarkshire, from deposits near Duns in Berwickshire, and from deposits at Edzell, near the Kincardine-Angus border (Fig. 1.1). These deposits are described below. It was also intended to sample material from the Polmont esker system, near the site of Falkirk. However, only one major commercial excavation existed when the deposits were examined (early 1968 and early 1969), and natural exposures were inadequate considering the size and complexity of the suite of deposits. It was decided therefore to concentrate on

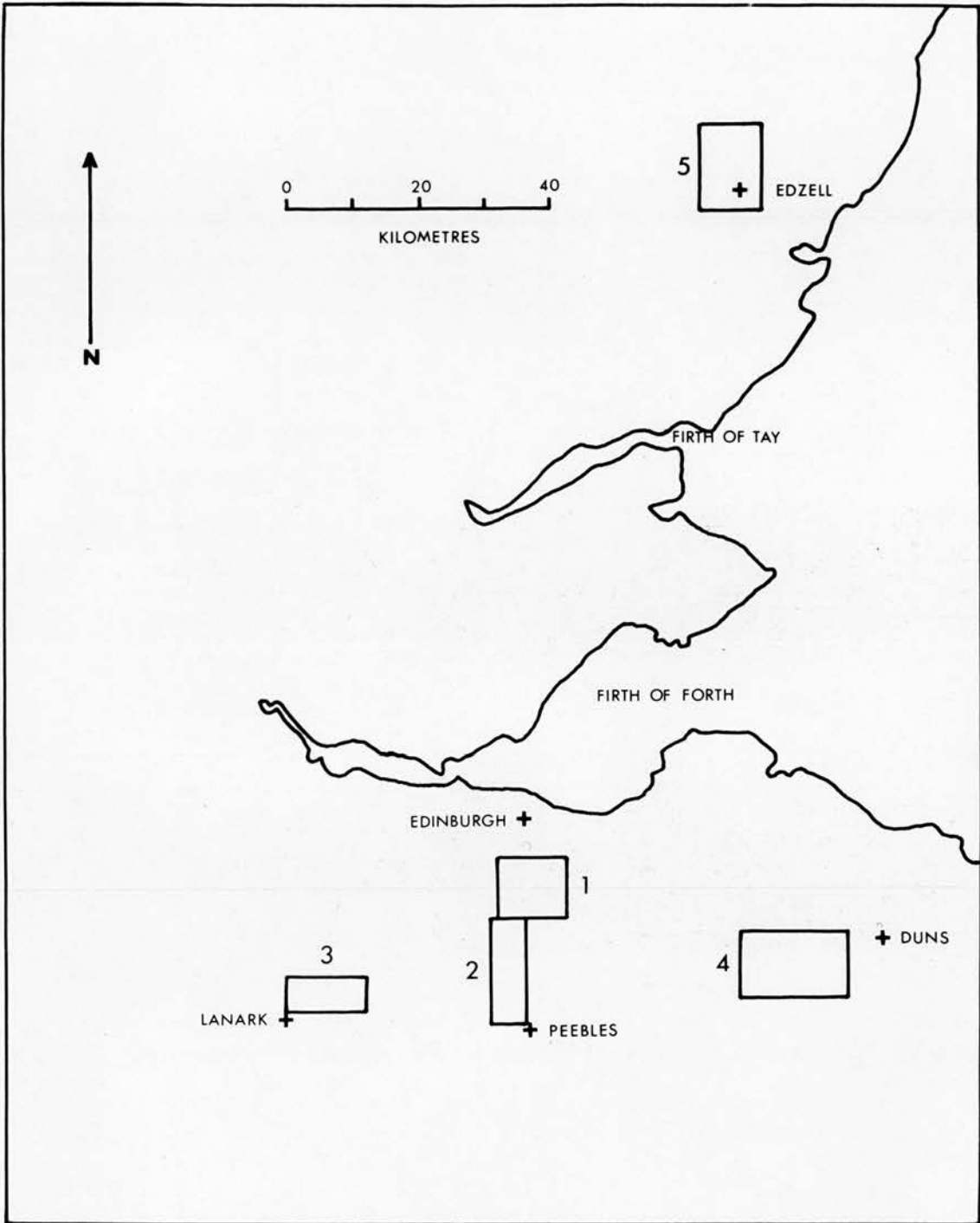


FIGURE 1.1. Location of study areas. 1. Midlothian; 2. Eddleston; 3. Carstairs; 4. Bedshiel; 5. Edzell

the deposits mentioned above and described below.

DEPOSITS OF THE MIDLOTHIAN BASIN AREA

The Midlothian basin is formed by relatively easily eroded synclinal Carboniferous sediments bounded to the west, on the upthrust side of the reverse Pentland Fault, by volcanic rocks of Old Red Sandstone age. Extensive sedimentary rocks of similar age lie further to the south-west. To the east, the Midlothian basin rises to the anticlinal Roman Camp Ridge of Carboniferous sediments and, further south, to Ordovician shales and greywackes on the east side of the Lammermuir Fault. Figure 1.2 shows sample site positions and a generalized picture of the distribution of fluvioglacial deposits in the area.

Kirby (1968 and 1969a) presents evidence of a total of three tills in this area. Till fabric analysis indicates an ice movement from the west or south-west associated with the deposition of the basal till. The Pentland Hills do not appear to have caused major deflection of this ice-stream. Fluvioglacial material on top of the basal till is itself covered by an intermediate till. Ice-movement from the south is indicated by fabric analyses within this till. Fluvioglacial deposits again overlie this till, and a third till, the Roslin Till, tops the succession. This last till is of very limited extent and thickness, but appears to represent a minor ice readvance from the north. Morphometric analysis of terraced fluvioglacial features in the Esk basin (Kirby 1969b) suggests that the

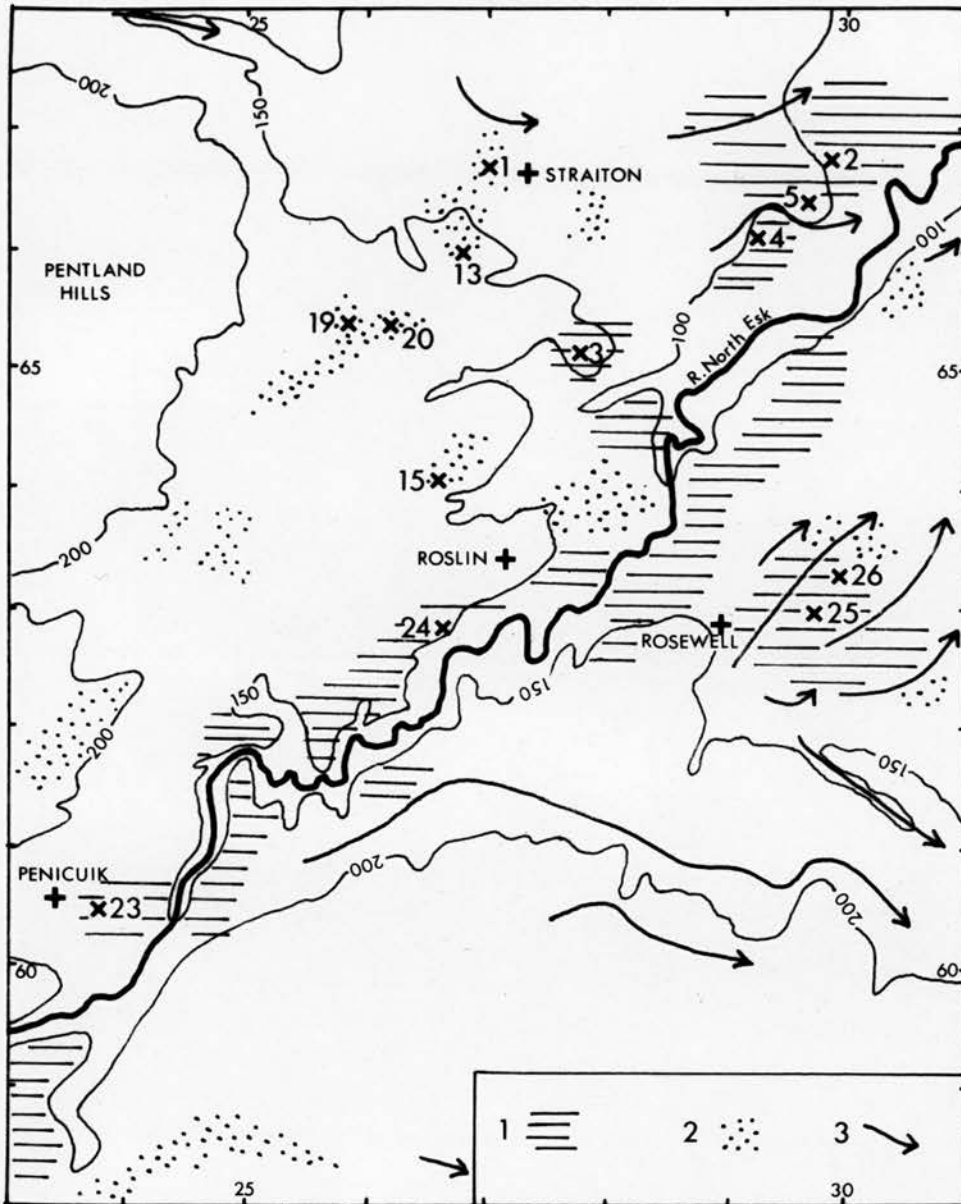


FIGURE 1.2. Location of Midlothian sample sites. Scale: National Grid lines at 1 kilometre intervals shown on margins of map. Contours at 50 metre intervals. Glacial morphology adapted from Kirby 1969b (Fig.1):- 1. Flat-topped fluvio-glacial deposit; 2. Hummocky fluvio-glacial deposit; 3. Glacial meltwater channel

Southern Uplands ice sheet, represented in the area by the intermediate till, split at the watershed to the south of the Midlothian basin, and the northern ice mass downwasted by retreat of the ice margin downslope towards the north. The deposits considered in the present study were consequently laid down by drainage of meltwaters from the south-west through the wasting ice-mass or parallel to its margin. A complicated sequence of deposition resulted, kame and outwash deposition seeming to alternate to some extent. The state of the englacial water table must have been relatively important in providing areas of standing water into which deposition took place. The deposits may be regarded as being intermediate between kame and outwash for the purposes of the present study.

EDDLESTON VALLEY KAME DEPOSITS

The Eddleston valley lies due south of, and leads directly off, the Midlothian basin. The present stream, Eddleston Water, is a southward-draining tributary of the River Tweed. The valley lies entirely within an area of Ordovician shales except for the last two kilometres before the River Tweed junction. This last section lies within greywacke/shale beds of Silurian age.

Bailey and Eckford (1956) studied the Eddleston gravels and concluded that they were in fact outwash gravels formed by proglacial streams flowing down the western side of the valley from a Southern Upland ice margin along the western slopes of the valley.

However, Sissons (1958) demonstrated a south to north meltwater flow through the Eddleston valley area parallel to the axis of the valley itself, by the inclination of meltwater channels. These channels, it was suggested, showed the direction of slope of the ice surface. They decline in height towards the north or towards the axis of the valley, showing that the valley itself was choked with ice when the channels were formed. Meltwater turned north-east after passing through the Eddleston valley area, and extensive fluvioglacial deposition took place to the north-east (Fig. 1.3). Within the Eddleston valley itself, deposition took place after the emergence of the watershed between this area and the Midlothian basin impeded drainage to the north and north-east. Small ice-marginal lakes developed in the Eddleston valley due to the formation of an englacial water table, and massive kame deposition took place (Fig. 1.3). Deposition ceased when a drainage system towards the south and the Tweed valley was established after further dissolution of the ice cover.

DEPOSITS OF THE AREA AROUND CARSTAIRS, LANARKSHIRE

Geologically, this is an area of some complexity. Extensive faulting has taken place, fracturing relatively soft Carboniferous sediments in particular. Bedrock around the site of Carstairs itself consists of Carboniferous calciferous sandstone. A few kilometres to the west lies an extensive area of Lower Old Red Sandstone. Basalts lie to north and south, while further south lie

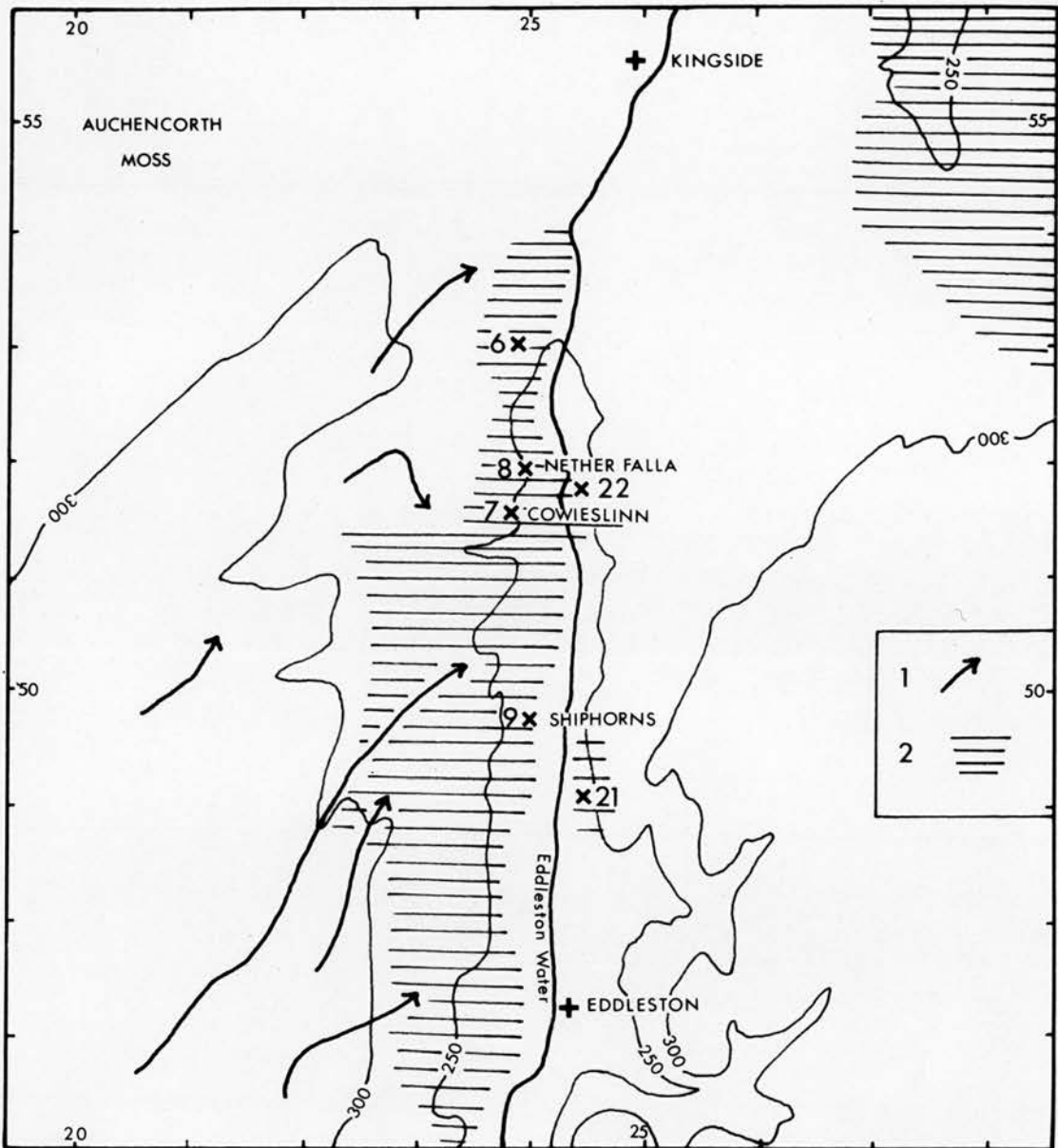


FIGURE 1.3. Eddleston Valley sample sites. Scale: National Grid lines at 1 kilometre intervals on border of map. Key: 1. Major meltwater channel; 2. Major area of fluvio-glacial deposition

small belts of Upper and Lower Old Red Sandstones. A two-kilometre belt of Silurian greywackes succeeds these in a southerly direction. Felsite intrusions abound in the area, while an off-faulted portion of Carboniferous sedimentaries lies further to the south-west. A much larger area of Silurian and Ordovician rocks some distance to the south-west is significant as Southern Upland ice, deflected by Highland ice from the north, moved in a south-west to north-east direction over this area.

Not only did ice move over this area in a south-west to north-east direction, but late-glacial meltwaters also moved in this direction. Sissons has demonstrated this effectively a few kilometres to the south, on the lower margins of the Tinto Hills (Sissons, 1961b). The deposits near the site of Carstairs form part of a large belt of water-sorted material stretching continuously for approximately 35 kilometres down the Douglas valley to the south-west, across the Clyde valley, and through the Carstairs area (Sissons, 1967). The features are best developed in the Carstairs area, where ridges of sand and gravel up to 20 metres high are found. The entire ridge system branches and rejoins in a series of braids. Ridges are sinuous in detail, though trending south-west to north-east in general, parallel with the last ice-movement in the area (Fig. 1.4). The ridge crests are undulating in long profile. Bedding is irregular and variable, faulting and slumping being common. Material sizes range from large boulders more than one metre across to fine sands. Ice-contact seems clear, and an esker-type formation in a series of subglacial or englacial tunnels is indicated.

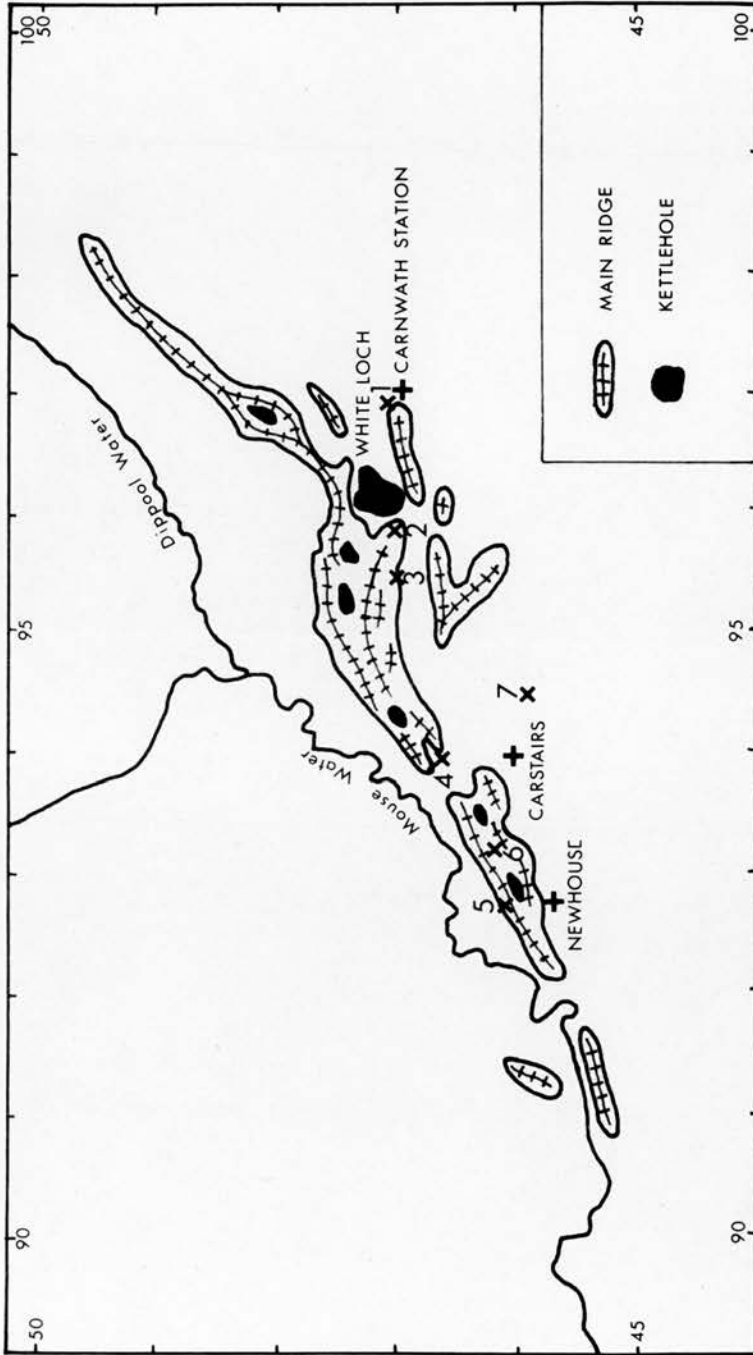


FIGURE 1.4. Sketch of Carstairs esker deposits, showing sample sites. Sites numbered according to Table 9.10. Scale: National Grid lines at 1 kilometre intervals on border of map. Base of ridges at about 210 metres O.D. in southwest rising to about 220 metres in northeast

However, a number of basically different origins have been suggested for these deposits. Charlesworth related the deposits to an end moraine of a Highland ice readvance (Charlesworth, 1926). He suggested that the steep and abrupt north-facing slopes of the ridges were in fact ice-contact faces. Sissons (1961c) suggested that the central and eastern parts of Charlesworth's Lammermuir-Stranraer Moraine, including the Carstairs deposits, were in fact fluvio-glacial dead-ice features rather than terminal moraine. Extensive field mapping of esker, kame and meltwater channel associations supported Sissons' conclusion that the Carstairs deposits were an esker system associated with the dissolution stages of a readvance of ice from the Southern Uplands.

Goodlet (1964) maintained that the Carstairs deposits were part of a moraine, deposited during a relatively protracted halt in the retreat of the margins of ice originating in the Southern Uplands and emanating from the Clyde and Douglas valleys. He interpreted basal deposits as being a "boulder drift" and used this as evidence in support of his theory of moraine deposition. McLellan (1967a and 1969) reaffirmed Sissons' contention that these ridges are composed of stratified drift, and are thus fluvio-glacial in origin. He also noted (1967a) that constituent material becomes progressively finer from west to east along the ridge. Stone orientation indicates a water flow from west-south-west to east-south-east, that is, parallel with the long axes of the ridges. The continuous relation with channel systems of subglacial origin underlies the esker origin theory.

Boulton (1972) notes (p.385) that the Carstairs group of deposits is "... quite unlike any known subglacial ice-contact feature, because of its complex morphology, its size and its internal faulting." He suggests a supraglacial, fluvial origin and implies that these, and similar, deposits are the inverted fluvio-lacustrine moulds of ice-cored moraines. He subsequently states (p.386) that "... the Carstairs deposit ... could be regarded as supraglacial 'eskers' which formed in a morainic zone." In other words, the ridges represent fluvial deposition between ice-cored end moraines. This implies, following Boulton's Figure 3 (p.367), that ice-movement took place at right angles to the ridges. This cannot be substantiated in the present case as such moraines would presumably be extensive features and would have some surface expression today, at least as sheets of flow till, to north and south of the Carstairs deposits. Further, ice-movement and continuous fluvioglacial deposition can be demonstrated to have taken place through this area in a south-west to north-east direction. Boulton's hypothesis does not appear to hold with present evidence, and a subglacial esker-type formation remains the most likely mode of deposition of the Carstairs deposits.

THE BEDSHIEL ESKER

The Bedshiel esker lies approximately four kilometres north of the site of Greenlaw, in Berwickshire. It is situated just to the north of the main "Merse" area of the lower Tweed basin and can be

associated with eastward-flowing meltwaters marginal to a dead-ice mass in the Merse and lower Tweed basin areas. Though connected to meltwater channels and fluvioglacial deposits to east and west, it is essentially a single feature, and was chosen partly for this reason. Full descriptions of the esker, the associated landforms, and the geology of the area are given in Chapter 5, and only a brief outline need be given here.

The esker is situated in a shallow basin area underlain by Upper Old Red sandstones, conglomerates and marls. To the north and east are found hills of Lower Old Red Sandstone intrusive felsites (Fig. 5.1). To the south, further volcanic rocks are found, mainly porphyritic intrusions of Upper Old Red Sandstone and Early Carboniferous ages. Silurian greywackes and shales are found to the west, while Lower Carboniferous calciferous sandstones occur to the east.

The esker itself is a steep-sided ridge varying in height from about three to fifteen metres. It is virtually continuous throughout its four kilometre length and displays the symmetrically-sloping sides, the undulating crest line and the rounded pebbles of the typical esker. Its relationships with other fluvioglacial features in the area are not clear at first sight, as may be seen from Figure 5.5, and these are discussed at length in Chapter 5.

THE EDZELL OUTWASH DEPOSITS

Consequent upon the valley glacier stage of the Pleistocene Ice Age, large spreads of proglacial material issued from several glens

to east and south of the Grampian Mountains. One of these, around Edzell in Angus, was selected for study. Meltwaters issuing from the ice fronts in the glens of the present North Esk and West Water coalesced to form a large outwash deposit spreading over this area of Strathmore (Sissons, 1967, pp.114-15). Positions of sampling points are shown in Figure 1.5. Limits of outwash deposition have not been shown on Figure 1.5 as these were difficult to determine in the field.

The Highland Boundary Fault crosses this area, causing a sharp demarcation between highland to north and east composed of Pre-Cambrian schists and gneisses and low-lying Old Red Sandstones to south and west. The outwash gravels contain only very small proportions of sandstone pebbles, about four per cent on average. It can be seen clearly in the field that the surface of the deposits slopes away from the Highland Edge, despite a certain amount of late-glacial and post-glacial terracing, and that a much higher proportion of cobbles is present close to the head of the deposits.

ORDER OF CHAPTERS

Before discussion of results is undertaken in the present work, the basic procedures for obtaining the raw data are laid down. Chapter 2 outlines the method of obtaining the individual field sample. Chapter 3 describes the laboratory preparation of each field sample for subsequent statistical analysis. Two processes are involved, namely the mechanical sieving of the field sample and the selection of a standard number of pebbles of restricted size for the

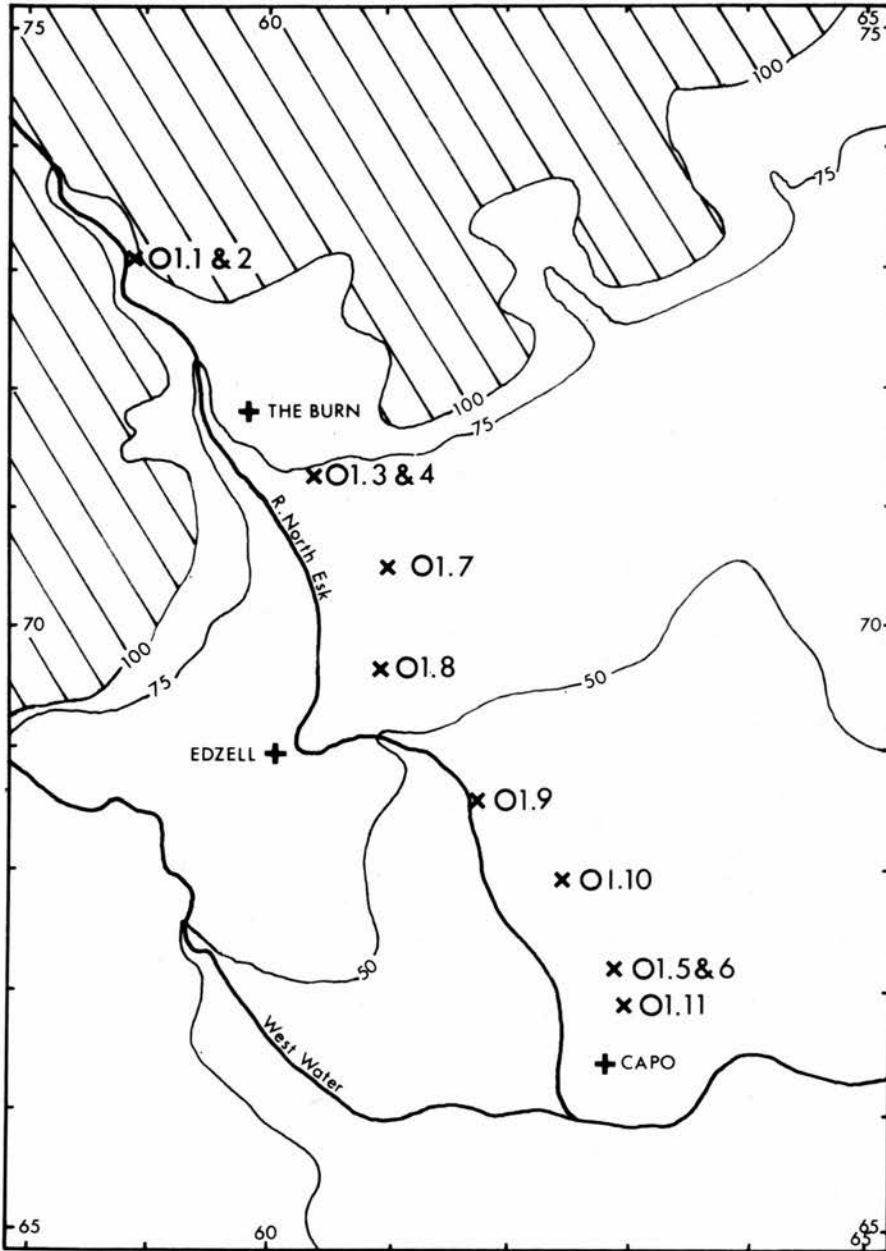


FIGURE 1.5. Location of sample points on North Esk outwash. Scale: National Grid lines at 1 kilometre intervals round margins of map. Ground above 100 metres shaded. Contours at 25 metre intervals

purposes of pebble morphology study. Pebble morphology parameters are selected. Chapter 4 deals briefly with the question of operator variance and then develops statistical parameters of grain size with respect to the raw mechanical analysis data. This concludes the preparation stage of the thesis.

Chapter 5 is entitled "The Bedshiel esker: a case study." This particular feature offered an opportunity to test laboratory techniques, mainly pebble morphology techniques, against a relatively uncomplicated field situation. Various tests were executed in order to determine the direction of deposition of this feature. Results are compared with conventional field mapping of the fluvioglacial landforms of the immediate area. Chapters 6 and 7 summarize the results of the mechanical grain size analysis of samples and the morphological analysis of selected pebbles respectively and suggest possible beneficial lines of enquiry. Both of these sets of statistics attempt, in different ways, to enable inferences to be made concerning such sedimentological variables as, for example, degree of sorting and direction of travel of material.

Chapter 8 discusses the two major techniques in parallel, and investigates the degree of information given by the two sets of results with respect to individual samples and local depositional conditions. Chapter 9, on the other hand, relates, as far as is possible, the two sets of statistics to sequences of deposition within the various fluvioglacial landform types. Finally, Chapter 10 summarizes the work, and comments on the value of the techniques in attempting to distinguish between environments of deposition in the case of fluvioglacial deposition.

STYLE OF PRESENTATION

In general, presentation of the thesis follows accepted literary procedures as exemplified by, for example, Royal Society (1965) and Turabian (1967). However, in essentially numerical passages all numbers will be given in numerals. This is to ensure comparability of numbers between zero and one hundred, which are conventionally spelt out, and either numbers greater than one hundred or numbers involving the use of a decimal point.

In the list of references given at the end of the thesis, the form adopted by the Association of Special Libraries and Information Bureaux will be followed. Abbreviations for journals are those advocated in the World List of Scientific Periodicals.

CHAPTER 2. FIELD SAMPLING

A sample can be defined as a small number of individuals drawn from a population. A population, in turn, may be defined as the entire set of individuals concerned. The nature of any population is determined by the operational definition, set up by the investigator. Chorley (1966, p.292) defines a geomorphological population as "... a class or aggregate of geomorphic objects or events from which samples are taken for the purpose of drawing geomorphic inferences and making geomorphic predictions about the class, through statistical analysis." The geomorphic objects concerned with in the present study are the individual constituent particles of the various types of fluvioglacial landforms. As such, the population is so large that it may be defined as an "infinite population" for the purposes of this study.

It is immediately obvious that not all of this infinite population will be available for sampling. In thick fluvioglacial deposits, for example, it is only possible to sample throughout the thickness of the deposits where there are pit faces formed during commercial exploitation. This factor places a constraint on the conclusions that can be drawn from analysis of the field samples obtained. The relative importance of this constraint cannot be measured directly. However, a considerable degree of within-site variation exists at the average sand or gravel pit. This suggests that by confining sample sites to existing pits, or similar suitable exposures,

conclusions to be drawn from samples obtained are limited.

THE AIM OF SAMPLING

With reference to suites of fluvioglacial landforms, it is necessary to base hypotheses on data that are not a complete set of the total population. This is necessary owing to the infinite size of the constituent particle population. The principal object of sampling is to obtain a representative fraction of the total population. The method of sampling adopted must vary with the nature of the data to be obtained, and the aims of the study must always be considered when the sampling plan is drawn up.

One of the most significant early contributions to the literature on sampling sediments was that of Otto (1938). Otto considered that laboratory measurements on samples of sediments are generally made for one of four purposes. Firstly, "engineering" sampling may be undertaken to determine the suitability of a deposit for economic utilization. This aims at average or representative samples, and ideally employs a channel sample at each location on a fixed grid over the whole area under consideration. This type of sampling is not suitable within the confines of the present study owing to the irregularity of fluvioglacial deposition over any given area and to the difficulties encountered in obtaining a sample where a grid intersection does not correspond to a suitable exposure within the deposits.

Secondly, Otto defined "descriptive" sampling as a series of systematically collected samples taken from lithological units,

these lithological units being defined in terms of agencies and time of deposition. A spot sample is taken at each intersection of a grid that is preferably three-dimensional. Again, the utilization of a fixed grid precludes such a sampling plan with reference to fluvio-glacial landforms.

The third category mentioned by Otto is "environmental" sampling. This attempts to establish relations between measurements made on each member of a series of samples and changes in the environment of deposition. Otto defines his unit for sampling, the "sedimentation unit" as "... that thickness of sediment which was deposited under essentially constant physical conditions" (Otto, 1938, p.575). The sedimentation unit is recognised in the field in terms of assignable and non-assignable causes of variation and their effect on the laminae of the sediment, a lamina being defined as the smallest recognisable unit layer of particles of a sediment. Non-assignable causes of variation in the characteristics of a sediment are those which determine the distinguishing characteristics of individual laminae. Assignable causes of variation are those that affect adjacent laminae to the same extent or to a uniformly changing extent. Only samples from the same sedimentation unit are comparable, the samples being channel samples extending the full thickness of the sedimentation unit and perpendicular to the base.

Otto's fourth category, "correlation" sampling, was aimed at establishing similarities or differences between two or more sets of samples from the point of view of geological correlation. He

notes that samples from sedimentation units, though desirable, usually cannot be selected as the determination of sedimentation unit boundaries presupposes that homogeneous units can be selected in the field.

In summary, the use of a fixed grid effectively debar's Otto's engineering sampling and descriptive sampling from use in the present study. His correlation sampling has marginal importance, but it is with the third of Otto's categories, namely environmental sampling, that the present work is concerned.

The problem of sampling by means of spot samples has also been discussed by Apfel (1938). Apfel's "phase" is an identical concept to Otto's sedimentation unit. This kind of sampling presupposes that homogeneous units can be selected in the field, and a stratification is automatically set up, random spot samples being selected from the strata. Two difficulties arise. Firstly, there is the problem of sampling the sedimentation unit or phase when it is very small, as it must be in, for example, fine sands, if the definition is to be fulfilled. Secondly, the choice of a homogeneous unit presupposes that the variability can be estimated to a certain extent before analysis. Taken to the extreme, the only guarantee of "constant physical conditions" would imply that the sampling unit is a single grain.

The main aim of sampling, however, is to obtain material representative of average site conditions. This material is used to study internal variation within fluvioglacial landform units and to attempt to differentiate between different landform types.

The immediate objective is therefore to obtain a representative sample for the purposes of grain size analysis and shape analysis of a selected number of pebbles. The sample selection procedure must be determined with this objective in mind.

SAMPLE SCHEME AND SELECTION PROCEDURES

Any sampling design at the level of sampling from suites of fluvioglacial landforms cannot be entirely random. Chorley (1966, pp. 293, 294) notes that there are three main procedures, of very different statistical significance, whereby samples may be selected. These are purposive selection, random selection and probability selection. Purposive selection is made purely on the basis of convenience, whereas random selection is made such that each individual is drawn separately and has an equal chance of being included in the sample. The term "probability sampling" refers specifically to a formal procedure for selecting one or more samples from a population in such a manner that each individual in the population has a known chance of appearing in the sample. This last sampling procedure is not directly applicable to infinite populations such as are under consideration.

With reference to fluvioglacial landforms, samples must be taken from suitable available exposures. Without proper excavating equipment, sampling designs are based essentially on a purposive selection. However, ~~proper~~ sampling plans can be applied to the individual faces within the pit. Again, the method of taking samples varies with the aim of the subsequent analysis of the sample.

Where the sample is taken to provide an approximation of conditions at the site and to provide a suitable quantity of material for the later pebble study, it is sufficient to take spot samples from "average" locations. Initially this involves a subjective assessment of which sedimentation units exposed in section represent average conditions at the site under investigation. A spot sample is then taken from the centre of the sedimentation unit. On a strictly practical level, the sample is taken only after digging a short way into the pit face. This is simply to avoid the effects of wind and rain in blowing or washing the smaller sand-sized particles off the exposed face.

With particular reference to fluvio-glacial landforms, it is obviously impossible to trace individual sedimentation units over distances of several kilometres from their visible occurrence in, say, four or five exposures throughout the fluvio-glacial unit. The question remains, therefore, of whether or not spot samples taken from gravel units at different pits are strictly comparable, especially in terms of grain size analysis.

It is necessary to obtain a series of samples, the arrangement of the series being an important factor in the overall sampling design. A number of plans have been specifically designed to fit certain environmental patterns such as beach sand, alluvial fan, or delta (Krumbein and Pettijohn, 1938, p.15). Such plans, by the mere fact that they are fitted to the environment, are liable to introduce bias into the results obtained from sampling. It would therefore be logical to choose a sampling scheme

which is symmetrical but not related to any expected value gradient in the population to be sampled if true random sampling is desired, that is, if every individual in the population has an equal chance of being selected.

Steinmetz (1962) carried out statistical tests of three types of sampling plans, namely sedimentation unit sampling, channel sampling and random grid sampling. He concluded that sedimentation unit sampling is most appropriate for well-layered deposits such as stratified drift or bedded beach gravel. He stated that channel sampling is most efficient for homogenized deposits such as glacial till, and that random grid sampling is most reliable for massively bedded deposits. This partly supports the method of sedimentation unit sampling employed in the present work, but still does not resolve the question of comparability.

Of the many types of sampling plans employed in physical geography, the most common are simple random sampling, stratified random sampling, random serial sampling, systematic grid or regular sampling and multi-stage or nested sampling. It is necessary to evaluate which of these methods is most applicable to the sampling of the various fluvioglacial landform types, both in theory and in practice. It is immediately obvious that the availability of suitable exposures places a severe practical restraint on sampling plan.

Simple random sampling implies that the required number of data points is chosen such that each is selected independently and has an equal chance of being selected. Data points are chosen with reference to a table of random numbers or coordinates. In an areal

context, this would inevitably mean that many, if not most, data points would fall on areas of no fluvioglacial deposition. This is quite apart from the relatively small probability of obtaining sample sites at all suitable commercial exposures. Even if simple random sampling were employed within an area whose boundaries had been predetermined, that is within the limits of fluvioglacial deposition, it would be expected that most data points would fall outwith suitable pit sites. Such predetermination of boundaries implies a different type of sampling plan, namely stratified random sampling.

Stratified random sampling is based upon predetermined population attributes which divide the population into a number of distinct units. In an areal context, this would imply selecting, from tables of random coordinates, only sites which fall within the bounds of previously-mapped fluvioglacial landform units. In an internal context, this would imply selecting at random a suitably weighted number of samples from each of a number of predetermined depositional units throughout the vertical extent of a fluvioglacial deposit. This sampling scheme has the advantage over simple random sampling that data points are concentrated on the features under consideration. As with simple random sampling, there is no guarantee that any data points will fall on sites from which it would be convenient to take samples. This would, however, be an effective method of selecting samples from a suitable pit face.

Random serial sampling involves the collection of data at a number of points with some predetermined, but usually equal, interval

between successive sample sites. This method is ideal for sampling along the length of linear features, such as eskers. The question of how far apart sample sites must be before the samples taken can be described as "different" depends entirely on the scale of the feature involved. This type of sampling was employed on the Bedshiel esker, to be described fully in a later chapter, where sample sites were taken at intervals ranging from 300 metres up to 700 metres along the 4 kilometre length of the esker. The interval between sample sites varied according to whether or not a suitable site was found at each 100 metre point beyond a minimum distance of 300 metres.

Systematic grid or regular sampling involves a regular, usually rectangular, grid which is laid in a random manner over the area to be sampled. A sample is taken from each grid intersection. The most obvious advantage of this method over simple random sampling is that the sample sites are less tedious to locate. The grid need not necessarily be rectangular and, with specific reference to alluvial fans, Krumbein and Pettijohn (1938, p.15) suggested a radial logarithmic grid for sampling the surface slope or pebble size of an alluvial fan. This sampling grid is designed to give more detailed data near the source of the sediment, and would be applicable to proglacial phenomena such as outwash fans. However, samples taken from grid intersections assume that suitable sites can be found there.

A regular grid was used by Krumbein and Miller (1953) to sample pebble transport conditions within a stream channel. Percentage of granodiorite pebbles at each sampling point was used to compare

local fluctuations due, for example, to the sorting action of cross-fluctuations of the currents, with regional variations in a downstream direction.

Multi-stage or nested sampling can also be used in certain situations. This technique is commonly applied where a regional study has to be made, and where certain critical local variations are known to occur. For example, the area may be divided into units by means of a regular grid. Each of a number of selected units are subdivided, then a number of minor units within these, and so on until finally a number of random data points are selected from within the "lowest level" units. Such a sampling scheme may not be valid in certain geomorphological problems, such as sampling from fluvioglacial landforms, as the uppermost level cannot be controlled. Initial selection of locations is essentially governed by the availability of suitable sites. A subjective assessment made at a high areal level will not necessarily be corrected by objective methods at lower areal levels.

In summary, the ideal sampling scheme for eskers and other linear features would seem to be random serial sampling. Outwash fans are amenable to sampling from the intersections of a radial logarithmic grid. Kames, kame terraces and other massive or non-linear features naturally lend themselves to sampling on a systematic grid or a simple random basis. These ideal sampling patterns, however, are seldom practicable owing to the lack of suitable natural or commercial exposures. Hand boring to the depths ideally required for sampling, free from frost action and below rooting depth, is not feasible in deposits containing

substantial proportions of gravel. A solution to this problem would be the use of a power borer. This would enable the ideal sampling patterns outlined above to be carried out.

The discussion so far has concentrated mainly on the areal positioning of spot samples over an entire suite of fluvioglacial features. Within one sample site, where a more rigorous attempt was made to obtain a representative sample from the entire pit face, a stratified grid sample was used. A rectangular grid was drawn over a sketch of the pit face and the required number of spot samples taken from the centre points of the rectangles such that the same number of samples was taken from each horizontal grid stratum and, similarly, an equal number from each vertical grid stratum. Channel samples were not used owing to the desire to cover the entire face yet retain the total amount of abstracted material at a manageable level.

With regard to the selection of a standard number of pebbles for size and shape analysis, this topic is fully dealt with in Chapter 3 as part of the laboratory procedure. Wolman(1954), however, has described a field method of sampling coarse river-bed material. His determination of the size of material on the bed of a stream is based on analysis of the relative area covered by particles of given sizes. Sampling consists of measuring the intermediate axis, the widest part of the pebble in the plane of maximum projection, perpendicular to the pebble long axis, of each of 100 pebbles picked from the channel bed from the intersection points of a rectangular or square grid. The advantages of this

method, according to Wolman, are that it is applicable to very coarse materials and that it provides a more representative sample of an entire reach of a stream. The use of this technique is limited with reference to fluvio-glacial landforms for a number of reasons, the more important of which are the lack of suitable horizontal faces over which to lay the grid, the extreme difficulty in attaching grids of the required size to a vertical face, and the occasional occurrence of more than one pebble of suitable size at the intersection points. Furthermore, even if it were practicable to place the grid on a vertical face, this would be in no way less subjective than the selection of sedimentation units from which spot samples may be taken.

SIZE OF SAMPLE

Although many publications refer specifically to weights of sand-sized samples for sieving, there is very little reference to the weight of gravel samples extracted for the purpose of sieve analysis. British Standard 812 (1960) refers to the minimum weight of sample to be taken for sieving as a function of the maximum size present in substantial proportions (Table 2.1).

There is no quantitative mention in British Standard 812 of how large a percentage "substantial proportions" represents. A subjective assessment was therefore required. In most gravels encountered in preliminary investigations, the upper 20 per cent by weight almost invariably fell between the 32 millimetre and the 16 millimetre sizes. It was therefore decided, on the basis of the

TABLE 2.1

British Standard 812 : Size of sample for sieve analysis

Maximum size present in substantial proportions	Minimum weight of sample to be taken for sieving
(millimetres)	(kilograms)
64	50
50	35
32	15
25	5
16	2

weights recommended in British Standard 812, to take samples weighing between 6 and 10 kilograms for gravels. This weight would almost certainly include a suitable representative of "the maximum size present in substantial proportions." Samples of not less than 2 kilograms were deemed suitable for sands, as these could be reduced in the laboratory if necessary.

SUMMARY

In summary, the field technique reduced to taking a spot sample of between 6 and 10 kilograms from the approximate centre of gravel sedimentation units as these were exposed on gravel pit faces. A subjective assessment was made as to which gravel unit represented average conditions at the individual pit faces. Where

a whole face was sampled, a stratified grid sample was taken such that each horizontal stratum was equally represented and, similarly, each vertical stratum.

Doubt may remain as to the comparability of the spot samples between sites, in terms of the grain size distribution. However, as far as possible, the sedimentation units sampled within each suite of features were similar. Only "gravel" samples are comparable, as a much larger sand fraction would be present in the total stratified grid sample, this latter being more representative of overall conditions at the site.

Ideal sampling schemes for different types of fluvioglacial landforms are seldom attainable owing to the paucity of good sample sites. This could be rectified by use of a power borer. Even ideal sampling schemes would not entirely solve the problem of strict comparability, as the fitting of a sample scheme to the environment is liable to introduce bias in the sampling. Different sample schemes would introduce differently-biased results.

CHAPTER 3. LABORATORY ANALYSIS OF FIELD SAMPLE.

The laboratory analysis undertaken had three main objectives, namely, the provision of raw data for future grain size analysis of entire samples, the selection of a standard number of pebbles from the sample, and an analysis of the shape of the selected pebbles. The present chapter traces the historical development of quantitative measurement of particle morphology. The major contributions from the literature are discussed and an evaluation made within the context of the present study. The description of the laboratory procedure is developed throughout the chapter and is summarized at the end.

PRELIMINARY PREPARATION OF SAMPLE

Each of the 70 samples taken in the field was initially air-dried. In most cases it was sufficient to leave the sample in the field sack with the neck of the sack open, stirring occasionally to ensure thorough drying. This drying process usually took several days. In samples where there was a large proportion of the silt and clay fractions, an air-drying cupboard was used. In such cases 24 hours was sufficient to ensure adequate dryness. A sample was deemed to be "dry" when particles did not tend to stick to the hand and when any clods present were easily broken by hand.

PROVISION OF RAW DATA FOR FUTURE SIZE ANALYSIS

The dry sample was then mechanically sieved, using a standard Ro-Tap Sieving Machine with a nest of 8-inch diameter sieves. The aim of the sieving process was to split up each sample into its constituent size fractions, and the choice of sieve apertures was conditioned by the desire to cover the size range from gravels to fine sands as thoroughly as possible with the sieves available. The maximum number of sieves that can be fitted to the machine is eight, plus a base. This immediately imposes limitations, as the range of sizes of material involved is from larger than 64 millimetres down to smaller than 0.0625 millimetres. The reference scale chosen was that developed by Wentworth from work done by Udden (1914).

HISTORICAL DEVELOPMENT OF GRADE SCALE

Udden was the first worker in the field to introduce the concept of a geometric scale, and he also introduced the term "grade". He separated the clastic particles into groups of different coarseness and called these "grades" (Table 3.1).

Udden arranged his grades in increasing order of diametric size, with a constant factor of one-half between the upper limits of successively finer grades. Wentworth modified Udden's scale slightly (Table 3.2), while still retaining the geometric progression of grade upper limits (Wentworth, 1922a). Wentworth also simplified the terms Udden used to describe the individual grades.

TABLE 3.1

Udden size grades (Udden, 1914)

Name of grade			Diameter in millimetres	
			From	To
	Large	Boulders	256	128
	Medium	Boulders	128	64
	Small	Boulders	64	32
Very	Small	Boulders	32	16
Very	Coarse	Gravel	16	8
	Coarse	Gravel	8	4
		Gravel	4	2
	Fine	Gravel	2	1
	Coarse	Sand	1	1/2
	Medium	Sand	1/2	1/4
	Fine	Sand	1/4	1/8
Very	Fine	Sand	1/8	1/16
	Coarse	Silt or Dust	1/16	1/32
	Medium	Silt or Dust	1/32	1/64
	Fine	Silt or Dust	1/64	1/128
Very	Fine	Silt of Dust	1/128	1/256
	Coarse	Clay	1/256	1/512
	Medium	Clay	1/512	1/1024
	Fine	Clay	1/1024	1/2048

TABLE 3.2

Wentworth size grades (Wentworth, 1922a)

Name of grade	ϕ units		Diameter in millimetres	
	From	To	From	To
Boulder	more than	-8.0	more than	256
Cobble	-8.0	-6.0	256	64
Pebble	-6.0	-2.0	64	4
Granule	-2.0	-1.0	4	2
Very Coarse Sand	-1.0	0.0	2	1
Coarse Sand	0.0	1.0	1	0.5
Medium Sand	1.0	2.0	0.5	0.25
Fine Sand	2.0	3.0	0.25	0.125
Very Fine Sand	3.0	4.0	0.125	0.0625
Coarse Silt	4.0	5.0	0.0625	0.0312
Medium Silt	5.0	6.0	0.0312	0.0156
Fine Silt	6.0	7.0	0.0156	0.0078
Very Fine Silt	7.0	8.0	0.0078	0.0039
Coarse Clay	8.0	9.0	0.0039	0.00195
Medium Clay	9.0	10.0	0.00195	0.00098

By means of a simple chart the logarithmic values may be converted to their diameter equivalents (for example, Page, 1955).

The covering of such a wide range of sizes inevitably gives rise to mathematical complications. To simplify calculations, Krumbein (1936) introduced the concept of the phi unit, phi (ϕ) being a symbol for the negative logarithm of grain diameters to the base 2 (Table 3.2). The advantages of the use of the ϕ symbol are that it simplifies geometric grade scales, it permits the application of common statistical procedures to the data, and yet it yields directly a series of values which express the logarithmic properties of the size frequency curve. The only apparent disadvantage of the phi-transformation is that phi values increase as the size of particle decreases. This could lead to occasional misinterpretations. The range of sieves chosen in the present study with their ϕ equivalents, is shown in Table 3.3.

TABLE 3.3

Sieves chosen in present study

Sieve aperture (millimetres)	Sieve number (where applicable)	ϕ value	Wentworth grade
64		-6	
32		-5	
16		-4	GRAVEL
6.35		-2.65	
2.0	10	-1.0	-----
0.5	32	+1.0	
0.21	72	+2.25	SAND
0.075	200	+3.75	-----
			SILT & CLAY

PROCEDURAL PROBLEMS INVOLVED IN SIEVING PROCESS

A number of procedural problems with regard to the sieving process had to be considered. A procedure of weighing sieve plus sample retained, then subtracting known weight of sieve, was followed throughout. This minimized loss of material due to transference from sieve to weighing pan. After weighing, the material was emptied and retained and the sieve carefully brushed to remove particles wedged in the sieve openings. This was especially important as wedged particles reduce the efficiency of sieving as well as falsifying succeeding weighings. The sieves were weighed at regular intervals to allow for any slight changes in weight due to semi-permanently wedged particles.

Having chosen the sieves to be used, a minimum sieving time was decided upon. King (1966,p.274) suggests fifteen to twenty minutes as a suitable sieving time. Folk (1965) states that fifteen minutes is the accepted time, referring specifically to sieve analysis of sand-sized particles at $1/2 \phi$ and $1/4 \phi$ intervals. With the wider sieve interval used in the present study, and consequent heavier load on each sieve, it seemed that this suggested time might well be too brief. A series of tests was carried out and a minimum sieving time of thirty minutes postulated on the basis of the results obtained.

Weight loss over a one hour period was negligible with the larger-aperture sieves. A progressive loss of weight was recorded with the sieves smaller than pebble size (Fig. 3.1). For only

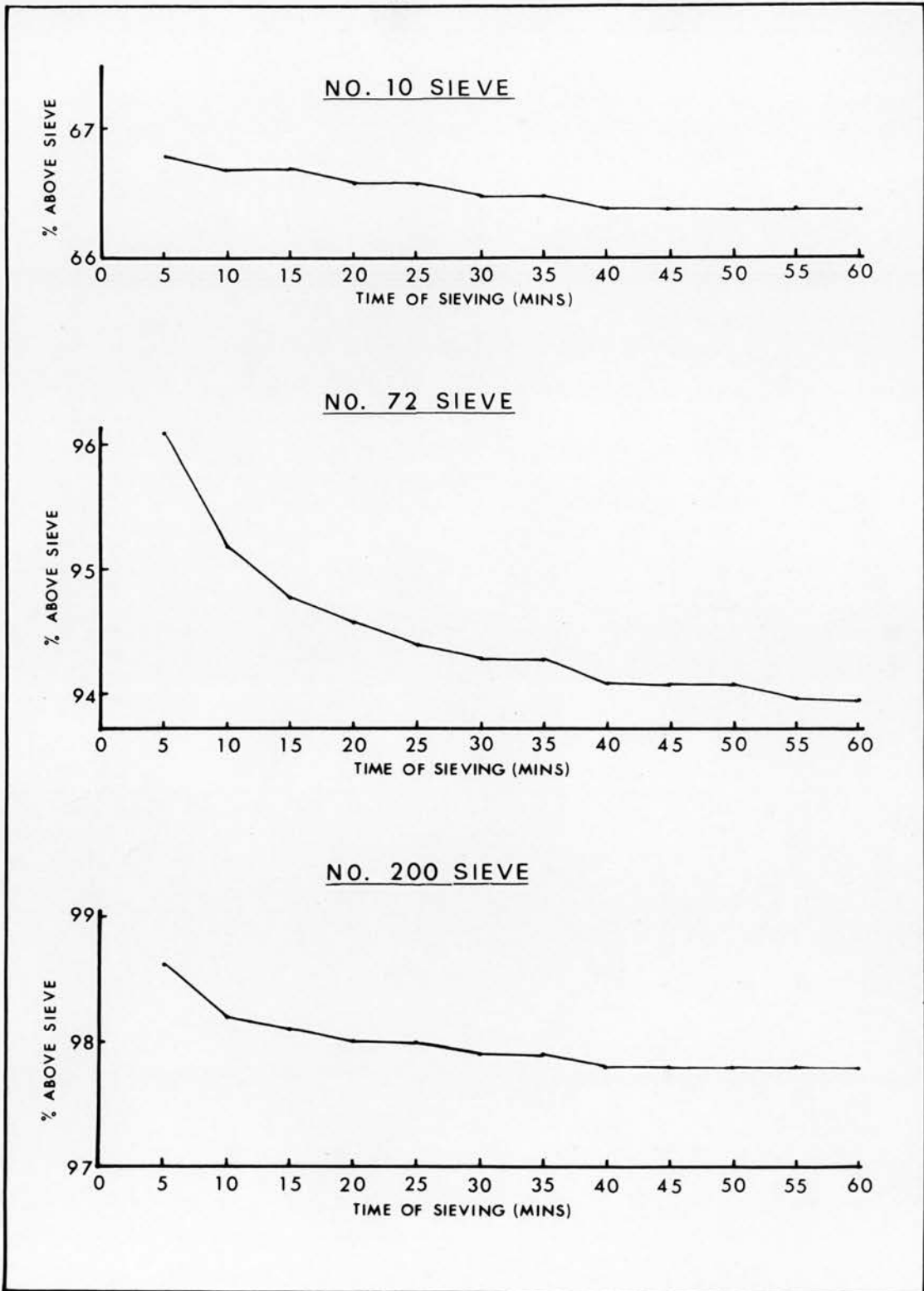


FIGURE 3.1. Mechanical sieving time trial. Percentage of material remaining above sand-sized sieves through time.

one sieve, the No. 72 (0.21 millimetre aperture) sieve, was this loss appreciable. Of the total weight of the sample larger than silt size, 1.5 per cent passed through the No. 72 sieve between five and twenty minutes, weighings being taken after every five minutes sieving time. A further 0.3 per cent passed through between twenty and thirty minutes and there was a further loss of 0.3 per cent in the succeeding thirty minutes. The exponential-type curve levels off at about thirty minutes sieving time.

It was decided at this stage to introduce a No. 30 sieve (0.5 millimetre aperture) in order to split the sand fraction and to ensure a lighter load on the No. 72 sieve. It was also decided to vary the amount of material sieved at one time according to size of constituent material. Where there was a relatively large proportion of gravel, 1.5 kilograms of the sample could be sieved at a time. The weight was reduced, with increasing percentage of fine fractions, down to 0.5 kilograms at a time for predominantly sandy samples or samples with large proportions of silt or clay. In most cases in the present study, a weight of material of between 1 and 1.5 kilograms was considered to be the normal load. Time of sieving could therefore be kept constant at thirty minutes by varying the weight of material loaded each time.

The next problem considered was whether or not to wash the sample after sieving, and a small test was carried out. A sample of 964.1 grams of various sizes larger than silt size was sieved for thirty minutes, each grade being weighed in the sieve, then washed thoroughly. After washing, the sieves were placed in a drying

oven at a temperature of 105°C. When thoroughly dried, total loss of weight of sample due to washing was found to be 13.9 grams (1.44 per cent). This loss was distributed throughout the range of material, the greatest loss of any grade being 3.42 per cent on the No. 30 sieve. While this magnitude of loss could conceivably be important for very detailed work, the deleterious side-effects of washing and drying outweigh the increase in accuracy gained. Quite apart from the extra time involved in drying the material, the process causes the break-up of fragments of soft rock (especially coal) and the disaggregation of soft sandstones that are not adversely affected by the sieving process prior to washing and drying. Furthermore, some of the sieves showed signs of rusting, extensive in some cases, and there is no practical alternative to drying the material on the sieve itself.

The procedure of grading by mechanical sieving action involves considerable time by the method described above. For the average sample of six to eight kilograms, sieved one kilogram at a time, about four or five hours is required, including the time that is necessary for weighing, cleaning and reloading between batches. This time interval is even larger when the sample being graded contains a large proportion of the smaller size grades. It is obviously impracticable to grade large amounts of material by this method for each separate field site.

SELECTION OF PEBBLES FOR SHAPE ANALYSIS

The size fractions retained on the 6.35 millimetre (1/4 inch) sieve and on larger sieves were separated for stone analysis. Davis, in studies of the size distribution of rock types in stream gravel and glacial till, demonstrated that the percentage of a given rock type in gravel varies with the size distribution of the particles in the sample taken (Davis, 1958). Accordingly, he suggested that most pebble counts of alluvial gravel should utilize restricted grade sizes. Sneed and Folk limited their Lower Colorado River study to pebbles 32 to 64 millimetres in length (Sneed and Folk, 1958). The grade sizes used throughout this work for the purpose of shape analysis were from 20 millimetres to 64 millimetres long axis length, larger cobbles being included in exceptional cases. This range corresponds closely to Wentworth's 'pebble' grade (64 millimetres to 4 millimetres) when one considers particle plan with long axis vertical as the criterion for deciding whether or not a particle will pass any given screen. "Plan" may be defined in the present context as the vertical projection downwards onto a horizontal plane. The actual range in pebble diameters was about 8 to 64 millimetres. The lower axis limit of 20 millimetres is essentially a limit of convenience associated with the use of a standard Grant Projector to be discussed shortly. Smaller particles are not easily handled or identified, but will almost certainly exhibit different sedimentary properties and may well be more certain indicators of specific trends.

The number of pebbles to be selected from each sample for shape study was the next problem to be considered. The minimum accepted number is 50, as advocated by Plumley (1948) and King and Buckley (1968) for example, while other workers have considered sets of 100 stones to be an acceptable number (for example, Nossin (1959)).

A simple test of sample size was run, 300 greywacke pebbles being selected from Cowieslinn Pit, Eddleston (Q.S. 1" SHEET 62, NT 238 516) (Figs. 3.2, 3.3, 3.4). It appeared from the figures obtained for average long axis length, sphericity and roundness that no one figure could be taken as representing average conditions with any degree of certainty. The minimum number of pebbles desirable would seem to be about 80 from the test made at this particular site. It was decided, therefore, to select 100 stones from each sample, as the extra effort in selecting 20 more than the minimum of 80 was outweighed by the mathematical benefits to be gained by taking 100 pebbles.

Before proceeding to the selection of pebbles from the sample, a rigid selection method had to be adopted. Unless complete objectivity is ensured, there will be a tendency, at least sub-consciously, to select well-rounded pebbles where previous work indicates an increasing roundness, to select smaller pebbles in a downstream direction, and so on. The method of obtaining 100 pebbles from each sample, with maximum objectivity, was to take the entire part of that sample remaining above the 6.35 millimetre sieve, and one and quarter that fraction. Two opposite quarters were rejected

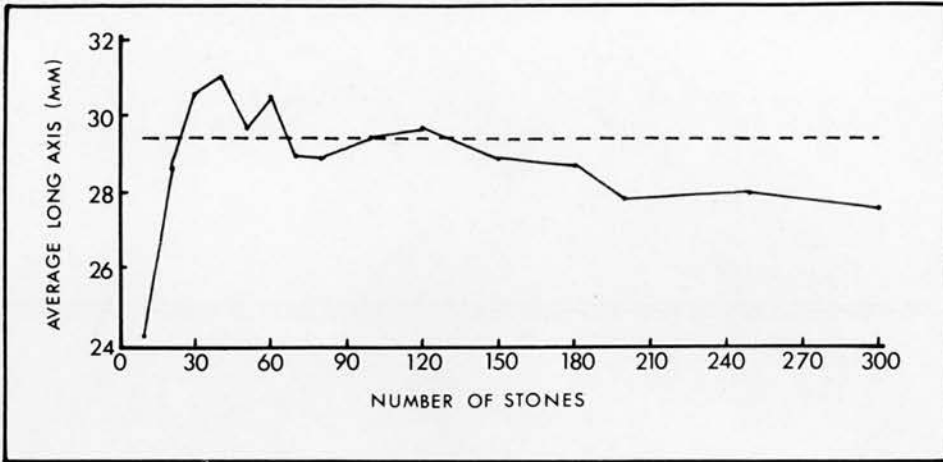


FIGURE 3.2. Number of stones versus average long axis length

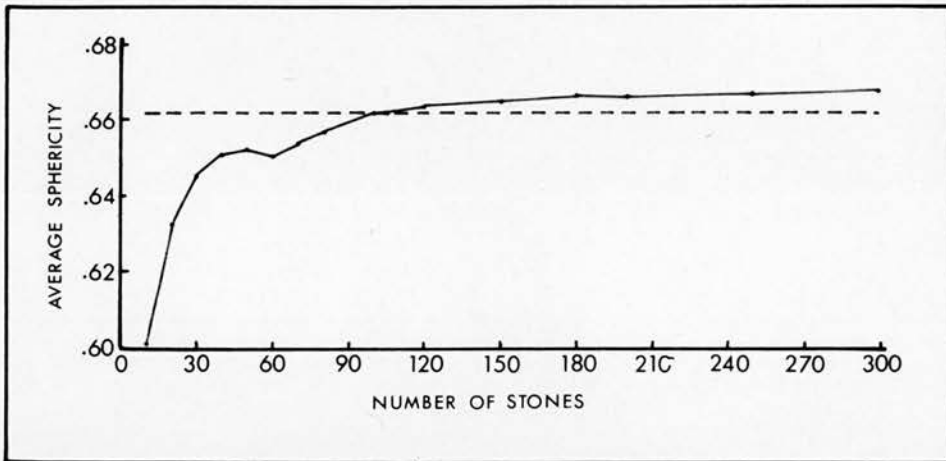


FIGURE 3.3. Number of stones versus average sphericity

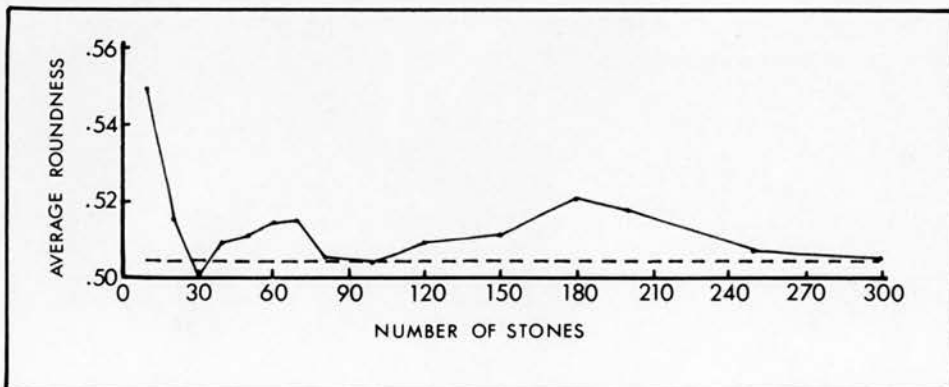


FIGURE 3.4. Number of stones versus average roundness

and 50 pebbles of long axis length approximately 20 millimetres or larger were then selected from each of the two remaining quarters. This was done by first flattening each pile gently then alternately selecting and rejecting pebbles along a straight edge applied perpendicularly to an extreme radius of the sector. If 50 pebbles were not obtained from a first complete treatment of a selected quarter, the material remaining in that quarter was itself coned and quartered. A similar alternate selection and rejection process was then carried out until the required number of pebbles was obtained, half from each of the two opposite quarters. If, after selection of all pebbles over 20 millimetres long axis length in any selected quarter, the number was found to be under 50, the appropriate number of pebbles was selected from the residue of the opposite quarter. In one case, even this was not sufficient to bring the number of stones up to 100. In that case, the number was made up by selecting the required number from one of the originally-rejected quarters, following the selection process outlined above.

The objectivity of this method, in fact a test of operator variance, was checked by comparing the sphericity and roundness of the first 50 stones in each of nine samples with the second 50 by means of Student's *t* test (Table 3.4).

As can be seen from Table 3.4, in most cases the difference was not significant, in the remainder barely significant. This would seem to suggest that the method of pebble selection was satisfactory.

TABLE 3.4

Test of operator variance : first 50 pebbles versus second 50

Sample No.	Location	Grid reference	Level of significance	
			Sphericity	Roundness
1.1	Straiton	NT 271 666	N.S	N.S
2.2	Melville Mains	NT 299 664	N.S	N.S
4.1	Haveral Wood	NT 293 662	N.S	N.S
7.5	Cowieslinn	NT 238 516	N.S	30%
7.7	Cowieslinn	NT 238 516	N.S	N.S
8.1	Nether Falla	NT 239 520	20%	25%
9.1	Shiphorns	NT 240 497	20%	12%
10.2	West Linton	NT 148 510	23%	N.S
11.2	Ladyurd	NT 148 426	N.S	N.S

All pits located on O.S. 1" SHEET 62 - Edinburgh

N.S. = Not Significant

The 100 pebbles thus selected were then washed, excepting fragments of soft rocks, such as coal or soft sandstones, which would have been adversely affected by washing. The stones were then numbered, washing and numbering being carried out in groups of ten according to order of selection.

PARAMETER MEASUREMENT - ROCK TYPE AND PARTICLE DIMENSIONS

The numbered stones were then identified for rock type by use of a $\times 10$ hand magnifier. Knowledge of the bedrock geology of the immediate area, plus information on direction of origin of the glacial feature from which the sample under consideration was taken, enabled the lithology of most pebbles to be identified with some degree of certainty. In some cases, it was almost impossible to differentiate between similar rock types. For example, rhyolites and felsites from the Southern Uplands look alike in hand specimen. Differences between the microdiorites, trachytes, and andesites and basalts of the Pentlands were not always apparent at such a low magnification. These rock types grade into each other to some extent. Thin sectioning is the obvious answer to such a problem, but this was not practicable within the confines of this thesis. Where possible, hand specimens were taken from quarries and outcrops of known rock type, and doubtful pebbles compared with these.

Following the identification of rock type, the analysis of pebble shape was undertaken for each pebble. A set of three mutually orthogonal axes was taken for each pebble according to the method proposed by Krumbein (1941). All axes were measured by eye to the nearest millimetre by use of a metre rule. This was quicker than using calipers and the loss in accuracy was negligible. The "long" or "a" axis is simply the longest axis of the pebble. The maximum projection plane was found by rotation

of the stone about the long axis. The "intermediate" or "b" axis is the widest part of this plane, measured perpendicular to the long axis. With the pebble held by its long axis and the maximum projection plane horizontal, the pebble is rotated through 90 degrees to a vertical position of the maximum projection plane. This places the short pebble diameter in the horizontal plane. The widest part of this latter plane, also measured perpendicular to the long axis, is the "short" or "c" axis. It may be noted that the three axes, although mutually perpendicular, do not necessarily intersect at any one point. Krumbein's "intercept method" is based on a triaxial ellipsoid as the reference solid to which the pebble is compared. Aschenbrenner approximated the sedimentary particle to a tetrakaidekahedron (Aschenbrenner, 1956) and attempted to define the shape of the particle simultaneously in terms of Zingg's shape factor (Zingg, 1935) and an approximation of Wadell's true sphericity (Wadell, 1932). Griffiths and Smith, however, stated that "... since any three mutually perpendicular axes appear to be equally useful as predictors the decision as to which three to choose may be based on convenience" (Griffiths and Smith, 1964, p.497). They suggested that the a and c axes together contribute 89 per cent to predictability, the b axis only a further 4 per cent.

PARAMETER MEASUREMENT - HISTORICAL DEVELOPMENT OF SHAPE PARAMETERS

The morphology of any particle depends on the interaction of a number of factors. The most important factors involved are the shape

of the particle when released from the parent rock, its internal characteristics, the size of the particle, the distance and effectiveness of transport, the agent of transport, together with chance factors such as the effect of chipping against obstacles. This last factor is virtually impossible to analyse, but it is possible to obtain some quantitative evaluation of the other factors by measuring rates of change of particle form. The first formal classification of particle shape was set up by Sorby (1880). His classification of quartz sand grains is mainly nominal, although it has some ordinal attributes (Table 3.5).

Classes 1 and 2 form an ordinal series to distinguish angular grains still near their source from rounded grains, which have presumably travelled a considerable distance although Sorby did not state that in the text. Class 5, on this basis, includes grains virtually at their source. Classes 3 and 4 infer that particle shape may be modified by chance collisions with obstacles and may be modified by chemical as well as by mechanical processes.

Wentworth expressed "rounding" as ratio-scale numbers by defining the roundness ratio for pebbles as the radius of curvature of the sharpest developed edge divided by the mean pebble radius (Wentworth, 1922b). A flatness ratio was also obtained by dividing the radius of curvature of the flattest developed face by the mean radius. In a later paper, Zingg developed a classification of pebble shapes based on the b/a and c/b ratios (Zingg, 1935) (Fig. 3.5).

TABLE 3.5

Sorby classification of quartz and sand grains (Sorby, 1880)

- | | |
|---------|---|
| Class 1 | Normal, angular, fresh-formed sand, as derived almost directly from granitic or schistose rocks. |
| Class 2 | Well-worn sand in rounded grains, the original angles being completely lost, and the surface looking like fine ground glass. |
| Class 3 | Sand mechanically broken into sharp angular chips, showing a glassy fracture. |
| Class 4 | Sand having the grains chemically corroded, so as to produce a peculiar texture of the surface, differing from that of worn grains or crystals. |
| Class 5 | Sand in which the grains have a perfect crystalline outline, in some cases undoubtedly due to the deposition of quartz over rounded or angular nuclei of ordinary non-crystalline sand. |

Wadell, in a series of papers between 1932 and 1935, was the first to show that there is a fundamental difference between "shape" and "roundness" and that these are really two geometrically distinct



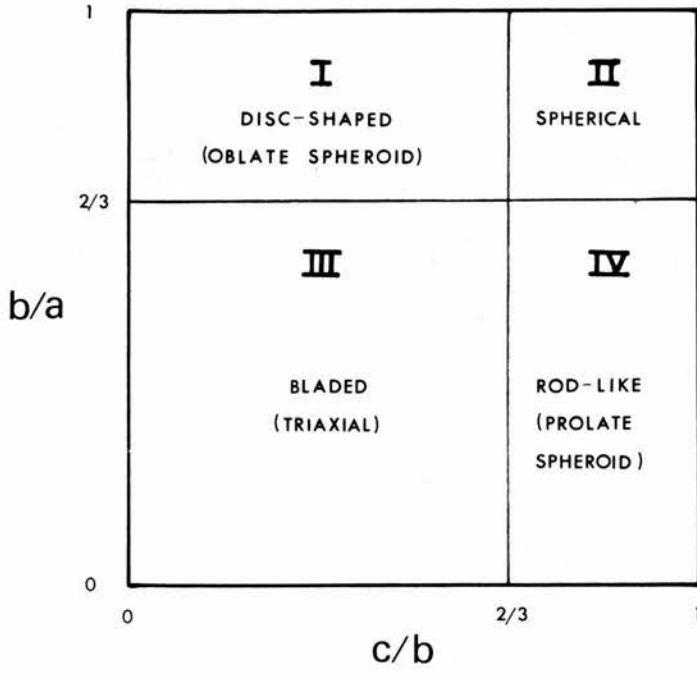


FIGURE 3.5. Zingg (1935) shape classification

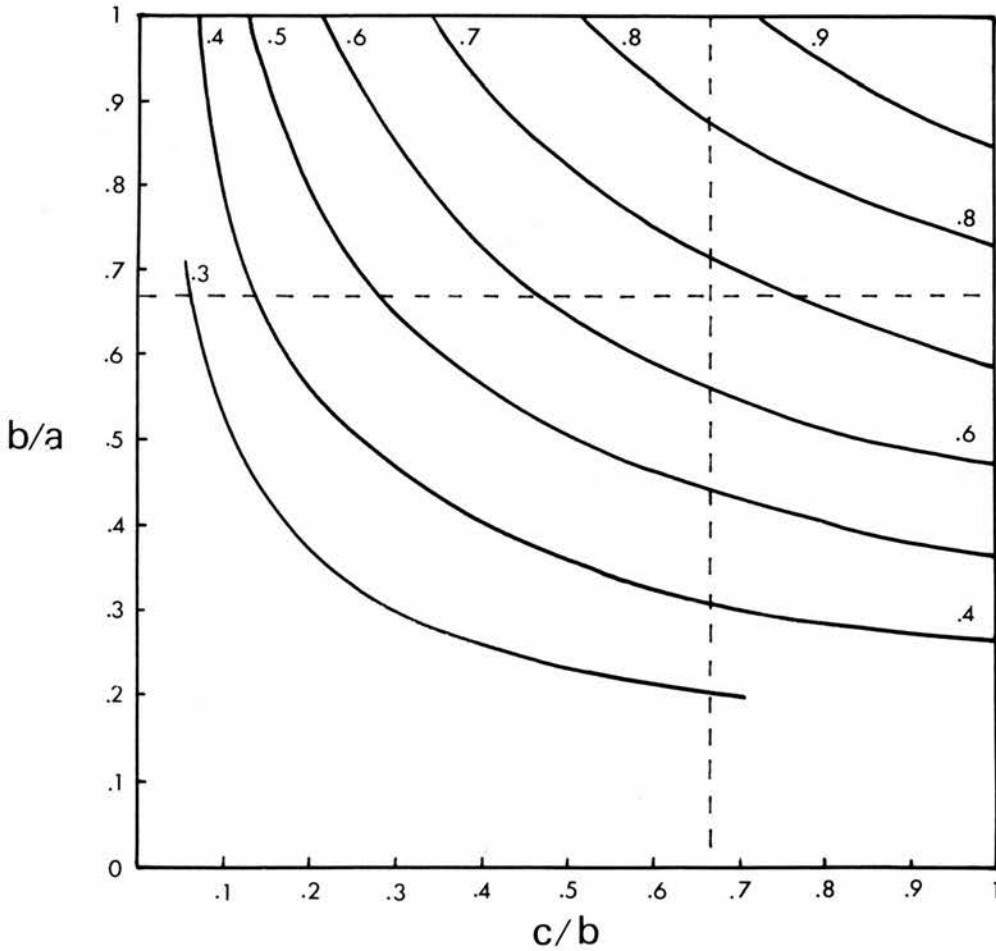


FIGURE 3.6. Krumbein (1941) sphericity grid

concepts (Wadell, 1932, 1933, 1935). An object may be quite spherical in shape but completely angular, for example a dodecahedron; or perfectly rounded but far from spherical, for example a cylinder capped by two half-spheres. The shape of a particle is its form, entirely independent of whether the edges or corners are sharp or rounded, whereas the roundness of a particle is a response to abrasional forces that round the edges of the particle. Wadell stated that fundamentally the shape of a particle is a measure of the ratio of the surface area of a particle to its volume (Wadell, 1932). For a sphere, this ratio is a minimum, and for all other forms it is larger. Hence the ratio of surface area to volume indicates how closely the particle approaches a sphere in form. For practical purposes this ratio is difficult to measure, and Wadell's actual measurement is expressed in terms of the ratio of the volume of the particle to the volume of its circumscribing sphere. The cube root of this ratio is called the "sphericity" of the particle. The diameter of the circumscribing sphere is considered as equal to the longest dimension of the particle. "Roundness" was defined by Wadell as the ratio of the mean radius of all corners and edges of the particle in its maximum projection plane to the radius of the largest inscribed circle in that plane. Wadell's method for measuring the roundness of a pebble requires drawing an image at a magnification to a standard long axis length of 70 millimetres.

It must be noted at this point that "shape" and "sphericity" are not identical concepts. For example, "discs" and "rods", although

having different shapes according to Zingg classification, may have identical sphericity values, yet will behave in different ways during transport and deposition. The use of sphericity values does not always permit the complete evaluation of shape influence. Roundness is influenced by intensity of wear and distance of transport, but has little or no effect on sorting or transport. Wadell's definitions of sphericity and roundness are essentially independent and it is generally assumed that only very great changes in one will influence the other (Pettijohn, 1949, page 54).

DEVELOPMENT OF QUANTITATIVE MEASURES OF SPHERICITY, SHAPE AND ROUNDNESS

Krumbein modified Wadell's sphericity formula to allow for more direct laboratory determination (Krumbein, 1941). He regarded the particle as a triaxial ellipsoid having the three diameters a, b, and c, where b is intermediate in length between the larger a and smaller c diameters. The volume of such an ellipsoid is $(\pi/6)abc$. The volume of the circumscribing sphere is $(\pi/6)a^3$, giving the ratio for sphericity, (volume of particle / volume of circumscribing sphere) $^{1/3}$, as

$$\left[(\pi/6)abc / (\pi/6)a^3 \right]^{1/3} = (bc/a^2)^{1/3} ;$$

that is, "intercept sphericity",

$$\psi_k = \sqrt[3]{\frac{bc}{a^2}} .$$

This can be modified in terms of axial ratios to give

$$(b/a)^2 = \Psi_k^3 / (c/b) .$$

This equation is of the parabolic form $y^2 = j/x$, where $y = b/a$, $x = c/b$ and $j = \Psi_k^3$. Successive values of Ψ_k of 0.3, 0.4, ..., 0.9 enable parabolic curves to be drawn in conjunction with a grid of c/b against b/a (Fig. 3.6). From this chart, sphericity can be estimated to within 0.01 directly from calculation of the axial ratios. Krumbein did not include sphericity values of lower than 0.3 as these occur very rarely in nature.

In the same (1941) paper, Krumbein introduced visual charts for the determination of roundness. An estimate of the roundness of each pebble can be made by comparing the pebble's outline with a set of nine outlines ranging from roundnesses of 0.1 to 0.9 by steps of 0.1. Although this is obviously very much quicker than Wadell's method, it has the disadvantage that the distinction between adjacent classes is often too fine for a definite value to be recorded. Being a visual method, it is open to operator bias, whether conscious or unconscious. The technique has undoubted value for reconnaissance work, but for accurate and detailed analysis its usefulness would appear to be limited.

Powers (1953) suggested that there were too many subdivisions in Krumbein's charts, and suggested a geometric, 6-division scale (Table 3.6).

TABLE 3.6

Powers geometric scale of roundness (Powers, 1953)

Grade terms	Class intervals	Geometric means
Very Angular	0.12 - 0.17	0.14
Angular	0.17 - 0.25	0.21
Subangular	0.25 - 0.35	0.30
Subrounded	0.35 - 0.49	0.41
Rounded	0.49 - 0.70	0.59
Very Rounded	0.70 - 1.00	0.84

The interval from 1.00 to 0.12 has been divided into six intervals in such a way that the ratio of lower limit to upper limit of each class is 0.7. He expressed this in a photographic chart of sand grains of varying roundnesses. As recently as 1963, Emrich and Wobber were advocating measurement of sedimentary parameters by visual estimation (Emrich and Wobber, 1963). A series of samples with known values are studied until a mental "image" of the values is formed. These samples are retained for later use as references. There is no evidence to suggest that their method is any less subjective than Krumbein's visual method.

Krumbein noted experimentally that roller-shaped particles generally have a higher settling velocity than discs of the same sphericity (Krumbein, 1942). Particles settling through a water column tend to orientate themselves with their maximum cross-section

normal to the direction of settling, regardless of the position in which they are released at the water surface. Sneed and Folk followed this up by noting that, although Wadell's sphericity measure is geometrically valid, it cannot be considered to be a parameter representing the true dynamics of particles under natural hydraulic conditions (Sneed and Folk, 1958). They suggested that a more representative measure of sphericity is obtained by comparing the volume of the particle with the maximum projection area, that is, with the surface area opposed to the direction of motion. The measure they introduced compares the maximum projection area of the particle itself (defined as the product of the a and b axes) with the maximum projection area of a sphere of the same volume as the particle, assuming that the particle shape is approximately that of a triaxial ellipsoid. They reasoned as follows:-

$$\begin{aligned}
 \text{Maximum projection area of particle} &= \pi/4 \cdot (ab) \\
 \text{Volume of particle} &= \pi/6 \cdot (abc) \\
 \therefore \text{Volume of equivalent sphere} &= \pi/6 \cdot (abc) \\
 \therefore \text{Diameter of equivalent sphere, } d &= (abc)^{\frac{1}{3}}, \\
 &\quad \text{as sphere volume} = \pi/6 \cdot d^3 \\
 \text{Maximum projection area of this sphere} &= \pi/4 \cdot d^2 \\
 &= \pi/4 \cdot (abc)^{\frac{2}{3}} \\
 \therefore \text{Maximum projection sphericity} &= \frac{\pi/4 \cdot (abc)^{\frac{2}{3}}}{\pi/4 \cdot (ab)}
 \end{aligned}$$

$$\Psi_{sf} = \sqrt[3]{c^2/ab}$$

It may be noted that the ratio Ψ_k to Ψ_{sf} is $\sqrt[3]{b^2/ac}$. For many particles this ratio is very nearly unity, but differences do occur between the two measures of sphericity. Ψ_k is approximately equal to Ψ_{sf} for bladed particles, is generally smaller than Ψ_{sf} for rod-shaped particles and often appreciably larger for discs. Sneed and Folk's disagreement with the Krumbein sphericity measure may be said to be mainly theoretical. Although theoretically valid, it is difficult to envisage the idealized laboratory conditions of pebble deposition, through a water column, being duplicated by particles in the turbulent waters of glacial streams that were strong enough to carry pebble-sized particles.

Sneed and Folk, in the same (1958) article, also introduced a more sophisticated set of shape classes than Zingg's classification. They argued that there are three end-points limiting the system of dimensional variation. An object may be a prolate spheroid with one long axis and two equal short axes; it may be an oblate spheroid with two of the axes equal and longer than the third; or it may be a sphere with all three axes equal. A triangular plot is most suited to graphic description of such a trivariate system (Fig. 3.7).

Form classes have been defined by the following reasoning. If the long and short dimensions of a pebble are assumed to be fixed, then the intermediate axis is free to vary at any value between a and c. Sneed and Folk suggested that it would seem logical, in setting up form classes, to divide this range into three equal intervals so that, geometrically at least, approximately

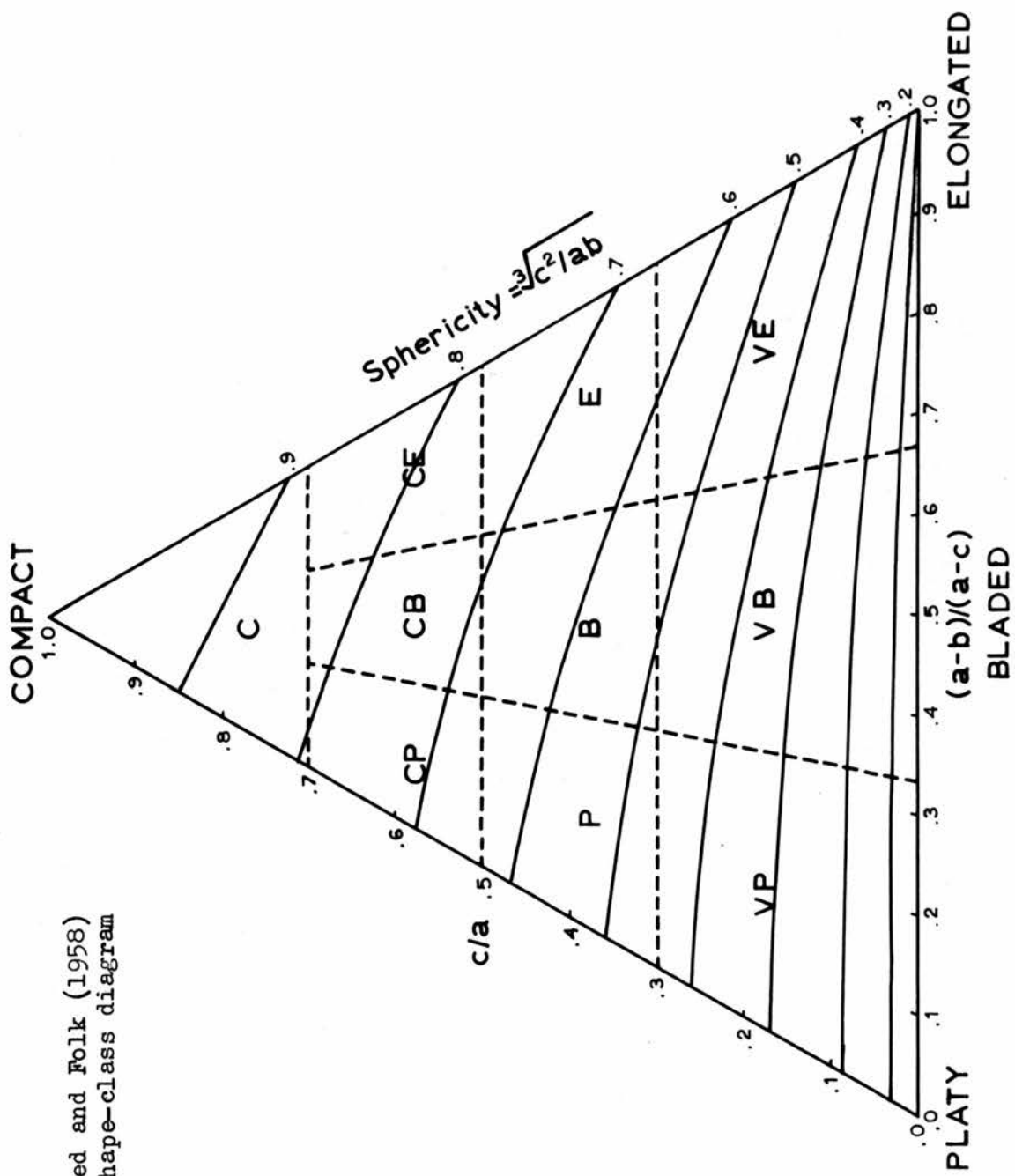


FIGURE 3.7. Sneed and Folk (1958) sphericity and shape-class diagram

equal numbers of particles would fall in each of the three classes. In Sneed and Folk's "form triangle" they express this as disc-like versus rod-like aspect, plotted on a linear scale by calculating $(a - b)/(a - c)$. As this varies between 0 and 1, 0.33 and 0.67 are used as boundaries in order to divide the range into three geometrically equal intervals. This is plotted against c/a to complete the form classes. Finally, isosphericity contours are added in order to facilitate direct reading of Ψ_{sf} after calculation of the ratios $(a - b)/(a - c)$ and c/a .

As noted earlier, Aschenbrenner (1956) approximated the shape of a particle to a tetrakaidekahedron. He attempted to define particle shape simultaneously in terms of Zingg's shape factor and an approximation of Wadell's true sphericity. Lengthy mathematical calculations are involved and this militates against the method. More recently, Gill also utilised Wadell's sphericity measure (Gill, 1969). He proposed an index of flatness rather than true sphericity itself. He defined flatness as the reciprocal of true sphericity and evaluated the flatness index, with a reasonable degree of accuracy, from only the volume and the intercepts of a particle, without actually measuring its surface area.

Another index of flatness is that proposed by Cailleux (1947). His shape factor is the flatness index $F = (a + b)/2c$, as originally proposed and used by Wentworth in 1922. This value does not distinguish between roller-shaped and disc-shaped pebbles, since it compares c with the average of a and b . Thus it does not offer a means of avoiding the deficiencies of Ψ_k . Cailleux also

suggested the ratio of the diameter of the sharpest corner ($2r$) in the plane of maximum projection to the greatest length (a) as a measure of roundness. A cylinder capped by two half-spheres is perfectly rounded, $2r = b$, and roundness according to Wadell's formula (R_w) equals unity. The roundness of this shape according to Cailleux (R_c), however, may have one of an infinite series of values, depending on the ratio b/a . As a mathematical concept, R_c is definitely inferior to R_w , as R_c is partly controlled by shape.

The determination of $2r$ for R_c is carried out by selecting visually the sharpest corner and determining its diameter to the nearest 0.5 millimetres by using a disc with concentric circles. With decreasing size and rounding, the accuracy of this technique also decreases rapidly (Berthois, 1952). The advantages of the method are its rapidity and the fact that it has been used by many workers (for example; Nossin, 1959; Elenk, 1960; King and Buckley, 1968) and therefore allows for comparison of results. However, the mathematical discrepancies of the method would seem to nullify these advantages.

Other workers have proposed measures of roundness or sphericity based on different criteria, few of which have attained wide currency.

MEASURES AND LABORATORY PROCEDURES ADOPTED

ROUNDNESS

From consideration of the proposals, it seems that Wadell's conception and measurement of roundness is the most sound, and it

has been used throughout this study. Wadell roundness is given by the formula

$$R_w = \frac{\sum_{i=1}^N r_i}{N \cdot R}$$

where r_i are the radii of individual corners in the maximum projection plane, N is their number, and R is the radius of the maximum inscribed circle in that plane. Krumbein's visual method of determining roundness has much to commend it and would certainly be most appropriate to any reconnaissance study.

In order to standardise measurements, the following procedure was adopted. Each stone was mounted, in the plane of maximum projection, on the object plane of a standard Grant Projector. The long axis is then brought to a standard length of 70 millimetres on the image plate, and R is measured to the nearest millimetre. This limits the minimum pebble long axis to around 20 millimetres, as the projector cannot magnify shorter pebbles to a long axis length of 70 millimetres. Individual corners are then measured to the nearest millimetre, summed, and R_w calculated according to the above formula. The time involved for complete determination of 100 roundnesses by this method is approximately 4 hours. The radial distortion pattern inherent in the Grant Projector was deemed negligible by ensuring that each pebble was mounted in the exact centre of the image plate.

SPHERICITY AND SHAPE

The choice of a sphericity measure was not so immediate.

Both Krumbein's method and Sneed and Folk's method have much to commend them. Ψ_k , coupled with the Zingg shape class determination, has the advantage of being more easily, and hence more quickly, calculated mathematically. It has been used by the majority of workers for almost 30 years and therefore has the advantage of comparability. As a parameter, Ψ_{sf} represents more truly the behaviour of particles under natural hydraulic conditions, and includes a more refined shape class. On this latter point, it is worth investigating critically the value of a ten-class division where only 100 measurements are involved. This question is even more pertinent when the fact that Sneed and Folk used only 50 pebbles in each sample is being considered. Brooks and Carruthers (1953) stated that the number of classes should not exceed 5 times the logarithm (to the base 10) of the number of observations. For 50 pebbles, the maximum number of classes by this definition should not exceed 8. This number rises to 10 only when 100 observations (pebbles) are considered.

In one sample evaluated according to Sneed and Folk's class divisions, 6 out of 10 classes contained 6 or fewer pebbles. One of the classes contained no pebbles. In a second trial, 6 classes yielded 8, 7, 5, 5, 4 and 0 pebbles. These results would suggest that the classification is in fact too fine for samples of 100 pebbles. Zingg's classification, although less refined, gives a more immediate picture of the relative proportions of pebbles of different shapes.

The correlation between values of Ψ_k and Ψ_{sf} is high. A correlation of +0.80 is usual in sets of 100 pebbles. This supports

the earlier consideration that the difference in the two methods of calculating sphericity is mainly theoretical. Considering all aspects of these two classifications it was thought that Sneed and Folk's had little extra to offer, and it was decided to adopt the mathematically simpler, and more easily calculated, Krumbein measure of sphericity in conjunction with the Zingg shape classification. Ψ_k was read directly from the chart after calculation of axial ratios b/a and c/b (Fig. 3.6). Zingg shape classes were read off from the position of each pebble on that chart (Fig. 3.5). The time involved in calculating sphericity and shape class for each sample of 100 pebbles was approximately 1 hour, 30 minutes required for calculation of axial ratios and 30 minutes spent interpolating sphericity and shape from the charts.

SUMMARY OF LABORATORY PROCEDURE

To summarize laboratory procedure, all field samples were initially air-dried, then sieved mechanically. The sample was sieved in batches weighing 1 to 1.5 kilograms. As each batch was sieved for 30 minutes and the average sample weighed 8 to 10 kilograms, total sieving time per sample was 4 to 5 hours. All fractions were weighed and the weights recorded. All material retained on the 6.35 millimetre and larger sieves was coned and quartered, and 100 pebbles selected objectively, 50 from each of two opposite quarters. Pebbles selected usually fell within the long axis limits of 20 to 64 millimetres.

The process of selection, washing and numbering of 100 pebbles took over 1 hour in all cases. Subsequently, the lithology of each pebble was recorded, and three mutually orthogonal axes were measured. Approximately 2 hours was required to conclude this stage. Measurement and calculation of roundness according to Wadell's formula followed, involving 4 hours' work for each sample of 100 pebbles. The calculation of sphericity and shape according to the methods of Krumbein and Zingg took about 1 hour. A summary of rock types, Zingg shape classes and average long axis length, sphericity and roundness were finally calculated for each sample, involving a further 1 hour's work on a desk calculator.

The total time required for complete processing of each sample was never less than 14 hours actual working time. The bulk of this time was spent in mechanical sieving and measurement of roundness. There is no satisfactory method of shortening substantially the time spent on deriving a measure of roundness. Krumbein's visual technique, although much quicker than the Wadell method, is useless for accurate quantitative analysis, and other methods such as that of Cailleux are mathematically unsatisfactory. To take smaller field samples is one obvious answer to the problem of sieving time, but smaller samples would not be representative of conditions at the field site. Thus there would appear to be no way of substantially shortening the lengthy laboratory procedure used in the present study.

CHAPTER 4. DEVELOPMENT AND THEORY OF STATISTICAL TECHNIQUES
OF GRAIN SIZE ANALYSIS

INTRODUCTION

In this chapter, the basis of the subsequent statistical analysis of grain size samples obtained will be discussed. Firstly, the question of operator variance, with respect to the laboratory methods, will be resolved. This will be followed by a section on preparation of the raw grain size data for statistical analysis. Statistical parameters of grain size will then be discussed. Where appropriate, the historical development of the measures used will be described.

Common statistical procedures of data analysis, such as the product moment correlation coefficient and regression line analysis, are used throughout subsequent chapters. However, it is not intended to describe these in the present chapter as these are in common use throughout geomorphology. Non-standard tests or procedures will be briefly discussed from a theoretical viewpoint as they occur throughout the text.

OPERATOR VARIANCE IN LABORATORY METHODS

In addition to the natural variation encountered at any sampling site and the significant variation occurring between sample sites, a further source of variation arises from the

collection of the raw data itself, namely operator variation. Krumbein (1934) distinguished between sampling errors and operational errors during mechanical analysis of sediments. Griffiths (1953) followed this by detailing the quantitative techniques for estimating the proportion of the total error that could be attributed to operator error in grain size analysis. He utilized an analysis of variance technique and concluded that the magnitude of the experimental error is considerably enlarged by differences between operators. He also concluded that there appears to be a relationship between the magnitude of error and the mean size of the sediment under analysis.

Rosenfeld and Griffiths (1953) tested operator variance in estimating the sphericity and roundness of quartz grains by use of visual comparison techniques, and Griffiths and Rosenfeld (1954) summarized a number of investigations into operator variation in petrological work. They stated that there are two sources of variation, namely constant bias within one operator and inconsistent differences within one operator and between a group of operators. Constant bias within one operator can be resolved by means of suitable experimental design and analysis of variance. The inconsistent differences within one operator and between a group of operators determines the level of sensitivity of the experiment. These two factors increase in importance as the experimental procedure changes from simple measurements to objective assessment, and from objective assessment to subjective assessment.

In the present work, inconsistent differences between operators do not exist as all measurements were made by the writer. Constant bias within one operator cannot be measured directly, and inconsistent differences within one operator were minimized by imposing a rigid procedure on all aspects of laboratory work, as discussed in the previous chapter. As detailed in that chapter, operator variance in the selection of pebbles for further analysis was checked by means of Student's *t* test. In most cases, there was no significant difference between the roundness and sphericity averages of the first 50 pebbles and those of the second 50 pebbles selected from each sample. Small errors were likely to have occurred during the measurement of roundness and the axes lengths from which sphericity values were obtained. The roundness value of a pebble depends on the projection plane in which the pebble is fixed, and care was taken to ensure that each pebble was fixed as exactly as possible in the maximum projection plane. Axis measurements were taken to the nearest millimetre and random errors could have occurred at that stage. These errors, however, were deemed to be negligible within the terms of reference of the thesis.

GRAPHIC PRESENTATION OF SIZE ANALYSIS DATA

The data obtained from grain size analysis may be plotted in several ways, different methods being more suitable for different purposes. All the methods commonly employed use grain size as the

abscissa, the horizontal scale, and a measure of percentage frequency as the ordinate, the vertical scale. Grain size analyses may either be plotted with the abscissa in millimetres using a logarithmic-base paper, or with the abscissa in phi units, in which case arithmetic-base paper is used. The latter method is much more convenient and more accurate to read.

The four main methods used, the histogram, the cumulative curve with arithmetic ordinate, the cumulative curve with probability ordinate, and the frequency curve, are compared graphically in Figure 4.1.

HISTOGRAM. A histogram is essentially a bar graph in which the percentages for each grade size are plotted as a column. The histogram is easily prepared and allows ready interpretation of the general features of the sediment. It is strictly a pictorial method and cannot be used for determination of any statistical parameters. Furthermore, its shape is greatly affected by the sieve interval chosen. The same sample may give a completely different histogram if it is analysed on a different set of sieves. The histogram proves of value in plotting distribution of sediments on a map, as the heights of the columns may be more easily compared by eye than if the data were plotted as cumulative curves.

CUMULATIVE CURVE, ARITHMETIC ORDINATE. The abscissa may be either in millimetres, in which case semi-logarithmic paper is used, or in phi units in conjunction with ordinary squared graph paper. The ordinate is an arithmetic scale running from 0 per cent to 100 per cent. In line with current convention, grain size is

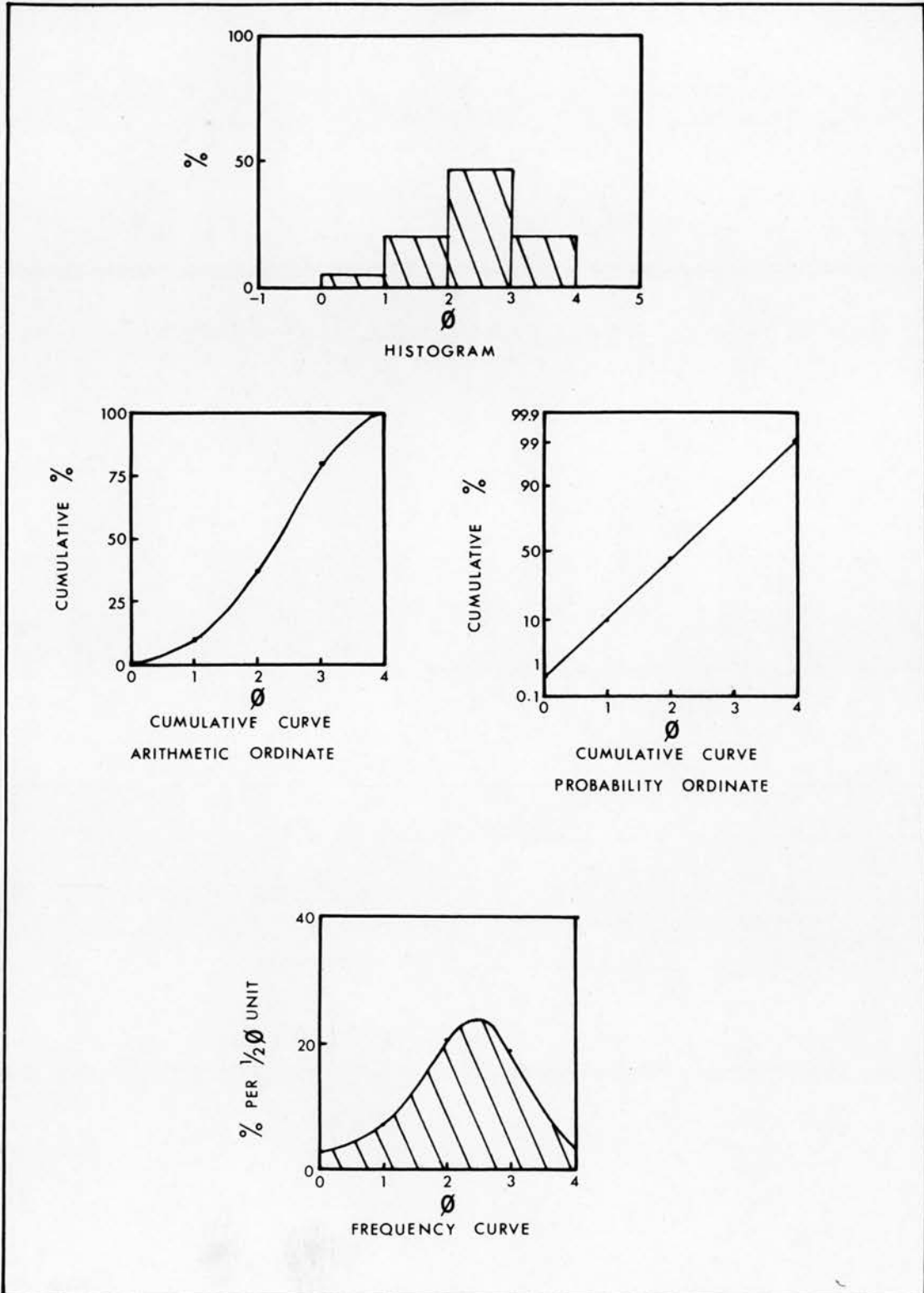


FIGURE 4.1. Various methods of graphic presentation of grain size analysis data. For explanation see text

plotted on the abscissa with coarser particles to the left. Cumulative percentages are plotted and a curve drawn through all the resulting points. The curve must pass through all the plotted points, and is always "smoothed". The sample analysis normally forms an S-shaped curve from which statistical parameters can be read. Compared with the histogram, this method of plotting size data has the advantage that the shape of the curve is independent of the sieves used. If, however, the sieve interval is wide, sketching the curve between data points is open to error.

CUMULATIVE CURVE, PROBABILITY ORDINATE. Most sediments tend to approach the "normal probability curve" in their size frequency distribution. The normal curve plots as a straight line on probability paper, that is, paper with an arithmetic abscissa in phi units and a probability ordinate. If the cumulative curve of a sediment with normal symmetrical probability distribution is plotted on probability paper, the resultant line is perfectly straight. The position of the line depends on average particle size and the slope of the line depends on the degree of the sorting. The effect of using the probability ordinate is to condense the middle of the distribution and expand the extreme limits, thereby straightening out the S-shaped curve which would result if an arithmetic ordinate was used.

The departure of sediments from the normal probability law can be studied by this method. Moreover, since the "tails" of the sediment plot are straightened out and the sample tends to plot as a straight line, it is possible to read the statistical

parameters with greater accuracy because of the ease of interpolation and extrapolation. Most workers in the field of sediment analysis now use this method of plotting. Thus results have the additional advantage of comparability.

FREQUENCY CURVE. Another type of curve occasionally used is the frequency curve. This represents a smoothed histogram. A continuous bell-shaped curve takes the place of a discontinuous bar graph. It is independent of the sieve interval used and is obtained by measuring the slopes of tangents to the arithmetic ordinate cumulative curve at selected points. Enough points are selected to ensure that all points of inflexion and all dips on the cumulative curve are found. This ensures that all maxima and minima are determined on the frequency curve. Modes may be fixed accurately by repeated approximation.

The main advantage of the frequency curve is that the most frequent diameter, the modal grain size, is readily obtained by reading the diameter value corresponding to the maximum height of the curve. This most common diameter reflects the most common current velocity in the depositing medium, but its exact implications are vague because the frequency curve must be symmetrical for this diameter to be most meaningful. This point is especially valid in the conditions of turbulent and seasonal flow typical of glacial meltwaters. The complexity of procedure necessary to obtain the frequency curve accurately militates against its extensive use. The probability ordinate cumulative curve remains the most used and most convenient method of estimating statistical parameters.

STATISTICAL PARAMETERS OF GRAIN SIZE

A large number of attempts have been made to introduce an objective approach to the comparison and interpretation of grain size frequency distributions by means of statistics. The main aim of these statistics is to summarize the characteristics of the various size frequency distributions, and the development of such statistics necessarily follows and depends upon the selected graphic procedures. There are two basic methods of obtaining statistical parameters. The more common of these methods involves plotting the cumulative curve of the sample and reading the diameter represented by the various cumulative percentages. The alternative method, the method of moments, is more complicated mathematically and is probably no more valuable than the best of the graphic methods.

The method of moments is a computational method in which every grain of the sediment affects the measure. The method is severely limited in "open-ended" distributions, such as are obtained from mechanical sieving, when there is a certain amount of material of undetermined size in the base pan. If the mud fraction is not analysed it is necessary to make an arbitrary assumption with respect to the grain size of the fines. The assumption most often quoted in the literature is that all material finer than 4ϕ is considered to be centred upon 10ϕ (for example: Folk, 1966). McCammon (1962a) noted that "The low-order moments of a size frequency distribution do not necessarily characterize its shape.

They may yield values which are misleading with respect to the geometrical properties of the distribution." Irregularly-sized sieves lead to considerable errors in the calculation of the third and fourth moments. In the calculation it is assumed that the particles within a given class interval have a centre of gravity on the half-way mark of that class. This last assumption is erroneous, especially when the relatively wide sieve intervals used in the present study are considered. For these reasons it was decided to use the graphic methods rather than the method of moments.

CENTRAL TENDENCY. The measure of central tendency most often used in early work was the median diameter (for example; Trask, 1930). This is the 50 per cent value on the cumulative curve and defines the size separating the sample into two equal halves by weight. The disadvantage of the use of the median is that it is not affected by the extremes of the curve. It takes no account of the distribution on either side of the 50 per cent mark. For bimodal sediments it is almost useless.

The mode is defined as the most frequently occurring grain diameter. It is found by locating the steepest slope on the arithmetic ordinate cumulative curve or finding the grain size interval, say one-quarter ϕ or one-half ϕ , and, by successively shifting this across the cumulative curve, finding the grain size interval which includes the greatest percentage of grains. The mode is a useful measure in sediment genesis and transport studies, especially when there is more than one contributory source (for

example, Curray, 1960). However, the relatively tedious determination of the mode and its independence of the grain size of the rest of the sediment are disadvantages to its extensive use.

The method of expressing central tendency most often used nowadays is to use the mean value. If the sample has a symmetrical distribution the mean and the median are identical. If the sample is asymmetrically distributed, the mean will differ from the median. With reference to graphic analysis, Otto (1939) suggested $M\phi = (\phi_{16} + \phi_{84})/2$ as the mean value. This value was also used by Inman (1952) and introduces the use of percentile measures. The value chosen by Otto and by Inman was selected as it gave the value nearest to that obtained by other mathematical methods of analysis not using the cumulative curve. As the use of this graph is so much quicker than other methods, it is much more preferable, and is nearly as accurate.

Folk and Ward (1957) have shown that Inman's value for the mean provides a good result for curves which are fairly normally distributed. Inman's mean, however, is not satisfactory if the curves are strongly asymmetrical or bimodal in character and they suggested a modified value for the mean,

$$M_z = (\phi_{16} + \phi_{50} + \phi_{84}) / 3.$$

This value is suggested as each of the three percentiles taken gives a reasonable average for each third of the sample. M_z corresponds very closely to the mean as calculated by the method of moments. It is much superior to the median as it is based on three points and gives a better overall picture.

McCannon (1962b) has calculated the efficiencies of percentile measures for describing the mean size of a sedimentary particle distribution. He defines the efficiency of an unbiased estimate as the ratio of the minimum possible variance to the variance of the estimate (Table 4.1).

TABLE 4.1

Efficiencies of percentile measures of mean size according to
McCannon, 1962b

Mean size measure	Author (where applicable)	Efficiency (%)
$(\phi 16 + \phi 84) / 2$	Inman (1952)	74
$(\phi 25 + \phi 75) / 2$	-	81
$(\phi 16 + \phi 50 + \phi 84) / 3$	Folk & Ward(1957)	88
$(\phi 20 + \phi 50 + \phi 80) / 3$	McCannon (1962b)	88
$(\phi 10 + \phi 30 + \phi 50 + \phi 70 + \phi 90) / 5$	McCannon (1962b)	93
$(\phi 5 + \phi 15 + \phi 25 + \phi 35 + \phi 45 +$ $\phi 55 + \phi 65 + \phi 75 + \phi 85 + \phi 95)$ $/ 10$	McCannon (1962b)	97

To quote Griffiths (1967, p. 85), "It seems clear that additional manipulation of the statistics now in use in an attempt to obtain more satisfactory summaries of size frequency data will suffer from the law of diminished returns." The amount of work

necessary to increase efficiency from 88 per cent to 97 per cent seems to outweigh the advantage of an undoubtedly more accurate value. As mentioned earlier, Folk and Ward's measure corresponds closely to the mean calculated from the method of moments, a measure which is sensitive to the entire distribution and not just three, or even ten, percentile points.

SORTING. The degree of sorting in the sample is another important aspect of sediment analysis. In a descriptive sense the term may be used to indicate the degree of similarity, with respect to some particular characteristic, of the component parts in a mass of material. Sorting may also be defined in a genetic sense or in a statistical sense, but neither definition suits the purpose of the present work better than the descriptive definition of sorting. In a genetic sense the term may be applied to the dynamic process by which material having some particular characteristic, such as similar size, shape, specific gravity, or hydraulic value, is selected from a larger heterogeneous mass. Statistically, sorting may be defined as the spread of a distribution on either side of an average.

There have been a number of attempts to define sorting quantitatively. Udden (1914) used the ratio between successive classes on a histogram as well as the total spread of the histogram in an attempt to define sorting. Van Orstrand (1925) used the standard deviation in millimetres, while Hatch and Choate (1929) gave a graphic approximation to the standard deviation as Mm_{84}/Mm_{50} . This latter method is only applicable to normal, hence symmetrical,

curves, which are in fact rarely found.

Trask (1930, 1932) put forward the measure which was used almost exclusively from the time of its inception for almost thirty years. The Trask Sorting Coefficient is used only with millimetre values and is given by the formula

$$S_o = \sqrt{\text{Mm}75 / \text{Mm}25} .$$

This can be expressed as $S_o = \sqrt{Q_3/Q_1}$, where Q_1 represents the lower quartile (the 25th percentile on the millimetre scale) and Q_3 the upper quartile (the 75th percentile). This measures only the sorting in the central part of the curve, and has been abandoned almost entirely. A recent example of its use is a paper by Mansikkaniemi (1970), who defines sorting as $S_o = \sqrt{Q_3/Q_1}$, and later in the same paper refers to this same ratio as D_o , the "Dispersion Coefficient." Krumbein (1934) defined the phi quartile deviation $QD\phi = (\phi_{75} - \phi_{25})/2$. This is the exact analogue of S_o but adapted to the phi scale.

On a normal curve, about two-thirds of the sample lies between the values given by one standard deviation on each side of the mean. Accordingly, Inman (1952) suggested the Graphic Standard Deviation, given by the formula

$$\sigma_G = (\phi_{84} - \phi_{16}) / 2.$$

This measure is very close to the standard deviation as computed statistically, but is obtained simply by reading two values on the cumulative curve instead of a lengthy calculation. The graphic standard deviation embraces the central 68 per cent of the distribution, but still ignores about one-third of the sample at the extremities of

grain size. Folk and Ward (1957) therefore introduced the Inclusive Graphic Standard Deviation, given by the formula

$$\sigma_I = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6} .$$

This formula covers 90 per cent of the distribution and is the average of the standard deviation computed from ϕ_{84} and ϕ_{16} , representing $\pm 1\sigma$; and ϕ_{95} and ϕ_5 , representing $\pm 1.65\sigma$. The standard deviation according to this formula is a measure of the spread in phi units of the sample, therefore the symbol ϕ must always be attached to the value for σ_I .

Folk and Ward (1957) suggested a verbal scale of sorting as shown below (Table 4.2). The best sorting attained by natural sediments is about 0.2ϕ to 0.25ϕ on this scale. Poorest sorting is found in glacial tills, mudflows and similar heterogeneous deposits where σ_I values of 5ϕ up to 10ϕ are common.

TABLE 4.2

Scale of sorting classification (Folk & Ward, 1957)

ϕ values of σ_I	Verbal scale
under 0.35ϕ	Very well sorted
$0.35\phi - 0.50\phi$	Well sorted
$0.50\phi - 0.71\phi$	Moderately well sorted
$0.71\phi - 1.0\phi$	Moderately sorted
$1.0\phi - 2.0\phi$	Poorly sorted
$2.0\phi - 4.0\phi$	Very poorly sorted
over 4.0ϕ	Extremely poorly sorted

It should be noted that sorting depends to a certain extent on the grain size of the material and is likely to be better in sand than in coarser material. However, sorting deteriorates for very fine material and a statement of the degree of sorting may be misleading unless two materials of the same general size are compared. This will be dealt with more fully in a later chapter.

McCannon (1962b) discussed the efficiency of graphic measures of estimating sorting and came to the conclusions set out in Table 4.3 below. As with McCannon's proposed mean size measures,

TABLE 4.3

Efficiency of graphic sorting measures according to McCannon, 1962b

Graphic sorting measure	Author (where applicable)	Efficiency (%)
$(\phi_{75} - \phi_{25}) / 1.35$	Krumbein (1934)	37
$(\phi_{84} - \phi_{16}) / 2$	Inman (1952)	54
$(\phi_{95} - \phi_5) / 3.3$	-	64
$(\phi_{84} - \phi_{16})/4 + (\phi_{95} - \phi_5) / 6.6$	Folk & Ward (1957)	79
$(\phi_{85} + \phi_{95} - \phi_5 - \phi_{15})/5.4$	McCannon (1962b)	79
$(\phi_{70} + \phi_{80} + \phi_{90} + \phi_{97} - \phi_3 - \phi_{10} - \phi_{20} - \phi_{30}) / 9.1$	McCannon (1962b)	87

the extra efficiency obtained by using his more complicated measures is outweighed by the increased work required to calculate them.

Furthermore, the open-ended nature of the distributions dealt with in the present study make the use of the 3rd and 97th percentiles virtually meaningless in the majority of cases.

SKWNESS. Curves may be similar in mean size and in degree of sorting, but may differ considerably in degree of symmetry. Symmetrical curves have the mean equal to the median, and have zero skewness. Positive skewness occurs if the size distribution is skewed towards the higher phi values and there is excess fine material. If skewness is negative, then there is a preponderance of coarser material and the mean is less than the median.

Trask's measure of skewness is defined as

$$Sk = (Q_1 \times Q_3) / Md^2 ,$$

where Q_1 and Q_3 are the lower and upper quartiles respectively and Md is the median diameter in millimetres. This measure has similar disadvantages to Trask's sorting coefficient. Phi quartile skewness, analogously, is given by the formula

$$Sk_{q\phi} = (\phi_{25} + \phi_{75} - 2(Md\phi)) / 2 .$$

These measures consider only the skewness in the central part of the curve, and are relatively insensitive. They are also greatly affected by sorting so are not true measures of skewness. In two curves with the same amount of asymmetry, one with poor sorting will have a much higher quartile skewness than a well-sorted sample.

As a measure of graphic skewness, Inman put forward the formula

$$Sk_G = \frac{\phi_{16} + \phi_{84} - 2\phi_{50}}{\phi_{84} - \phi_{16}} .$$

This measures the displacement of the median, ϕ_{50} , from the mean,

the average of the ϕ_{16} and ϕ_{84} points, expressed as a fraction of the standard deviation. Thus the measure is geometrically independent of sorting. It is advisable to take some account of the tails of the curve also, as most skewness in fact occurs in the tails. Inman recommended a second skewness measure to accomplish this, given by

$$\alpha_{\phi} = \frac{\frac{1}{2}(\phi_5 + \phi_{95}) - Md\phi}{\sigma_{\phi}}$$

Folk and Ward combined these two formulae to give the Inclusive Graphic Skewness,

$$Sk_I = \frac{\phi_{16} + \phi_{84} - 2\phi_{50}}{2(\phi_{84} - \phi_{16})} + \frac{\phi_5 + \phi_{95} - 2\phi_{50}}{2(\phi_{95} - \phi_5)}$$

This is a pure number as measures of phi occur in both numerator and denominator. The mathematical limits of this formula are +1 to -1, but few natural curves exhibit a skewness greater or less than +0.8 and -0.8. Folk and Ward suggested the following verbal limits of skewness (Table 4.4).

TABLE 4.4

Verbal skewness classes (Folk & Ward, 1957)

Skewness	Class
+1.00 to +0.30	Strongly fine-skewed
+0.30 to +0.10	Fine-skewed
+0.10 to -0.10	Near-symmetrical
-0.10 to -0.30	Coarse-skewed
-0.30 to -1.00	Strongly coarse-skewed

A relationship has been demonstrated between skewness and size for bimodal sediments, giving a sinusoidal curve. The skewness is small if there is one mode or when the two modes present are nearly equal. As one or other of the modes increases relative to the other the skewness increases, the grain sizes involved determining the sign.

KURTOSIS. Kurtosis is a measure of peakedness, or degree of concentration of the sample. In the normal probability curve the phi diameter interval between the ϕ_5 and ϕ_{95} points is exactly 2.44 times the phi diameter interval between the ϕ_{25} and ϕ_{75} points. If the probability ordinate cumulative curve plots as a straight line this above ratio is obeyed, the sample is normally distributed, and kurtosis is normal. Departure from normality alters the kurtosis which in fact measures the ratio between the sorting in the tails of the curve and the sorting in the central portion. If the central portion is better sorted than the tails the curve is said to be excessively peaked, or leptokurtic. If, on the other hand, the tails are better sorted than the central portion, the curve is said to be platykurtic. Strongly platykurtic curves are often bimodal with subequal amounts of the two modes.

The kurtosis measure used in the present study is the Graphic Kurtosis of Folk and Ward (1957), and is given by

$$K_G = \frac{\phi_{95} - \phi_5}{2.44(\phi_{75} - \phi_{25})}$$

Kurtosis according to this formula is a pure number. K_G seems to

reach a maximum value of about 8.0 under natural conditions. The mathematical minimum is 0.41, but most samples fall within the range from 0.60 to 5.0. The following verbal limits are suggested by Folk and Ward (Table 4.5).

TABLE 4.5

Verbal kurtosis limits (Folk & Ward, 1957)

Kurtosis	Class
K_G under 0.67	Very platykurtic
0.67 - 0.90	Platykurtic
0.90 - 1.11	Mesokurtic
1.11 - 1.50	Leptokurtic
1.50 - 3.00	Very leptokurtic
K_G over 3.00	Extremely leptokurtic

The distribution of K_G values in natural sediments is itself strongly skewed since most sediments have values around 0.85 to 1.4. Values as high as 3 or 4 are common, however. Thus for any statistical analysis of kurtosis itself, for example finding mean or standard deviation of kurtosis, the kurtosis distribution must be normalized by using the transformation $K_G / (1 + K_G)$.

SUMMARY. In summary, the statistical parameters of grain size used in the present study are those developed by Folk and Ward (1957). These are:-

mean,

$$M_z = (\phi 16 + \phi 50 + \phi 84)/3 \quad ;$$

inclusive graphic
standard deviation,

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

inclusive graphic
skewness,

$$Sk_I = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)} \quad ;$$

graphic kurtosis,

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

CHAPTER 5. THE BEDSHIEL ESKER : A CASE STUDY

The properties of clastic grains are generally very sensitive to the nature of and variations in geomorphic environments, often much more so than the landforms themselves. In other words, measures such as sphericity, roundness and shape ought to reveal different modes of sedimentation and different directions of sedimentation. It was decided to test these measures at a relatively small scale of operations to determine whether or not trends of sphericity and roundness were reflected in direction of sedimentation. The esker at Bedshiel, Berwickshire, seemed to offer an ideal situation in which to make a case study. Isolating one particular feature in this way enables mode of sedimentation to be assumed constant for all practical purposes. The esker under consideration is located some 4 kilometres north of Greenlaw. The grid coordinates of its extremities are NT 678 504 and NT 707 513 (O.S. 1" Sheet 63 - DUNBAR).

SITUATION DESCRIPTION

The feature is almost continuous throughout its length of approximately 4 kilometres. There are five major breaks in the feature, some of which are almost certainly post-depositional, a fact which will be discussed fully later in the present chapter. It is a steep-sided ridge ranging in height from about 3 metres to 15 metres above the surrounding land surface. Slopes of the sides are commonly at 30° to the horizontal and exceptionally may

exceed 45° . Slopes are invariably symmetrical on either side of the feature at any given point. The crest-line undulates, but the entire feature is at approximately 210 metres O.D. throughout its length. Many rounded pebbles can be seen in exposures on the slopes, almost entirely of local origin. There would appear to be rude stratification of reddish sands, but this was not clear from the exposures available at the time of the fieldwork. In general form, there can be no doubt that the feature is in fact an esker. The points noted above are typical of eskers, as summarised by Flint (1928). The fact that eskers are composed of bed-rock material found locally was proved conclusively by Hellaakoski (1931) in his study of the Laitila esker in southwest Finland. Hellaakoski noted that pebbles in the esker had clearly been derived from the till underlying the area and on the average had travelled approximately 4 kilometres in a distal direction.

The Bedshiel esker is situated in a shallow basin area just off the main "Merse" area of the lower Tweed Basin. This first-mentioned basin is bounded by intrusive hills of felsite to the north (Dirrington Little Law, Dirrington Great Law and Blacksmill Hill) and to the east (Kyles Hill). These intrusions are of Lower Old Red Sandstone age. To the south, the basin is bounded by porphyritic extrusions of ages ranging from Upper Old Red Sandstone to Early Carboniferous. These lavas are expressed in the conical hill at Hallyburton and in larger linear masses eastwards from Hexpath and northeastwards from Greenlaw. A low watershed separates the basin from lower ground to the west. The watershed occurs near the site of Westruther (Fig. 5.1).

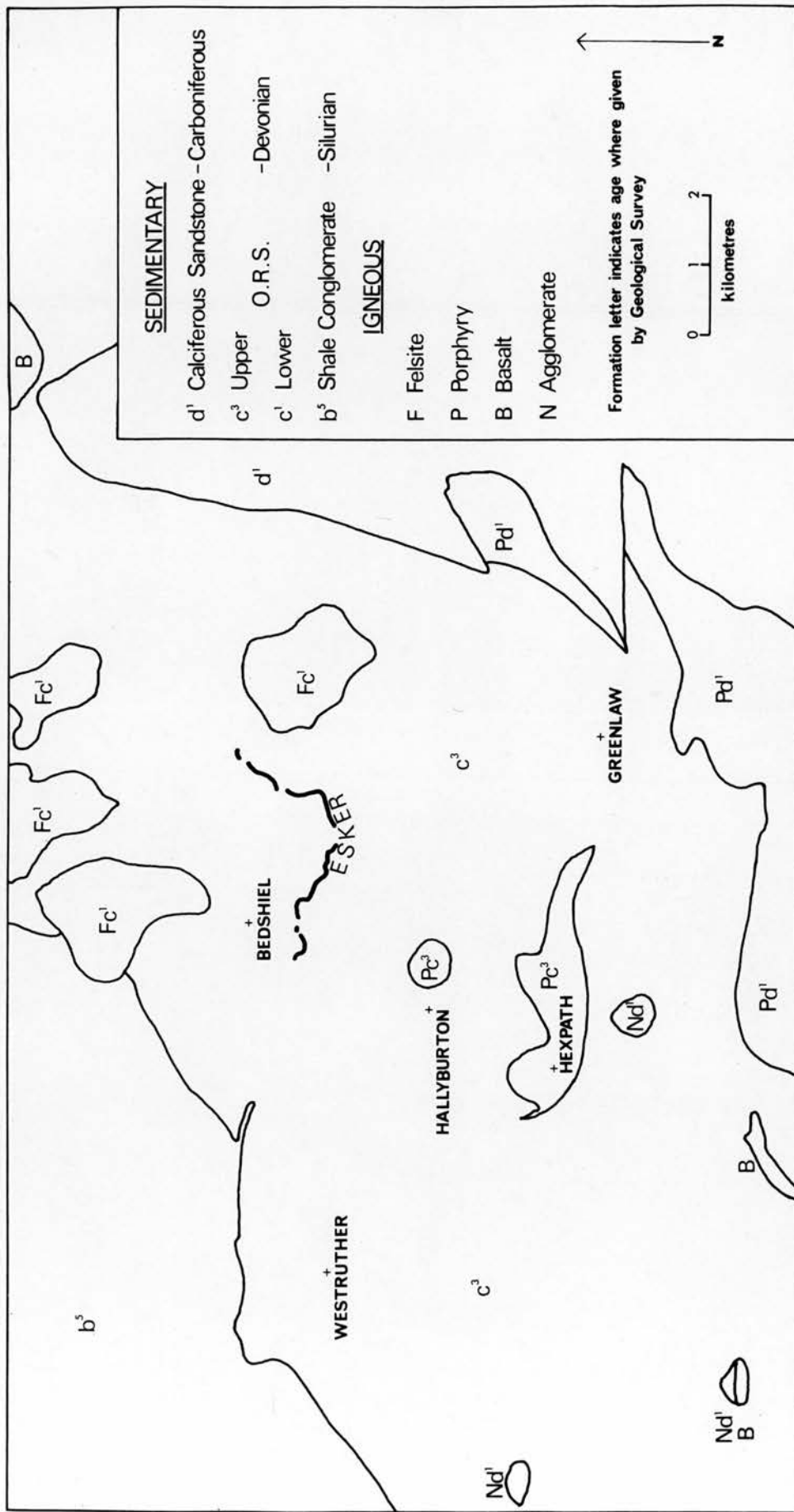


Figure 5.1. Simplified geology of Bedshiel area

The rock underlying the basin is Upper Old Red Sandstone in age, consisting of interbedded conglomerates, red sandstones and marls. Bedding is almost horizontal throughout the area. To the northwest lie Silurian greywackes and shales, while Lower Carboniferous calciferous sandstones occur to the east (Macgregor, 1938).

PREVIOUS LITERATURE

The so-called "Bedshiel Kaims" were first mentioned in the literature by Stevenson in 1864. Stevenson postulated a submarine origin when the sea stood relatively 210 metres higher than at present. This was in tune with theories of marine submergence current at that time. He noted that sand predominated, at the east, and gravel at the west, end of the feature, the gravel having been derived from the Devonian and Silurian rocks to west and northwest. Stratification was said to be "... very irregular and frequently inclined at various angles" (Stevenson, 1864, p.124). Stevenson found no organic remains. He noted a concordance in height above sea level between the "Kaims" and similar ridges at Raecleuch Head some 4 kilometres to the north-east, and also with the "Cammerlaws Knoll" and nearby "Kaims" 2 kilometres to the west. Similar ridges near Duns to the east and Earlston and West Morriston to the southwest were also mentioned as having summits at 210 metres O.D. He found pebbles of greywacke, porphyry and sandstone, all derived from rocks seen

in situ to the west, and many pebbles of quartz "... apparently of Grampian origin", in an excavation near West Murrison.

Goodchild later hypothesised that the feature originated from debris washed into crevasses in ice (Goodchild, 1898). He envisaged material working its way up through the ice to the surface prior to being deposited as an esker form via surface washing. He recognised this feature as an esker, the term "esker" having first been used to describe such features by Close (1867) in Ireland.

Carr (1937) subsequently proposed two separate sheets of ice, "... side by side on land sloping towards each other and each discharging the debris it is carrying into the crevasse between them." He interpreted layers of fine sand as representing deposition at times when the crevasse had been full of water. He noted no clay in or on the esker, suggesting that the esker had been formed later than the till blanketing the area. A lack of clay in component material was one of the characteristics noted by Flint (1928) as being typical of esker deposits. Carr concluded that the Bedshiel esker represented "... low-country evidence of a recurrence of Arctic conditions after the glaciers had left the low lands."

More recently Ragg (1960) mapped the extensive area of Brown Forest soils developed upon the large accumulations of fluvioglacial sands and gravels to the west and southwest of the esker. The boundaries of his "Eckford" and "Hexpath" associations agree closely with fluvioglacial deposition as mapped in the present study.

In summary, Stevenson's early, and excellent, description of the Bedshiel esker postulated a marine origin of the feature. Goodchild first recognised that the feature was in fact an esker and envisaged an origin via surface washing of material into crevasses in the ice which was present. Carr's later paper added little to the excellence of Stevenson's description or to Goodchild's suggestion of formation in a crevasse in the ice. At no time was a subglacial origin invoked. What is more surprising is that there is no mention in the literature of the substantial meltwater channel system found in the immediate vicinity of the Bedshiel esker.

PRIMARY INVESTIGATION

Initially, samples were taken from each end of the esker and compared for sphericity and roundness of pebble grade. At the west end of the esker 41 sandstone and 39 greywacke pebbles were found in the 100 selected pebbles. At the east end, the corresponding numbers were 39 and 43. Values of average sphericity and roundness are tabulated below (Table 5.1).

TABLE 5.1

Average sphericity and roundness values of preliminary
Bedshiel esker samples

	Average Sphericity		Average Roundness	
	West	East	West	East
Greywackes	0.661	0.643	0.677	0.589
Sandstones	0.634	0.689	0.572	0.464

The results for average roundness showed a substantial difference between the two points, the values at the east end of the esker being substantially less than those at the west end. These preliminary results would seem to indicate an east-to-west direction for the formation of the esker, as roundness increases theoretically with increased distance of travel. The much higher sphericity of sandstones at the east end than at the west end seems to support an east-to-west origin. The difference in greywacke sphericity values is not large enough to be significant. While no conclusions could be drawn from values obtained at only two sample points, a substantial difference in values, at least of average roundness, was found.

It was decided, on the basis of these preliminary results, to sample throughout the length of the esker. Samples of about 10 kilograms were taken from a further eight points along the length of the esker. Distances between sample points varied from 300 metres up to 700 metres, according to whether sites deemed to be suitable for sampling were found at the end of each 100 metres from the previous sample site, with a minimum distance between samples of 300 metres. Samples were taken from suitable cuttings on the sides of the esker, where slumping had provided a small cut. The sample was taken after digging in a horizontal distance of about one metre. It was reasoned that even such slumped material would provide a valid sample, as the distance of slump downslope at any site was always negligible compared to the distance the particles had travelled to reach that site from their previous resting position in till or point of release from bedrock.

Tabulated below are the distances between sample sites (Table 5.2) and the lithologies encountered in the 100 pebbles selected from each site (Table 5.3).

TABLE 5.2

Distances between Bedshiel esker sample sites

Sample Number	Distance to next sample (metres) (From east to west)
El. 1	0
El. 5	400
El. 6	300
El. 7	500
El. 8	500
El. 9	700
El. 10	500
El. 11	500
El. 4	400
El. 3	300

From the values of average sphericity and roundness of sandstone and greywacke pebbles for the ten sites taken, graphs of sphericity and roundness against distance were drawn (Fig. 5.2 and Fig. 5.3). A plot of the percentages of sandstone and greywacke pebbles selected as they vary along the length of the esker was also drawn (Fig. 5.4).

TABLE 5.3

Lithological analysis of Bedshiel esker samples

Sample Number	Rock Type (percentage)							Unidentified	
	Sandstone	Greywacke	Siltstone	Felsite	Porphyry	Quartz	Mudstone		Basalt
EL. 1	39	43	10	0	1	2	1	0	4
EL. 5	14	66	9	3	1	3	0	0	4
EL. 6	23	60	8	3	3	1	1	0	1
EL. 7	30	54	12	0	0	1	2	0	1
EL. 8	21	51	10	3	4	0	1	0	10
EL. 9	36	50	5	3	1	1	1	0	3
EL. 10	34	50	12	0	0	3	0	0	1
EL. 11	26	57	12	2	0	0	1	0	2
EL. 4	47	39	8	0	0	0	1	0	5
EL. 3	41	39	4	1	2	0	4	2	7
Average Percentages	31.1	50.9	9.0	1.5	1.2	1.1	1.2	0.2	3.8

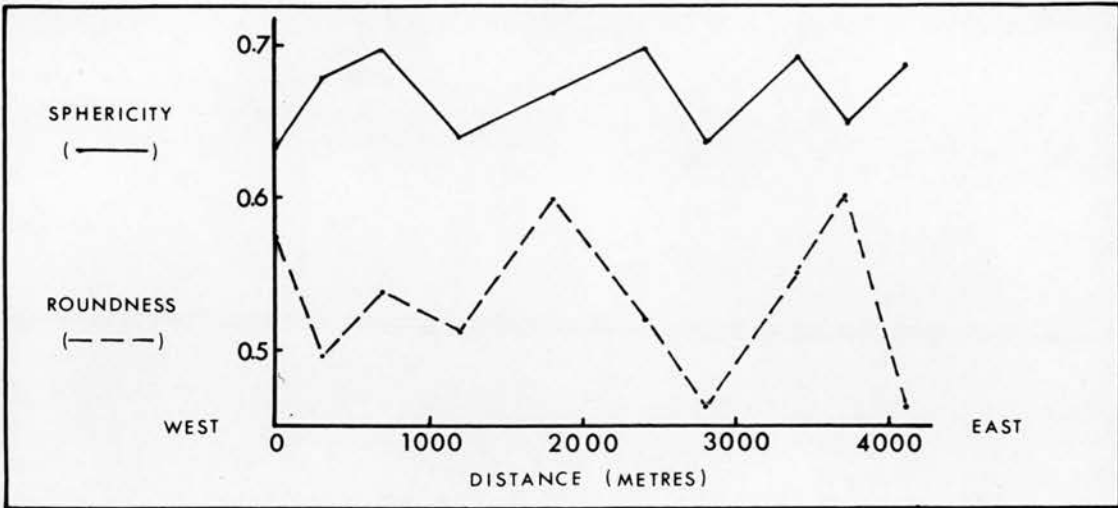


FIGURE 5.2. Distance versus sphericity and roundness of Bedshiel esker sandstone samples

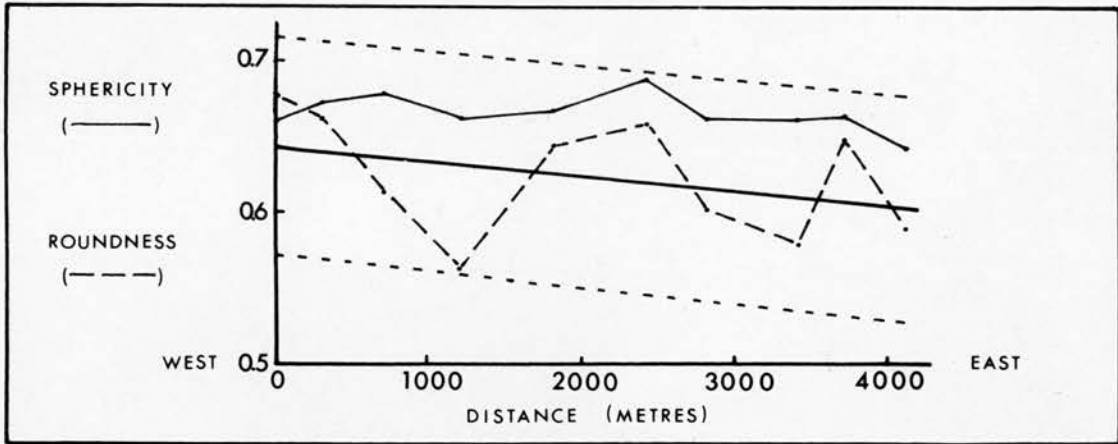


FIGURE 5.3. Distance versus sphericity and roundness of Bedshiel esker greywacke samples

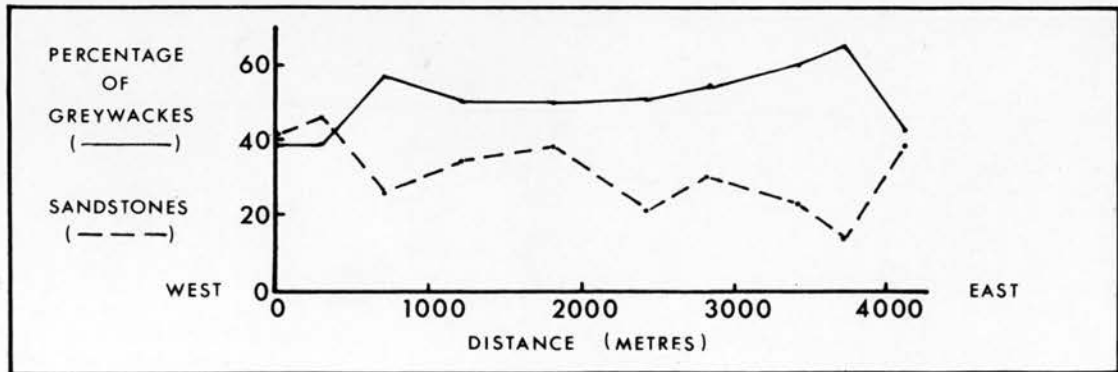


FIGURE 5.4. Varying percentages of greywackes and sandstones in Bedshiel esker samples. See also Table 5.3

Figure 5.2 shows that the values of average roundness of sandstone pebbles fluctuate with no apparent trend. Sphericity values also fluctuate, and again there is no apparent trend. Figure 5.3 seems to show an overall decrease in both sphericity and roundness of greywacke pebbles over the length of the esker, from west to east. As increasing roundness indicates further fluvial travel, this would mean, in the case of roundness, that the esker was in fact laid down from east to west. A decrease in sphericity from west to east corresponds to further fluvial transport and indicates a west-to-east formation. These facts would seem, at first sight, to indicate a basic contradiction, but in fact no statistical weight can be attached to the results here presented. This can be shown by the regression line drawn through the greywacke roundness values. The 95 per cent confidence limits are so wide as to make any interpretation statistically meaningless.

It may be noted at this stage, with reference to Figure 5.4, that a study of the relative proportions of greywacke and sandstone pebbles selected from each site suggests that, while the proportion of greywackes rises more or less continuously from west to east, the proportion of sandstones drops in that direction. The proportions selected from the sample at the extreme east end of the esker would seem to be anomalous in this respect. The general trend would seem to suggest a west-to-east formation for the esker, as one would expect the softer sandstone pebbles to be more quickly worn than the relatively harder greywackes. This

would result in a decrease in the number of sandstone pebbles with long axis lengths over 20 millimetres, in a downstream direction. Hence there would be a greater probability of selecting greywacke pebbles that are more resistant to wear.

As sandstone is the local bedrock, sandstone pebbles in the esker cannot be far-travelled. For this reason, and as it is a relatively soft rock, it would be reasonable to expect that sandstone pebbles would exhibit a noticeable increase in roundness value in a downstream direction. This is not the case with the set of samples taken as described above.

There are two possible conclusions from these preliminary investigations, namely, either the trend indicated by roundness of greywacke pebbles is correct but the tests are too crude at this scale of operations, or the trend indicated is incorrect and the sampling scheme is inadequate.

FIELD MAPPING OF ADJACENT LANDFORMS

To test the latter hypothesis, it was decided to map the district including and surrounding the Bedshiel esker, paying particular attention to the fluvio-glacial landforms. The field mapping was carried out at the scale of 1:25,000 after preliminary study of aerial photographs of the area at a scale of about 1:10,000. From the photographs, any fluvio-glacial features noted were sketched onto the 1:25,000 map by use of a Zeiss Aero-Sketchmaster. The sketch map was then checked in the field and a map of fluvio-glacial landforms drawn up (Fig. 5.5).

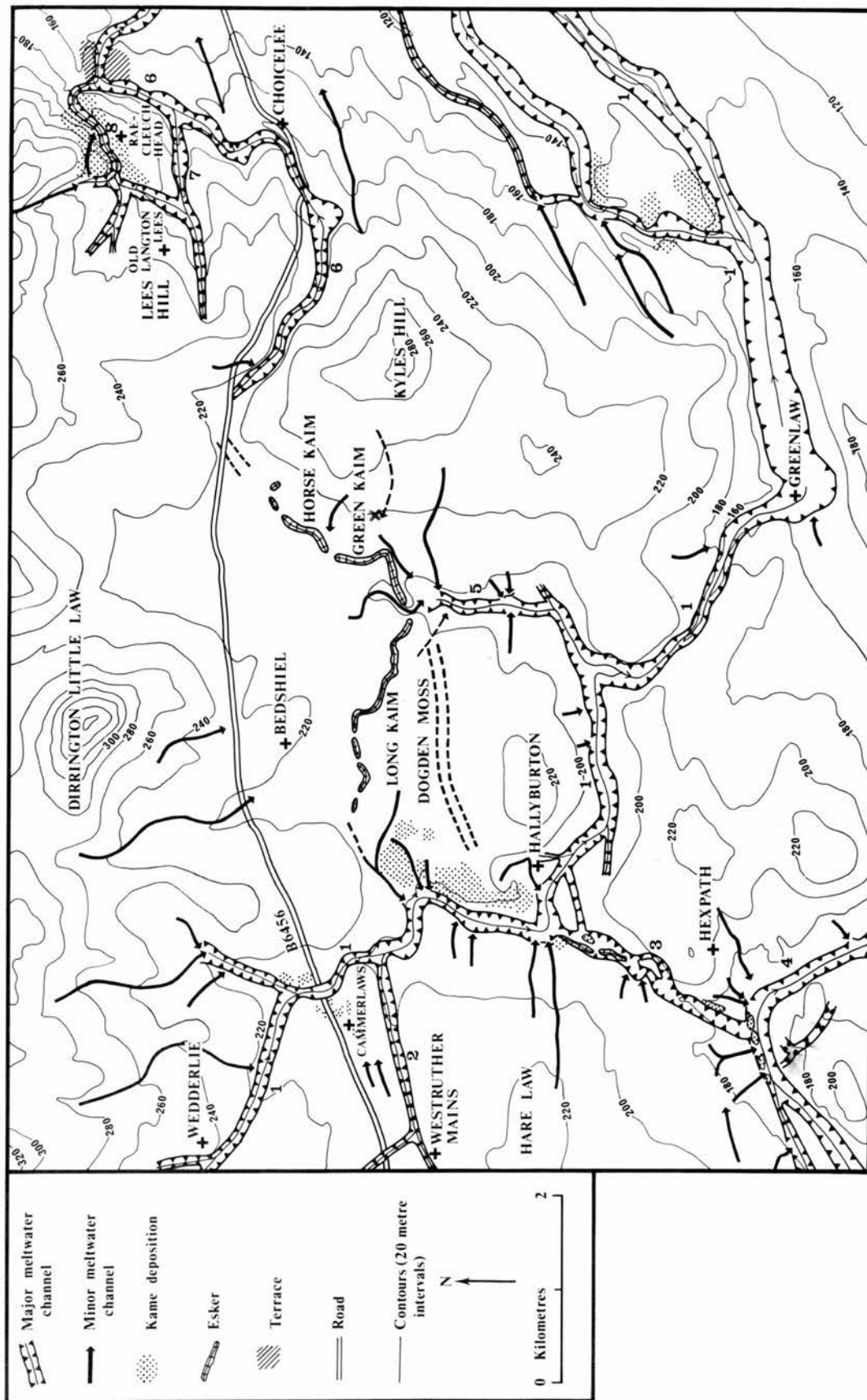


FIGURE 5.5. Fluvio-glacial features of the Bedshiel area

There is a well-developed meltwater channel system present in the area, as can be seen from Figure 5.5. The main channels have been numbered to facilitate description. That such a system of glacial drainage channels almost certainly would have been formed subglacially has been demonstrated in Scandinavian work done by Mannerfelt (1945), Ström (1945) and others.

A number of early workers in the field of glacial drainage phenomena followed Kendall's (1902) assumption that many channels in the Cleveland Hills had been formed by the overflowing waters of ice-dammed lakes, and that meltwaters rarely, if ever, flowed under, over or through the ice. Sissons (1960 and 1961a) recognised the importance of Mannerfelt's theories of subglacial drainage in the context of Highland Britain. He noted that several factors give lie to Kendall's hypothesis. The rarity of shoreline features in Highland Britain would seem to indicate that large numbers of lakes did not in fact exist in late-glacial times. This conclusion is strengthened by the general absence of lacustrine features. One would expect delta formations at channel exits if channels debouched into ice-dammed lakes. Carruthers (1939) interpreted certain banded deposits as subglacial "bottom-melt" rather than lake-floor deposits. Downwashing of ice in situ during deglaciation would have led to the emergence of many nunataks. Where nunataks developed, the ice must have escaped supraglacially, englacially or subglacially. Many channels with an "up-and-down" long-profile are difficult to explain by Kendall's suggestion of reversal of meltwater flow. Such channels are

invariably continuous features throughout their lengths, suggesting a unidirectional water flow. Water can only flow uphill under hydrostatic pressure, therefore up-and-down channels could only have been cut by subglacial water.

The absence of channels in some locations is significant. If Kendall's hypothesis of subaerial channel formation is followed, it follows that on every spur down which the ice-margin retreated, a continuous parallel series of channels would have been formed. These channels would have been successively excavated as the next higher one was abandoned. Such ideal sequences are found, but rarely. More often, large gaps in such sequences are common, with no visible channels. This presents no problem once drainage into the ice is assumed. Further considerations such as channels on "reverse" slopes and on minor summits on spur crests, some aspects of col channels, and evidence from modern glaciers suggest that Kendall's concept of glacial ice forming an impenetrable barrier to meltwater was in fact erroneous in almost every case. The "parallel roads" of Glen Roy and adjacent glens provide an outstanding exception to this general rule.

Sissons (1960) also stressed the importance of downwasting, as opposed to backwasting, of continental ice-sheets. With the amelioration of climate accompanying deglaciation phases, "we may ... envisage the ice surface as a very gently inclined plane that was lowered onto the irregular land surface buried beneath" (Sissons, 1967, p.101). Ice became stagnant, as the emergence of nunatak areas cut off the source of supply, in lowland areas

such as the Tweed Basin. The meltwaters released by decaying ice were able to escape downslope, marginally to large blocks of ice, or through or under the rotten ice masses. That ice was stagnant, or nearly so, in lowland areas during deglaciation is demonstrated by the relative freshness of erosional and depositional features in recently deglaciated areas.

In the context of the Tweed Basin, a large stagnant ice mass centred on The Merse to the south and east of the site of Greenlaw can be envisaged. Marginal channels would be expected along the lower slopes of the Lammermuirs in this area, but none are found. This immediately suggests drainage through or under the ice in a southeasterly or easterly direction towards lower ground.

That drainage was in fact under the ice is suggested by the small esker on the floor of the north-south channel from Hallyburton to Hexpath (channel 3). The channel must have been cut before the esker was formed. At the northern end of channel 3 a mass of fluvioglacial material constricts the opening of the channel. The floor of this connecting channel is some 5 metres above the floor of the main channel (channel 1), through which the present-day Blackadder Water runs. The esker runs along the west flank of channel 3, leading directly from the constricting mass of fluvioglacial material. Both fluvioglacial material and esker must therefore be subglacial. One section in the esker parallel to the channel length (at NT 663 482) shows subrounded pebbles, commonly up to 15 centimetres long axis length, exceptionally 30 centimetres long, in a reddish sandy matrix. Bedding is

distinct in the section, but the strata have slumped and the dip of the bedding is not significant.

The esker tails off southwards from a maximum height of 10 metres down to about 2 to 3 metres. The bed of the channel has an up-and-down profile, rising southwards at first, then starting to fall towards the south at the point where the esker terminates. This up-and-down profile is further evidence of a subglacial origin, having been formed by waters forced to flow uphill due to hydrostatic pressure.

The main channel in this part of the Tweed drainage basin is that now occupied by the Blackadder Water (channel 1). This is a substantial channel throughout the 13 kilometres from its origin to the northwest of Wedderlie (NT 643 519) to Greenlaw (NT 710 460). Cut through horizontally-bedded sandstones after the first 4 kilometres of its course, it reaches a maximum depth of approximately 50 metres south of the junction with channel 5 at NT 693 481. It continues for some distance beyond Greenlaw in a northeasterly direction, parallel with the axis of The Merse.

Channel 1 descends from Wedderlie in a broad, shallow valley some 200 metres wide and between 10 and 15 metres deep. It appears to cut through the till which blankets the hill slopes in this area, and its edges are indefinite. Channel 1 takes a southward right angle bend just north of Cammerlaws (at NT 658 512). There is a short channel section joining channel 1 from the north at this bend, but many small channels indenting the hillside suggest a collection area here, emphasised by the broad basin a few hundred

metres to the north. Two large knolls occur at the bend, exposures showing stratified reddish sand with occasional thin beds of small gravels. These kames are at about 210 metres O.D., as are the elongated mounds at Cammerlaws a short distance to the south. The B6456 road crosses an undulating elongated kame. Similar elongated mounds running east-west through the site of Cammerlaws farm appear to be associated with two small parallel channels to the west. In general form and location these may be short esker sections. The evidence, however, is not conclusive.

Parallel with these last-mentioned channels, a major channel joins the Blackadder system a few hundred metres to the south (channel 2). This channel, which extends from beyond Westruther Mains (NT 643 496), is remarkably straight in plan. It varies between 50 and 100 metres wide and is approximately 10 metres deep throughout its length. The south bank is noticeably steeper than the north, and appears to have been cut through a red till.

South of the line of the B6456 road, channel 1 is entrained in a rock-cut gorge some 50 metres wide at the base with 20 metre high sides. The gorge is cut through horizontally-bedded sandstones. This gorge opens out where the channel takes a sharp southward bend. The main channel is about 100 metres wide southwards from this point, being about 20 to 30 metres deep with 30° to 60° sides and a notably flat bottom. Numerous small channels join the main drainage line from the area of Hare Law throughout the kilometre length during which the main channel runs due south. Massive fluvioglacial deposition has taken place at 210 metres O.D. along the east bank of channel 1 in this section of its course.

If one is looking for possible westward extensions of the Bedshiel esker system, the area round NT 670 500 is critical. Two small channels lead off from the area of Dogden Moss towards this point. The more northerly of these is relatively small, 50 metres across at the widest and rarely more than 5 metres deep. The channel is very shallow by the time it is traced back to the level of the surface of Dogden Moss, although reeds suggest a marsh infill. The channel finally becomes lost in heath moor about 800 metres from the end of the esker. The more southerly channel is a shallow depression, only a few metres at its deepest and again soon lost in heath moor. Where these two channels coalesced their combined flow was sufficient to excavate a relatively deep channel, apparently through the fluvioglacial deposits. This channel dips steeply to the level of the floor of channel 1. This suggests that these two small channels drained the area of Dogden Moss after deposition of the fluvioglacial material on the east bank of channel 1, and are most likely connected with a very late stage of deglaciation.

A further shallow depression runs across Dogden Moss under the peat. This was found by construction of a bottom contour map from information on depth of peat surveyed by the Scottish Peat Commission (Department of Agriculture and Fisheries for Scotland, 1961). This relatively long (2 kilometres) channel running parallel with the immediate contour of the land indicates that water ran along the slope. It could therefore have a marginal or submarginal origin.

There is therefore no direct esker-meltwater channel link at the west end of the Bedshiel esker. The upper Blackadder channel towards Wedderlie and the channel extending towards Westruther Mains are approximately in line with the west end of the esker, but higher ground intervenes.

The fluvioglacial deposits between channel 1 and Dogden Moss suggest a sudden checking of the velocity of the water in channel 1, perhaps caused by ice blocking the exit to the south. This could have caused large quantities of meltwaters to have been forced uphill under hydrostatic pressure and on to the Dogden Moss area. Dissipation of energy during this phase would have caused a lowering of carrying capacity of the meltwaters, and esker deposition may have commenced in a tunnel at or near the base of the ice. The esker in channel 3 is at a lower altitude, approximately 190 metres O.D., and could have been formed by a similar process of exit blocking and subsequent diversion of meltwaters, but at a later stage of ice dissolution. This would coincide with a lower level of the englacial water table.

An alternative hypothesis can be put forward, namely, that channel 1 was not developed to the south of the level of the esker until after esker formation. Meltwaters initially coursed directly along the slope from channels 1 and 2, and only subsequently cut southward downslope. Channel 3 represents the second stage of drainage, after the esker had been abandoned due to a lessening of hydrostatic pressure in a downslope direction. Channel 3 was gradually abandoned as meltwaters found a lower course eastwards,

enlarging and extending channel 1. This hypothesis will be re-examined in the light of subsequent evidence.

About 1 kilometre to the east of the Bedshiel esker the channel occupied by Langton Burn is encountered (channel 6). This is a fairly substantial channel, being some 40 metres wide on its floor, having 30°- to 45°-sloping sides, and being approximately 15 to 20 metres deep. Exposures on valley sides and residual mounds in the channel bed show a poorly-consolidated conglomerate, many well-rounded pebbles in a matrix of coarse reddish sand. One section on the valley floor shows 2 metres thickness of conglomerate, grading both upwards and downwards into horizontally-bedded sandstone. On disaggregation, many of the contained pebbles, although stained, can be recognised as greywackes. Some local volcanic rocks are also found. Pebbles are extremely rounded and many are almost spherical. Large numbers of highly-rounded and highly-spherical pebbles are not found in the esker, which might suggest that the esker was laid down from west to east. If the subglacial water movement had been from east to west, then channel 6 would presumably have been excavated and large numbers of highly-rounded and highly-spherical pebbles released from the conglomerate would have been redeposited in the esker material, assuming contemporaneous esker formation.

Channel 6 swings eastward, then northward to join the system of channels descending from the area of Raecleuch Head (NT 744 532). A series of irregular conical mounds are encountered at 180 metres O.D. west of Choicelee (NT 747 513). A step on the 210 metre contour

suggests a terrace form, subsequently masked by fluvioglacial deposition as the channel extends only up to the 170 metre contour.

Channel 6 then swings northwards, in a channel about 60 to 80 metres wide at top, 12 metres deep, and 30 metres wide at bottom, until opposite Raecleuch Head farm. At that point, it bends sharply to the east. At this juncture the channel is constricted and is over 30 metres deep. A terrace flat approximately 200 metres long by 100 metres wide is seen to the north of the channel, and a similar flat can be seen to the south. The channel is steep-sided and appears to be related to a later stage of deglaciation as it dissects the terrace flat. Undulating topography with occasional marked mounds is seen looking eastwards towards Duns.

An interconnecting series of channels is found in the area between Lees Hill and the eastward bend in channel 6. Large masses of fluvioglacial material have been deposited at 210 metres O.D. in the vicinity of Raecleuch Head farm. A striking channel some 30 metres deep with 45° sides and a 30 metre-wide bed cuts through these masses of fluvioglacial material (channel 8). Exposures show mainly greywacke and sandstone pebbles up to 30 centimetres long axis length, in a fine red sandy matrix. Many shattered fragments are present. Upstream, three distinct channels converge. Presumably the convergence of the relatively large amounts of meltwater collected here caused initial deposition and the subsequent dissection. The connecting channel running north-south past Old Langtonlees farm (NT 734 525) is steep-sided with much evidence of postglacial slumping.

A substantial channel comes down off Camp Moor (channel 7). At the point where it bifurcates, it is about 200 to 250 metres wide and approximately 15 to 20 metres deep. The edges are indefinite. There are signs of slope washing and postglacial soil creep. Channel 7 gradually tapers out uphill until it becomes non-definable on the watershed. There are no traces of any channel to the west of the watershed. It is unlikely that channel 7 is an overflow for the waters which caused the esker formation.

The form of deposition at Raecleuch Head is similar to that north of Hallyburton (NT 672 486). Both seem to have been deposited, by waters moving in an easterly direction, against the west-facing slope of a projecting and constricting hill mass. There is no gradual build-up of deposition in either case, the west walls of the channels being considerably lower than the east walls. The coincidence of heights cannot be ignored, nor can the coincidence with height of esker deposition. The fact that all fluvioglacial deposition has taken place at 210 metres O.D. over a distance of 10 kilometres suggests that the Bedshiel esker is an integrated part of a much larger deglaciation phase during which drainage was subglacial and submarginal in the northern part of The Merse.

The exact relation between the Bedshiel esker and the channel system is complicated by the position of the channel occupied by the present Fangrist Burn (channel 5). This channel originates a few hundred metres to the south of one of the major breaks in the esker and could not have been cut by the relatively insignificant present-day stream. It is cut through horizontally-bedded sandstones,

to a depth of 15 to 20 metres, within 600 metres of the esker. A flat floor some 50 metres across is bounded by 45° slopes on either side. Channel 5, steep-sided throughout, deepens throughout its 2 kilometre length until its junction with channel 1. At this point the gorge of both channels is about 40 to 50 metres deep.

The similarity in size and form of channel 5 with channel 1 suggests that these channels were formed contemporaneously. Small channels on the slopes of Dirrington Little Law to the north suggest that the small basin to the north of the Bedshiel esker acted as a collection area for meltwaters which subsequently excavated channel 5. It is reasonable to assume that this channel was choked with ice at the same time as channel 1, this blocking being a suggested cause of esker formation and fluvioglacial deposition. Thus channel 5 could not have been utilised by meltwaters during esker formation, causing the esker to be extended eastwards and northwards towards the col at 210 metres O.D. between Lees Hill and Kyles Hill. In a later stage of deglaciation, this col would have been abandoned as channels 1 and 5 were reopened and meltwaters were drawn off via these lower outlets.

Water would have collected subglacially in the area between the esker and the channel (Fig. 5.6). The esker is 10 metres high at this point and summits are exactly concordant on each side of the gap. This suggests that the esker had been cut through after deposition rather than that the gap had occurred during esker formation. The breach in the esker is approximately 100 metres wide. A terrace flat just south of the base of the esker drops down abruptly to the channel bed a few metres lower. A small plunge

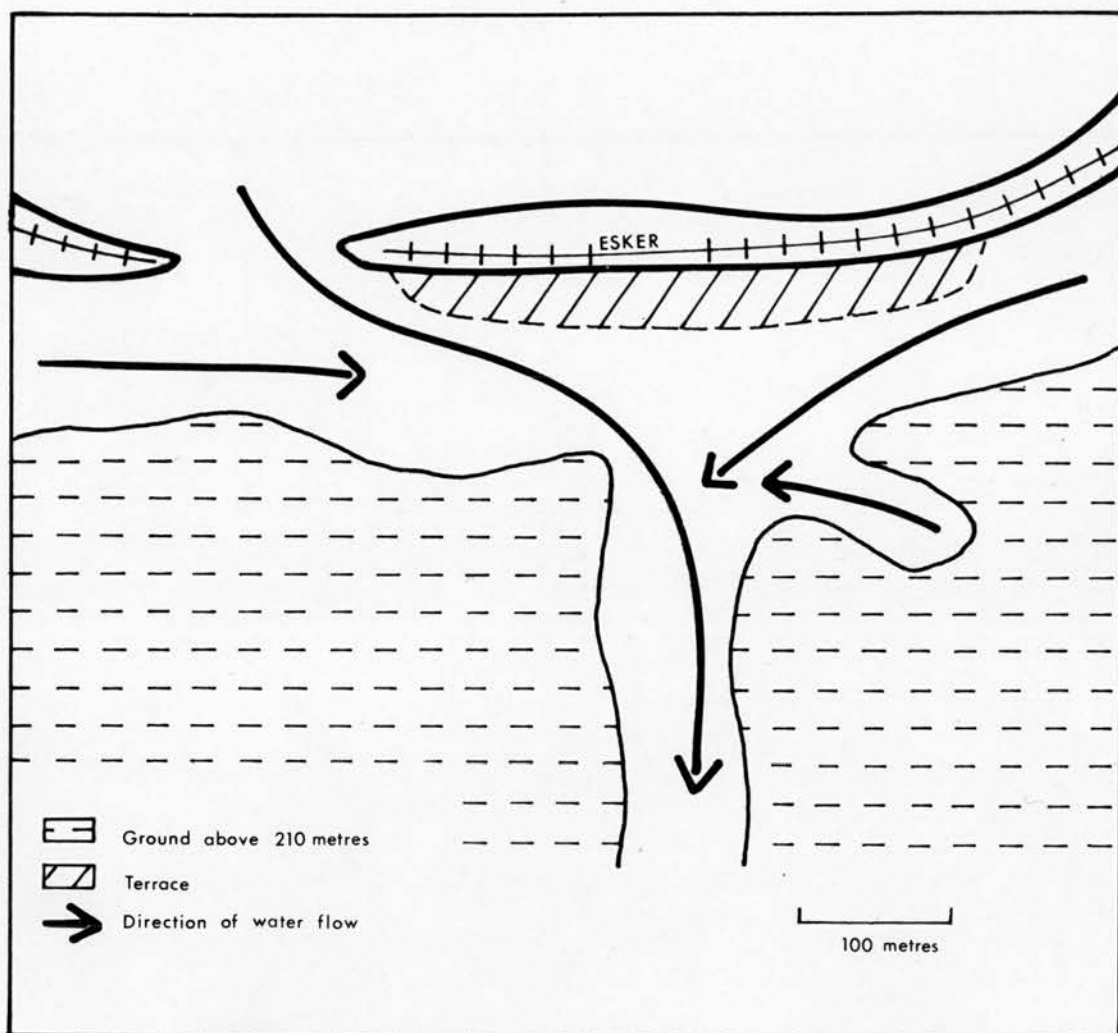


FIGURE 5.6. Detail of Bedshiel esker - Channel 5 formation

pool can be seen, emphasising the fact that water collection was likely here. Water collection would also have taken place to the north of the esker, a subglacial lake being formed until the esker was fully breached. The major break in the esker to the northeast, between Green Kaim and Horse Kaim, was most likely caused by breaching by meltwaters collecting from the slopes of Kyles Hill to the east. At this latter point, as with the Fangrist Burn breach, the esker summits are concordant on either side of the gap.

Numerous small channels on the slopes of Kyles Hill seem to support the suggestion that water collected subglacially to the north of, and was impounded by, the esker. Closer examination of material exposed by present-day stream cuts as examined at several cuttings confirms this. One particular section at point X serves to illustrate typical conditions. This section in a recently-gullied stream shows the top 1 metre to be of poorly-stratified fluvioglacial material. Below this is found a sand layer some 10 to 15 centimetres thick. Bedding dips upstream, against the slope of the land. Another section a few metres upstream shows sand with small gravel at the surface. No ablation debris was recognised above these deposits. This suggests ice melting in situ leading to sheet floods down the hill slopes, occasionally concentrated into shallow channels. This gave rise to collection of water subglacially on low ground leading to breaching at at least two points in the esker, followed by cutting of channel 5. As these wash deposits are found up to at least 230 metres O.D., it is reasonable to postulate an ice cover up to at least 240 to 250 metres O.D. during the period of formation of the

channel systems. In all probability, the thickness of ice present at that time would have been considerably greater.

SUMMARY OF CONCLUSIONS FROM FIELD MAPPING

Any conclusions to be drawn from the field mapping undertaken must be viewed in the context of a large, relatively stagnant mass of decaying glacial ice centred on The Merse to the south and east of the field area. Downwasting during deglaciation had led to this large mass of ice being cut off from active source areas to the west by the emergence of the Lammermuirs to the north and Ettrick Forest to the west as nunatak barriers. Drainage to the north of The Merse was essentially marginally or submarginally to the east, controlled by hydrostatic pressures within the decaying ice mass.

In the particular area under consideration, drainage appears to have been almost entirely subglacial. The main drainage line was that of channel 1, presently occupied by the Blackadder River. This channel runs essentially downslope as far as the site of Greenlaw, where it turns northeast, indicating a submarginal direction parallel to the long axis of The Merse. This can be interpreted as a response to hydrostatic pressure preventing further drainage in a downslope direction.

From the concordance of heights of fluvioglacial and esker deposition in the area it is reasonable to assume that the Bedshiel esker forms part of an integrated system of submarginal drainage. The initial esker deposition could have been triggered off in one of two ways. Either the lower reaches of channel 1 were not developed

and water from channels 1 and 2 flowed directly on to the Dogden Moss area, or channel 1 had already been formed by the time of esker deposition and blocking by dead ice caused the diversion of meltwater flow. Assuming that channel 1 was already established, even allowing for the fact that it would almost certainly have been deepened after esker formation, it is difficult to see how channel 5 could have been cut, to the same size and depth as channel 1, in the period between the re-extension of channel 1 southwards after esker completion and the final dissolution of the ice cover. Furthermore, if channel 5 had been formed entirely after the esker formation, it would be logical to assume that comparable amounts of erosion took place in channels 1 and 5 in that period of deglaciation, owing to their remarkably similar dimensions. This would indicate that channels 1 and 2 must have been relatively insignificant before esker formation. It is difficult to see how large amounts of material as were deposited in the Bedshiel esker could have been transported without the aid of large volumes of meltwater.

It would seem more likely that, in a late phase of deglaciation, after the establishment of the main drainage lines, the main outlets, channels 1 and 5, became choked with dead ice. The checking of meltwaters initially caused fluvioglacial deposition at 210 metres O.D. near the site of Cammerlaws and to the north of the site of Hallyburton. Similar deposition at 210 metres O.D. at Raecleuch Head to the east suggests that channel 6 was also choked at that time to the east of Raecleuch Head.

Waters flowed uphill from the west on to the area of Dogden Moss, were concentrated into a tunnel at the base of the ice, and subsequently deposited the Bedshiel esker. Deposition was probably triggered off initially by a reduction in carrying capacity of the meltwaters due to dissipation of energy in overcoming the rise in altitude from the level of channel 1 to the level of the surface of Dogden Moss. As channel 5 appears to have been blocked by dead ice at that time, the esker was able to extend eastwards until dissipation of meltwaters in the area of the col at 210 metres O.D. between Lees Hill and Kyles Hill caused the cessation of deposition.

At a later stage of deglaciation the main channels became sufficiently freed of dead ice, and any debris which might have collected, for the initial subglacial drainage pattern to reassert itself. Meltwaters collected in the basin to the north of the esker from the slopes of Kyles Hill to the east and Dirrington Little Law to the north. Eventually the collecting meltwaters breached the esker at two main points, between Horse Kaim and Green Kaim and between Green Kaim and Long Kaim.

Thus field mapping of the area suggests a west-to-east formation of the Bedshiel esker, in keeping with the eastward flow of meltwaters during the deglaciation of this part of the Tweed Basin. This indicates that the east-to-west trend indicated by the initial pebble roundness analysis is in fact incorrect. A further, more rigorous, run of samples over the length of the esker was deemed to be necessary. Prior to this, a closer study of the fabric of the esker was undertaken in order to confirm the conclusions suggested by the field mapping.

FABRIC ANALYSIS

In an excavation in the extreme east end of the esker a side exposure at base level showed laminations of sand and fine sand, each 2 to 5 centimetres thick. Exposures on the sides of Horse Kaim showed mainly coarse sand with some included gravel. Deeper excavations on the lower slopes of the esker showed almost entirely sand and fine sand beneath an external layer of coarse sand and gravel. Stratification was rude in most exposures, in no case sufficiently clear to enable firm deductions to be made. Scree from either end of the Horse Kaim - Green Kaim gap suggests a gravel capping overlying a core of sand and fine sand. Slumped material and small amounts of ablation moraine would account for the coarser "skin" found on the sides of the esker.

In the absence of observable stratification, five deeper pits were dug in the esker for the purpose of stone orientation analysis (Fig. 5.7). One of these was unusable owing to the number of very large cobbles encountered (up to 1 metre a axis and 50 centimetres b and c axes). Pits were dug to a depth approximately 2 metres down from the crest of the esker and, as accurately as possible, on the axis of the feature. These precautions were taken to ensure, as far as possible, a section undisturbed by frost heave, root movement, or by slumping down the sides of the esker.

It has been long recognised that fluvial particles dip upstream, and Jamieson noted, as early as 1860, that the dip of elongated particles of fluvioglacial valley gravel was consistently upstream

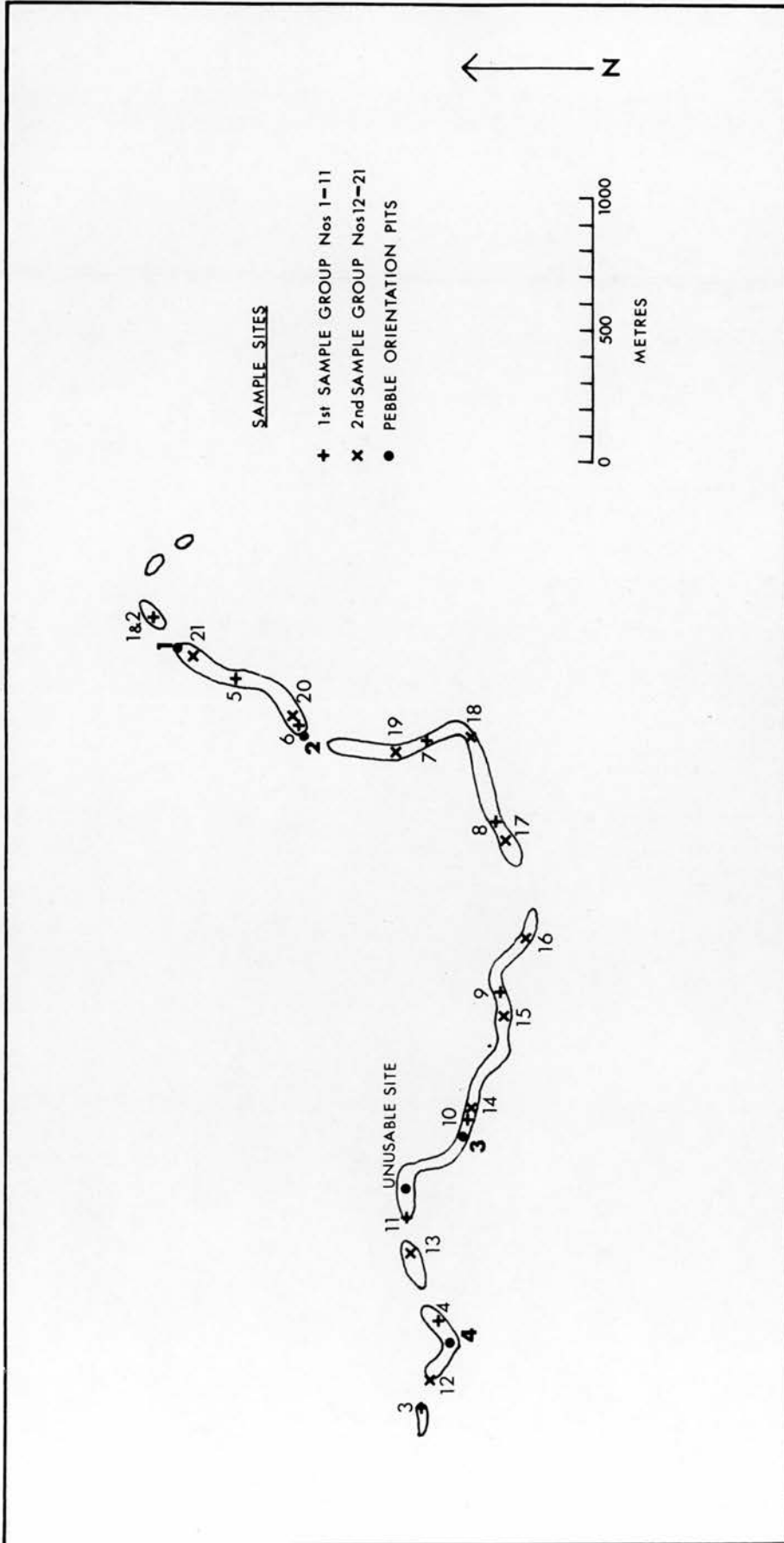


FIGURE 5.7. Bedshiel esker sample sites

(Jamieson, 1860). Most workers in the field since that date have applied the stone orientation technique to observation of particle attitude in till, almost invariably for the purpose of indicating direction of ice-movement during deposition of the till under observation. The technique evolved is suitably summarized by Kirby (1969a), and his field technique was adopted in the present case. The work of Holmes (1941) and Harrison (1957) represent the major contributions to date.

In the present study, a pit was dug at each selected site and a horizontal face prepared approximately 2 metres down from the crest line. The number of particles selected from each site was 100, the pebbles being exposed by careful brushing. It was decided fairly arbitrarily, on the grounds of convenience of handling, to limit size for selection to long axis lengths between 10 and 100 millimetres. Occasional cobbles larger than this were accepted.

For each pebble, the azimuth and dip of the a axis were measured in situ and the a, b and c axes measured after removal from the face. Where the pebble selected was triangle-shaped, and hence upper surface dip and lower surface dip differed, dip was taken through the axis of symmetry of the stone or as near as possible to the average dip of the two surfaces. This in no way greatly reduced the accuracy of the results, as broad, diamond-shaped particles were rejected. Only particles with long axis to intermediate axis ratio greater than 3:2 were considered, as it is difficult to determine accurately the long axis orientation of more equidimensional pebbles. All other particles were rejected.

Contiguous particles and those showing flow structure round larger cobbles were also rejected. Particles dipping in excess of 60° were rejected, as azimuth became difficult to read accurately beyond this point. In fact, few particles were found dipping in excess of 60° , so the rejection of steeply-dipping particles causes little distortion in the overall fabric diagram. Azimuth and dip were measured to the nearest 5° by use of a Suunto compass. Kirby (1969a) estimated his accuracy of this method as $3^{\circ} - 4^{\circ}$ for azimuth and $4^{\circ} - 6^{\circ}$ for dip. This is an acceptable degree of accuracy.

The particle measurements were recorded on a field booking sheet rather than plotted directly on to a circular diagram. This ensures greater objectivity in the choice of particles. The actual digging of the pit took well over an hour in all cases, and selection of 100 stones from each prepared face took three to four hours, depending on the frequency of occurrence of suitably-shaped particles. The pebbles and cobbles selected ranged in size in the first pit from 14 millimetres up to 118 millimetres long axis length. This range was not exceeded in two of the three succeeding selections (Table 5.4).

Average long axis length of the first 100 particles selected was 44.7 millimetres. This was not exceeded subsequently. The average ratio of length to breadth in the first group of particles was 1.70. This lies between the 2:1 ratio advocated by Glen, Donner and West (1957) and the 3:2 ratio suggested by Young (1966), and was judged to be satisfactory within the bounds of the present investigation. Succeeding selections yielded slightly higher axial ratios (Table 5.4).

TABLE 5.4

Long axis statistics of Bedshiel esker stone orientation samples

Site number	Maximum long axis (mm)	Minimum long axis (mm)	Average long axis (mm)	Average intermediate axis (mm)	Average axial ratio
1	118	14	44.70	26.28	1.70
2	93	13	25.09	13.99	1.79
3	113	15	32.51	18.65	1.74
4	177	11	33.66	19.51	1.73

The azimuth and dip figures were plotted on polar equal-area nets (Fig. 5.8). Each particle was plotted by first finding the radius appropriate to the compass direction noted in the field, then plotting dip at the appropriate point on a linear scale reading from horizontal on the outermost circle to 60° on the innermost circle of the net. Horizontally-dipping particles in the same general azimuth direction were plotted alternately on opposite sides of the net. The point diagrams obtained were redrawn as rose diagrams by grouping the pebbles into 20° classes and plotting on a linear scale from the centre, along the radius corresponding to the mid-point of each class (Fig. 5.9). Thus all pebbles dipping in a direction of 0° to 19° were plotted along the 10° direction; those dipping in a direction 20° to 39° , along the 30° direction; and so on. This procedure gave a simple visual plot of overall direction of dip of the pebbles selected at each site.

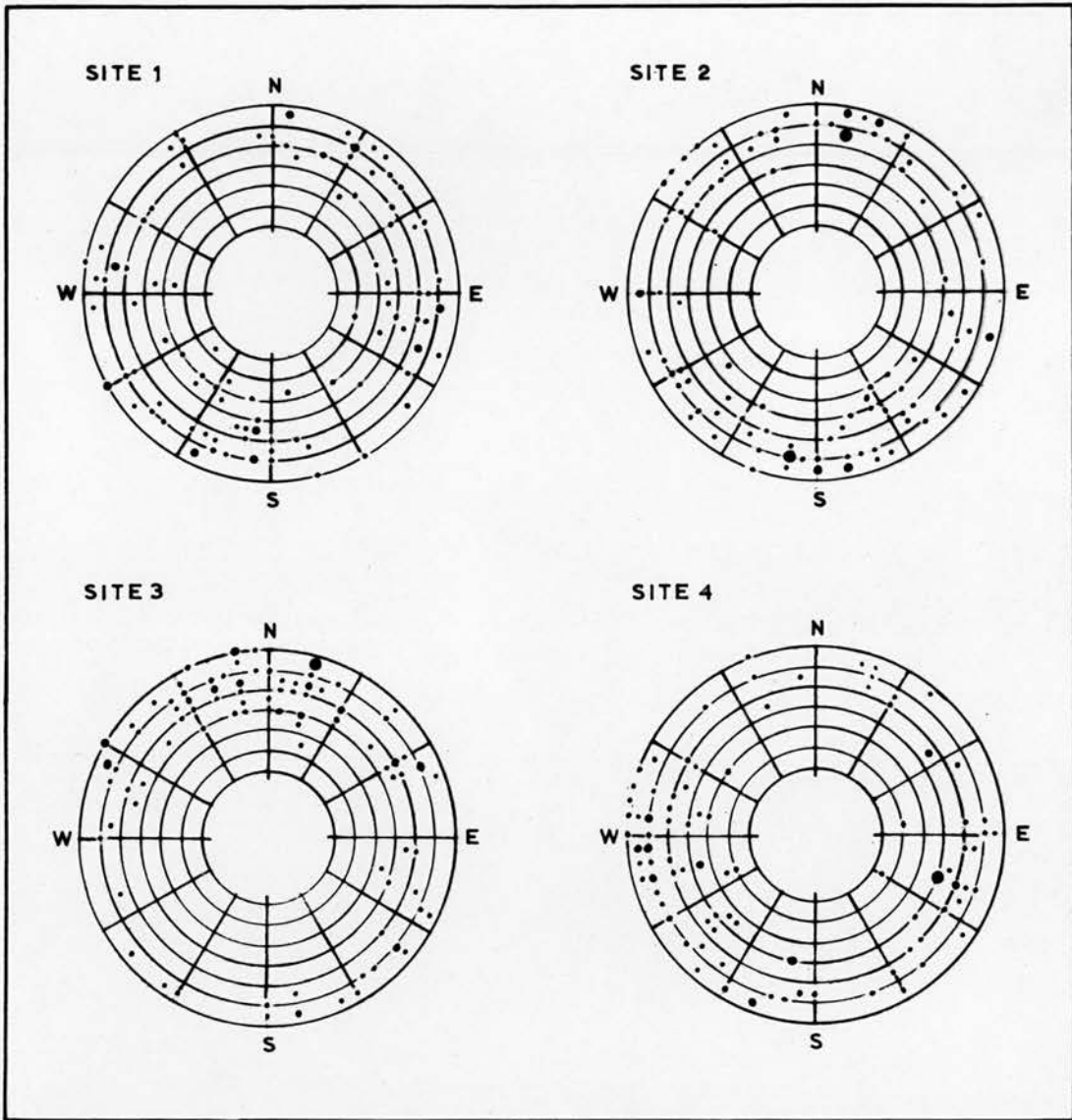


FIGURE 5.8. Esker fabric diagrams. Plots of azimuth and dip on polar equal-area nets

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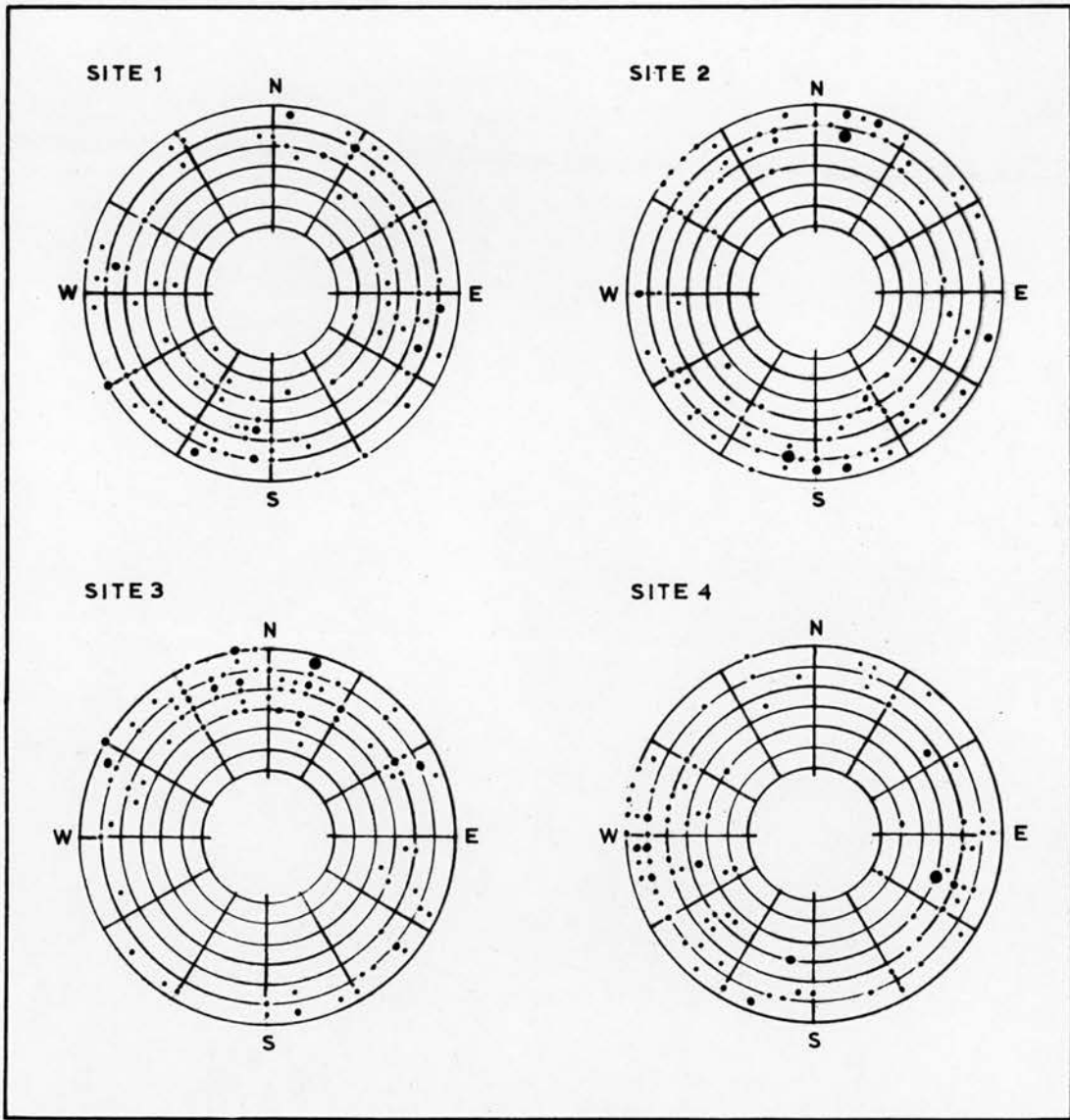


FIGURE 5.8. Esker fabric diagrams. Plots of azimuth and dip on polar equal-area nets

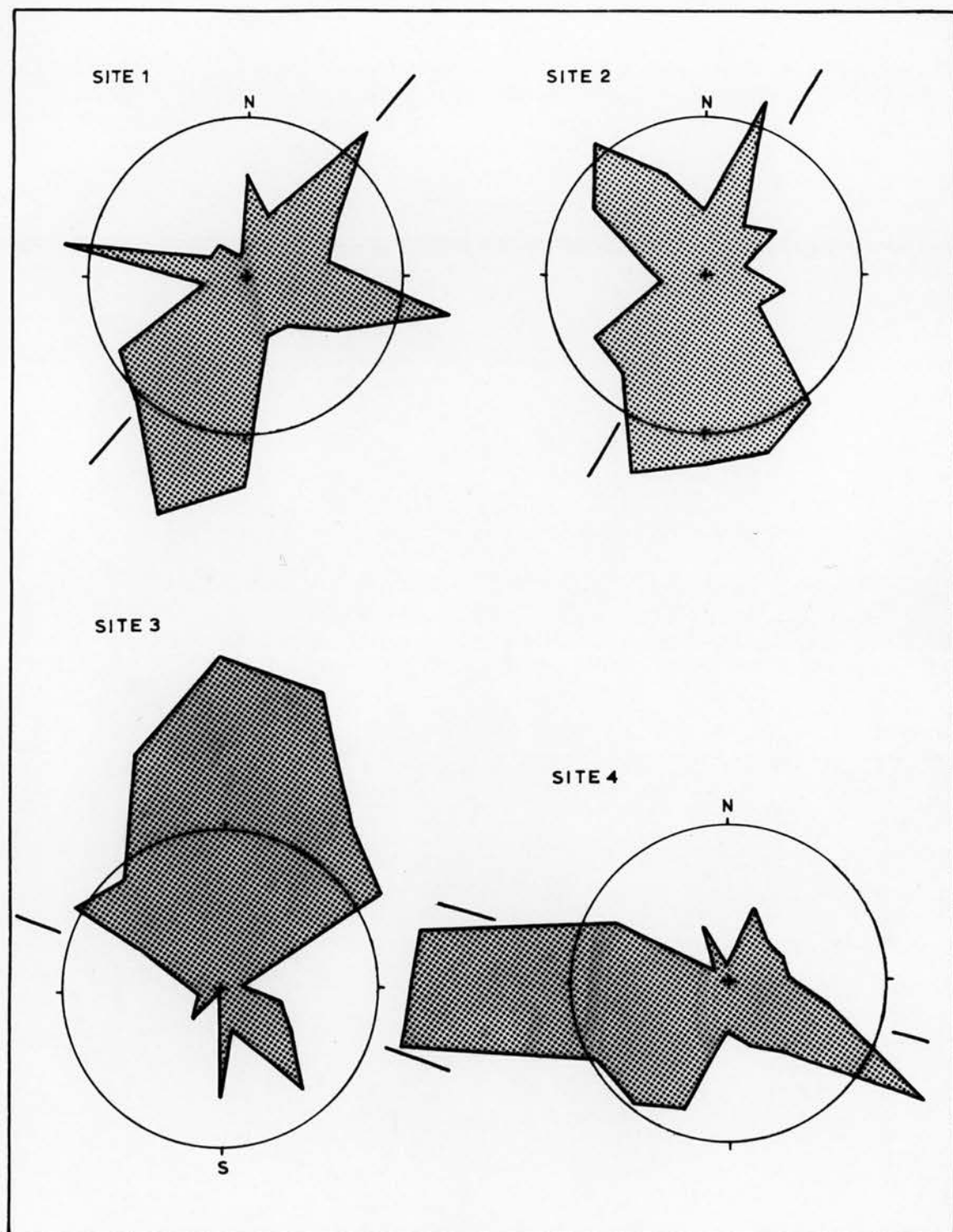


FIGURE 5.9. Simplified fabric diagrams. One centimetre from centre equals three pebbles. Broken line represents esker orientation at site

It is obvious from three of the four rose-diagrams drawn that most pebbles dip in a direction consistent with a west-to-east subglacial origin for the esker. Fabric would not have survived as clearly if the esker had initially been formed englacially. Site 3 gave a completely anomalous result, the overwhelming direction of dip being almost at right angles to the orientation of the esker ridge at that point. The inference in this case is that slumping, caused either by late-glacial river scour or by post-glacial soil creep, has been extensive and has occurred as far back as the axis of the ridge, hence disturbing the original fabric. Slumped material had been noted on the northern slopes of the esker at this point but it had not been anticipated that this would have affected the fabric on the long axis of the ridge.

Two further points of note emerged from the orientation analysis. Firstly, a transverse peak of stone orientation is most clearly developed at site 1, the most easterly pit. The diagram abstracted from site 2 shows an intermediate, more diffuse, transverse peak development, while there is no appreciable transverse peak in the most westerly pit (site 4). This supports, however tentatively, the contention of Glen, Donner and West (1957), who stated that suitably-shaped particles placed at random in a flowing liquid soon develop a long axis orientation parallel with the direction of liquid flow. A transverse peak is also developed but after a longer distance of travel in the liquid.

Secondly, the fabric at site 1 would seem to support the contention made earlier that the major breaks in the esker were in

fact caused by water breach some time after the esker had been deposited. Site 1 was on the north end of Horse Kaim. The excavation was made horizontally into the ridge at a depth of 3 metres below crest level so as to allow for the preparation of a face 2 metres below the crest. If the esker had been inherently discontinuous at this point, fabric would have been chaotic. Pebbles this near to the discontinuity would have dipped in a northeasterly direction owing to there having been no firm bed on which pebbles could settle with up-current dip.

Thus the orientation analysis provides strong evidence that the Bedshiel esker was deposited by easterly-flowing subglacial streams. When the results of field mapping and orientation analysis are viewed in conjunction, there seems little doubt that the esker had a west-to-east origin.

FURTHER INVESTIGATION OF SPHERICITY AND ROUNDNESS TRENDS

In view of this evidence, it was decided to take a further series of samples for sphericity and roundness study, but with a more rigid sampling framework than had been used with the initial run of samples. Samples were taken along the length of the esker at a fixed distance of one metre down from the crest, each excavation being made on the axis of the esker. This was designed to ensure that only material in situ was sampled and that stone-breakage due to frost or root action was minimised. Even with these precautions, many frost-shattered sandstone flags were

encountered, and the large numbers of boulders up to one metre in length encountered were such as to make excavation difficult at almost every site. Many of the boulders were greywacke although most were local sandstone.

The material was hand-sieved in the field, only the fraction retained on the 6.35 millimetre (1/4 inch) sieve being taken in for laboratory analysis. A further modification was to select 50 greywacke and 50 sandstone pebbles from each sample. The selection of a fixed equal number of greywackes and sandstones was undertaken in an attempt to standardise the results obtained from the measurement of sphericity and roundness.

The values of average sphericity and roundness were calculated and graphed (Figs. 5.10, 5.11). Average sphericity, more noticeably that of greywacke, shows a trend best described as sinusoidal. A general rise and fall over the length of the esker is not apparent. However, average roundness of both greywacke and sandstone appears to rise in an easterly direction over the length of the esker. This is more noticeable in the case of sandstone, as would be expected from earlier considerations. A regression line drawn through the ten points involved rises from west to east, but the number of points involved is so small and the 95 per cent confidence limits are so wide that no statistical weight can be attached to this trend. Despite this, the trend does support, however tentatively, the conclusion reached from field mapping and orientation analysis that the esker was laid down from west to east. The more rigid sampling procedure would seem to have gone some way towards producing the desired results, and a greater density of sampling would no doubt prove productive.

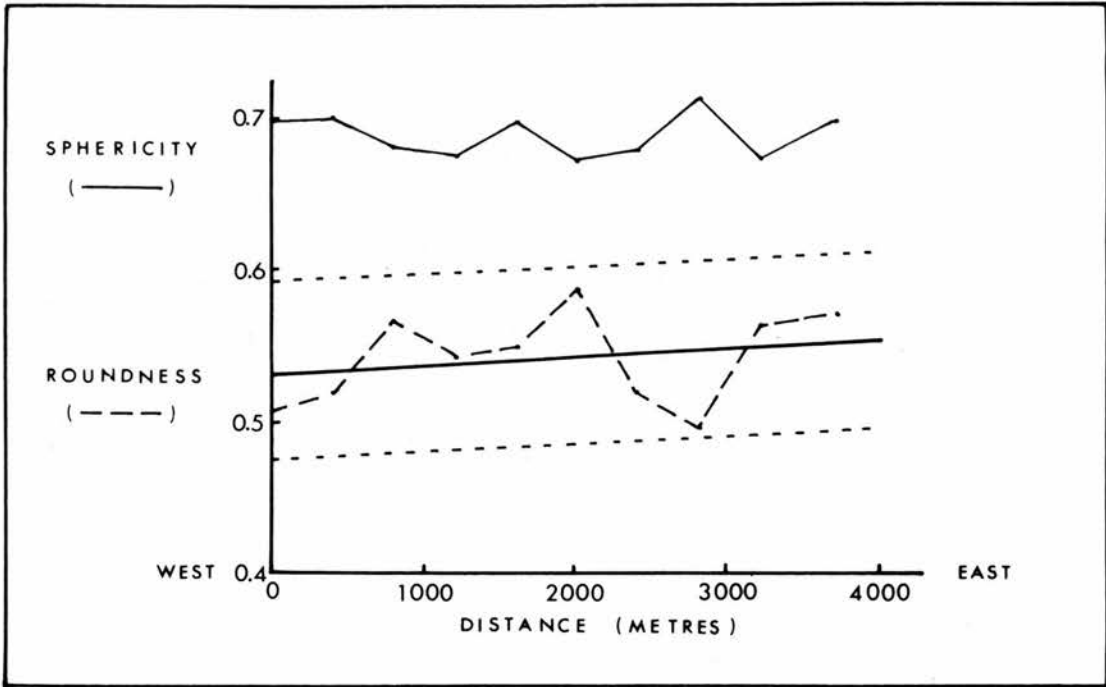


FIGURE 5.10. Sphericity and roundness of selected sandstone pebbles against distance. Second trial. For regression line see text

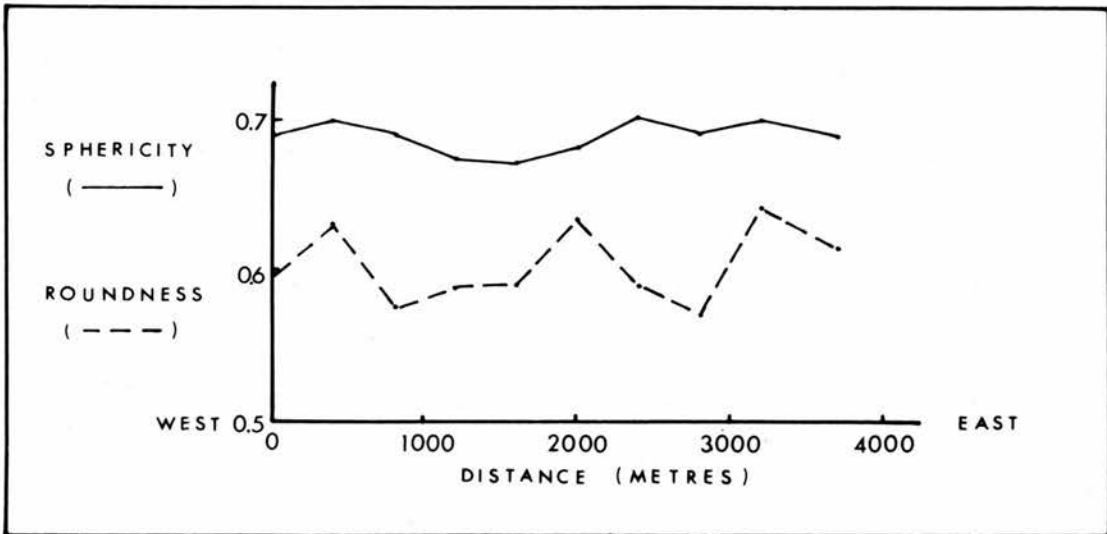


FIGURE 5.11. Sphericity and roundness of selected greywacke pebbles against distance. Second trial

CONCLUSIONS

The conclusions to be reached from this case study are twofold. Firstly, it is obvious that a rigid sampling scheme must be adopted in sampling material over the length of linear features such as eskers. Secondly, it would appear from the work done that, provided the sampling procedure is suitably rigid, the measurement of roundness and sphericity of lithologically similar pebbles along the length of a linear feature would indicate the direction of formation of such a feature. This necessarily involves features probably more than twice the length of the Bedshiel esker (say a minimum of 10 kilometres) before definite statistical conclusions could be drawn.

CHAPTER 6. RESULTS OF THE MECHANICAL GRAIN SIZE ANALYSIS OF SAMPLES

The purpose of mechanical grain size analysis in the present study is to attempt to distinguish between suites of fluvioglacial landforms, and to investigate the essential differences in environment of deposition, if suitable differentiation can be proved. This type of analysis has been used fairly widely to differentiate between environments of sand deposition, notably by Mason and Folk (1958) and Friedman (1961), but no application to fluvioglacial landforms has been published to date other than that of King and Buckley (1968).

The measures used in the present study are those set out in Chapter Four. These are calculated from the cumulative curve, probability ordinate, and are as follows:-

mean,	$M_z = (\phi_{16} + \phi_{50} + \phi_{84})/3$
inclusive graphic standard deviation,	$\sigma_I = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6}$
inclusive graphic skewness,	$Sk_I = \frac{\phi_{16} + \phi_{84} - 2\phi_{50}}{2(\phi_{84} - \phi_{16})} + \frac{\phi_5 + \phi_{95} - 2\phi_{50}}{2(\phi_{95} - \phi_5)}$
graphic kurtosis,	$K_G = \frac{\phi_{95} - \phi_5}{2.44(\phi_{75} - \phi_{25})}$

In order to interpret the data more fully and discover trends, the data were applied to an adaptation of an Edinburgh Regional Computing Centre library routine, "Curvefit" (Classification 00.018.201, Atlas Autocode). "Curvefit" fits a polynomial of given degree to a given set of data points. It gives the coefficients of

the best-fit polynomials for all degrees less than a specified maximum degree. The maximum degree specified in the present case was 12. If n , the number of data points to be fitted, was less than 12, then the maximum degree coefficients printed out were the coefficients of degree $n-1$. Otherwise, "Curvefit" printed out the coefficients of the best-fit polynomials of degrees zero to 11 inclusive. "Curvefit" also gives the sum of squares of residuals obtained from these polynomials.

The aim of using "Curvefit" in this way was to indicate the curve which would give the best prediction, even when points were widely scattered, of mean versus standard deviation, mean versus skewness, and so on, both for all samples considered as one group and for the groups of samples taken from individual suites. Each of the four measures, mean, standard deviation, skewness and kurtosis, was plotted against all others, so that six sets of graphs were obtained. For each comparison, all 70 samples were plotted on the same graph, once by landform suite and once by percentage of gravel. Individual suites were then plotted separately by percentage of gravel.

In many cases the polynomial of degree 3 or 4 was sufficient to approximate to the best-fit curve, as the sums of squares of residuals for polynomials of higher degree were not significantly less. The use of these polynomials corresponds to theoretical variation in the grain size parameters studied, discussed where appropriate later in the present chapter. The third degree curve has 2 points of zero gradient, corresponding to one maximum and

one minimum in the range of values covered by the plots of mean versus standard deviation and mean versus kurtosis. The fourth degree curve typically has 3 points of zero gradient. In the plot of mean versus skewness, this corresponds to 2 maxima and 1 minimum in the range of values found.

Although "Curvefit" supplied the coefficients of polynomials of degrees 5 to 11 these were not in fact used after preliminary testing. The curves given in no cases improved on the third or fourth degree curve fitted, neither in terms of the general trend involved nor in terms of substantial reduction in the sum of squares. In cases where very few points were involved, for example the Edzell outwash samples, either no meaningful curve could be drawn or a simple first or second degree curve was fitted in an attempt to distinguish trend. In such cases, only one section of the general distribution was covered and the first or second degree curve was deemed appropriate for that section.

The question inevitably arises, in respect of the fitting of non-linear curves to a relatively small number of data points, as to how many points are required to justify statistically the construction of, say, a fourth degree curve. The minimum number of points required for a simple first degree regression line is an obvious starting-point. A search of statistical texts either related specifically to Geography or commonly used by geographers provided no direct answer. Ten points seems to be the generally accepted minimum, although this is never directly stated but rather inferred from examples quoted. In fact Griffiths (1967, p.444)

gives an example of only 8 values in calculating the regression equation between carbonate content and pore space in a Pennsylvanian oil-bearing sandstone. It may be significant that this same example reappears on page 449 with 9 plotted values.

With reference to curves of higher than first degree, Croxton and Cowden (1968, p.420) calculate a best-fit second degree curve through 20 values of diameter against volume of ponderosa pine trees. In discussion of the third degree curve, they give a 15-point example of the relationship between percentage nitrogen in fertilizer and yield per acre of tobacco (Croxton and Cowden, 1968, p.427). Their values in this latter example covered only one section of the calculated third degree curve, and it could be argued that many more points would be required to cover the entire range of values implied by the use of the third degree curve.

From these considerations it seems clear that the use of third and fourth degree regression curves is fully justified where the plots of all samples are considered, as 70 points are more than sufficient to satisfy statistical requirements. Similarly, the 26 plotted samples from the Eddleston kame suite would seem to allow the construction of non-linear regression curves. It is also obvious that the construction of such curves through groups of samples comprising less than 10 values cannot be justified statistically. Their only justification lies in visual comparison of the theoretical second, third or fourth degree curve drawn through a relatively small number of points

with the curve of corresponding degree constructed through the comprehensive plot of all samples.

One example illustrates this. The third degree curve drawn through the plot of mean against standard deviation for the Carstairs esker samples follows the distribution of the points closely, even allowing for one anomalous sample (Fig. 6.1f). Sums of squares of residuals for first to fourth degree curves are 7.41, 5.36, 3.41 and 3.21 respectively. The third degree curve is obviously the optimum solution in terms of the balance between the simplest suitable curve and progressive reduction of the sum of squares of the residuals. Although not statistically significant in this case, the third degree curve is simply the best curve to describe this particular distribution of values. Its use can be justified in this and similar cases in general terms, to indicate possible trends, when relatively few data points are available.

GRAPHIC MEAN Vs. INCLUSIVE GRAPHIC STANDARD DEVIATION

One immediate point emerging from Figures 6.1a and 6.1b is the apparent dearth of natural sediments with graphic mean values between -0.5ϕ and $+1.5\phi$. This corresponds to a lack of material containing between 21 and 40 per cent gravel. As can be seen from Table 6.1, over one-third of the samples taken in the study contained between 61 and 80 per cent gravel.

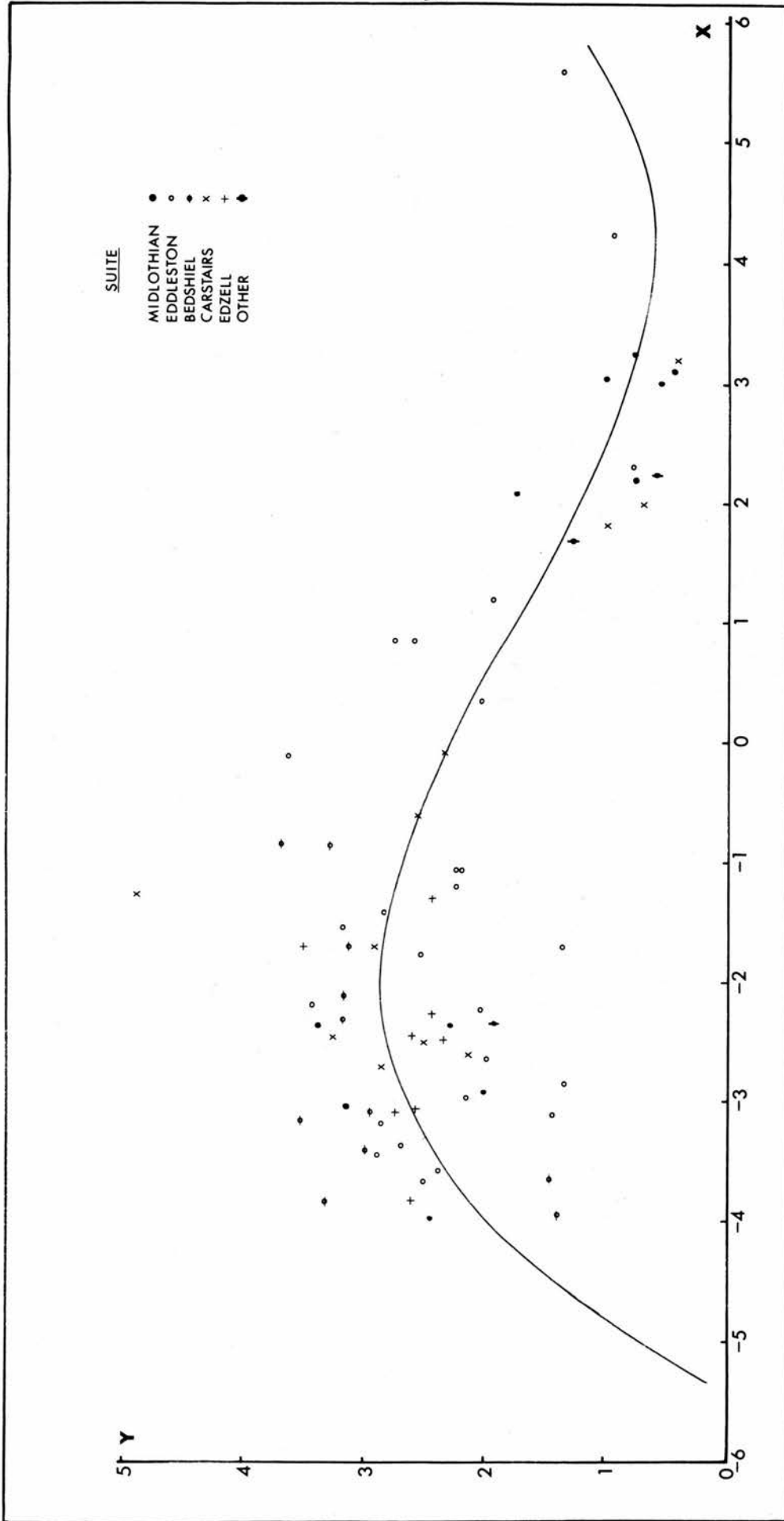


FIGURE 6.1a. All samples, differentiated by suite. Graphic Mean (ϕ units - X axis) versus Inclusive Graphic Standard Deviation (ϕ units - Y axis). Third degree curve fitted

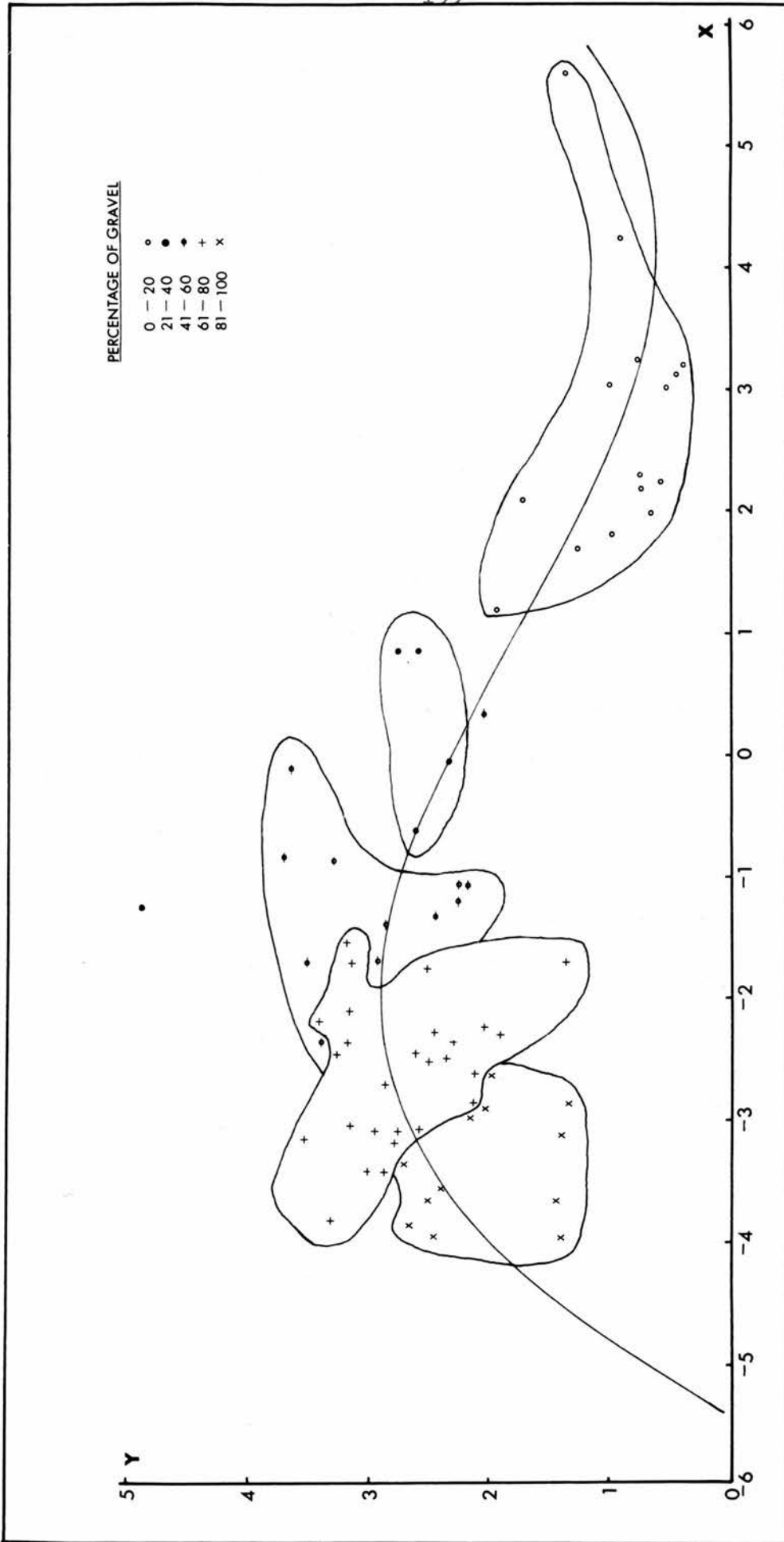


FIGURE 6.1b. All samples, differentiated by percentage gravel. Graphic Mean (ϕ units - X axis) versus Inclusive Graphic Standard Deviation (ϕ units - Y axis). Third degree curve fitted

TABLE 6.1

Number of samples containing specified percentages of gravel fraction

Percentage gravel in sample	Number of samples
0 - 20	15
21 - 40	5
41 - 60	12
61 - 80	26
81 - 100	12
	—
TOTAL	70
	—

Samples containing 41 to 60 per cent and 81 to 100 per cent gravel occurred with equal frequency. Values of 0 to 20 per cent gravel were also common. Only 5 of the 70 samples contained between 21 and 40 per cent gravel. This deficiency is largely due to the method of selection of samples, rather than to any real lack of this grain size in fluvioglacial materials. However, the phenomenon of apparent grain size deficiencies in natural sediments has been noted by many workers. Udden (1914) noted a gap at 3 to 4 ϕ . Wentworth (1933) found gaps at -1 ϕ , 8 ϕ , and a weaker gap at 3.5 ϕ . Hough (1942) noted deficiencies at -1 to -1.5 ϕ and at 4 to 4.5 ϕ , while Pettijohn (1949) found gaps at 0 to -2 ϕ and at 3 to 5 ϕ . Pettijohn's findings have since been confirmed by many other writers.

Griffiths (1957) attributed these apparent deficiencies to changes in analytical techniques, that is, from direct measurement to mechanical screening to pipette analysis. This does not apply in the present case, as the distributions were measured entirely by mechanical screening.

The implication of a gap between -0.5ϕ and $+1.5\phi$ is that material found in the fluvioglacial landforms studied originated as medium to very fine sand-sized particles or as gravels. These two modes mix to a greater or lesser extent, but coarse and very coarse sand-sized particles seldom predominate. This could be due to some extent to the seasonal volume of meltwaters, summer turbulence depositing gravels and causing more intense corrasion, and winter lessening of flow producing conditions suitable for deposition of the finer sand grades. Alternatively, it could be due to a natural lack of material in the coarse and very coarse sand-sized particles.

If a wide range of average grain sizes is present in any analysis, the ideal trend would be sinusoidal in form (Folk and Ward, 1957). Minima of best sorting, and hence lowest standard deviation, would coincide with prominent modes in the sediment. Maxima of poorest sorting would correspond to mean sizes approximately half-way between modal diameters. This theoretical trend is borne out by Figure 6.1b, showing percentage of gravel in all samples. In general, the higher gravel values show a lower standard deviation. Samples analysed with less than 20 per cent gravel also have relatively low standard deviations. The mixed

samples intermediate in mean grain size between these two modes have relatively high standard deviations. Only one sample, from the Carstairs esker system, gives a completely anomalous result. It consisted of sands of various grades plus one large greywacke cobble. This cobble contributed 23.0 per cent by weight of the total sample, while all other gravels totalled only 16.7 per cent. by weight. This one sample appears in an anomalous position throughout all relevant diagrams.

In Figure 6.1b, it can be seen that the centres of gravity of the sets formed by the various percentage groups tend to follow the fitted third degree curve, allowing for occasional anomalies. This suggests that the spread of individual results is such that virtually any 70 samples taken from any combination of fluvio-glacial landforms would give a similar fitted curve. Where the concentration of samples is strongest, in the 61 to 80 per cent group, the spread of results is widest, as can be seen from Figure 6.1b. In view of the necessarily small number of samples taken from the individual landform suites, it must be restated that no statistical significance can be placed on curves fitted to the data. Yet general conclusions of a preliminary nature can be drawn, as can be seen by studying Figures 6.1c to 6.1g.

With the exception of the Edzell outwash samples (Fig. 6.1g), it can be seen that the sinusoidal-type variation is followed by all groups of samples when second or third degree curves are fitted. Although there is no clear grouping, the Bedshiel esker samples seem to show a generally higher standard deviation than the

KEY to FIGURES 6.1c to 6.1g

X-axis: Graphic Mean (ϕ units)

Y-axis: Inclusive Graphic Standard Deviation (ϕ units)

Percentage of Gravel in individual data points denoted as follows:

0 -	20% Gravel -	1
21 -	40	2
41 -	60	3
61 -	80	4
81 -	100	5

Where curve fitted, degree of curve shown in top right-hand corner of Figure

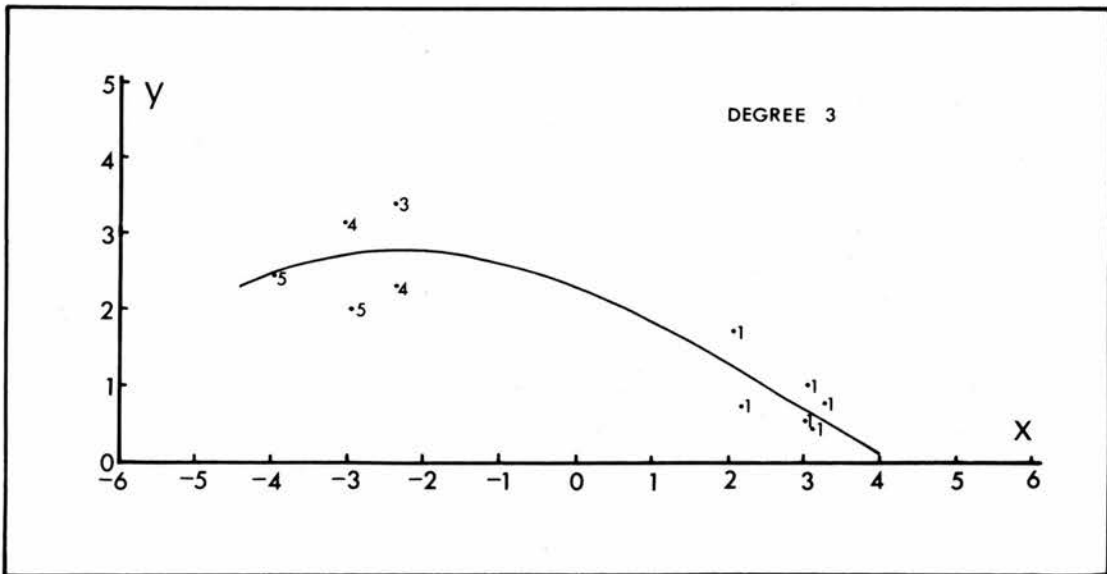


FIGURE 6.1c. Midlothian

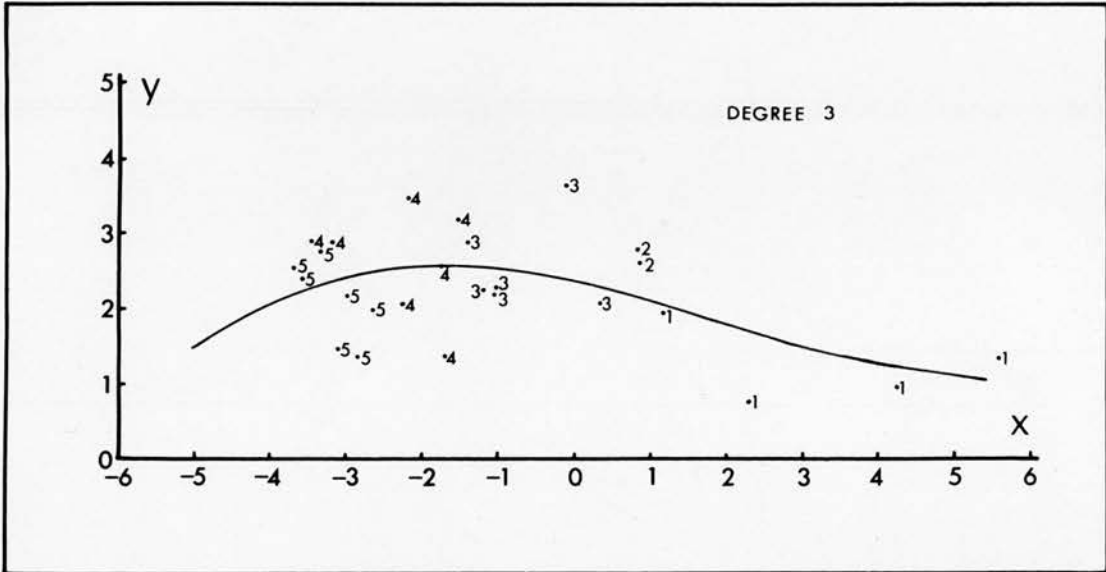


FIGURE 6.1d. Eddleston

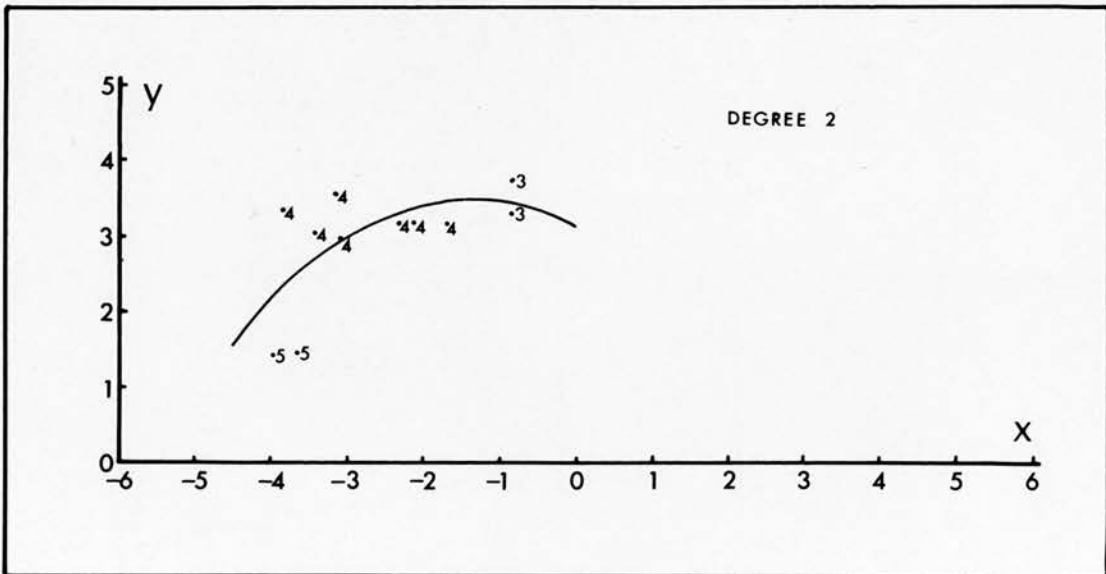


FIGURE 6.1e. Bedshiel

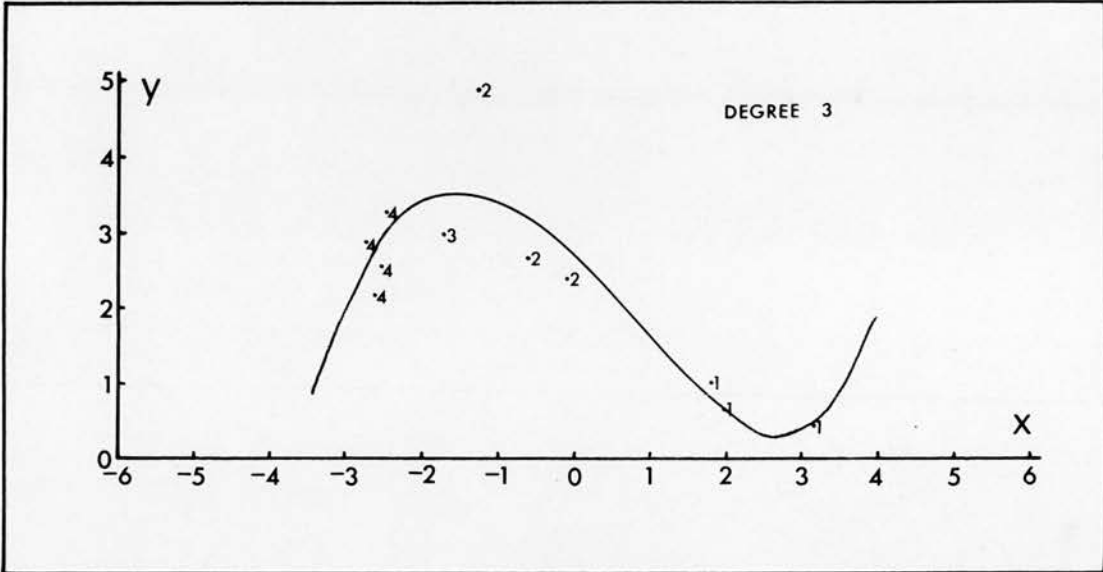


FIGURE 6.1f. Carstairs

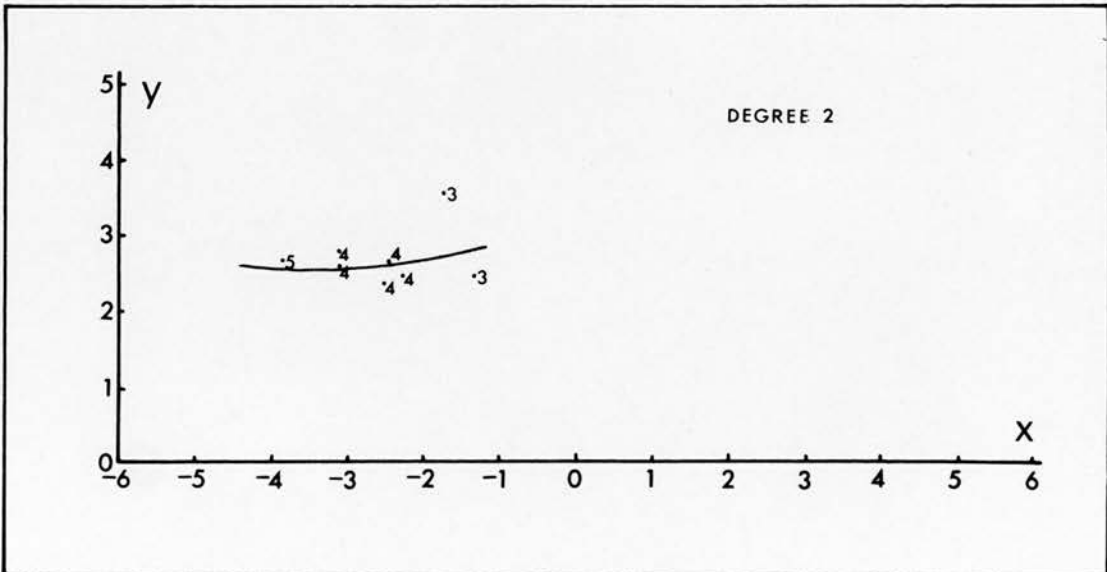


FIGURE 6.1g. Edzell

outwash samples. In turn, outwash samples appear to have a higher standard deviation on average than samples taken from kames. This is probably due to the slightly higher average gravel content of the kame samples taken.

The maximum standard deviation seems to occur in most cases where the mean size is about -1.5ϕ . This depends entirely on the particular curve fitted to the data, but suggests that poorest sorting occurs in fluvioglacial material containing between 50 per cent and 70 per cent gravel. The anomalous trend shown by the outwash samples taken is partly explained by a close similarity of standard deviation around the 2.6ϕ mark, despite a gravel content ranging from 52.9 to 80.1 per cent. The one sample containing over 80 per cent gravel shows the second highest standard deviation of all samples in the group. Were standard deviation of that sample nearer the average for the group, then the trend of increasing standard deviation with decreasing gravel content would be followed in this suite, as it is in the others.

The sinusoidal trend is particularly noticeable in the third degree curve fitted to the Carstairs esker samples (Fig. 6.1f), but this is partly due to the anomalous sample previously mentioned. This sample has the highest standard deviation encountered in the study, 4.89ϕ .

In summary, it is not possible to distinguish clearly between fluvioglacial landform suites by plotting graphic mean against inclusive graphic standard deviation, but the grouping of samples by percentage of gravel is noticeable, despite the variable nature

of the deposits sampled. This grouping tends to follow the theoretical sinusoidal trend with a maximum of poorest sorting corresponding to a mean grain size of about -2ϕ and a minimum of best sorting in the region of $+4\phi$.

GRAPHIC MEAN Vs. INCLUSIVE GRAPHIC SKEWNESS

The theoretical curve in this instance is again of the periodic sinusoidal form (Folk and Ward, 1957). Within the average size limits covered by the present results, this takes the form of a shallow U-shape, with a minimum of negative skewness at around 0ϕ to $+1\phi$ mean grain size. Theoretically, the pure sand mode when it occurs by itself produces a symmetrical size curve of zero skewness. The addition of small amounts of silt imparts a positive skewness. The addition of increasing amounts of gravel to a sand sample would impart an increasingly-negative skewness up to a certain percentage of gravel. From Figure 6.2b, this balance point could be estimated at about 40 to 50 per cent gravel. The addition of more gravel beyond this point causes more and more positive skewness. After a maximum positive skewness corresponding to a mean size of about -3ϕ , skewness decreases to a theoretical zero skewness in a pure gravel mode.

To generalize, the pure sand or gravel modes produce zero skewness. The mixing of the two modes produces negative skewness if the sand mode is more abundant, and a positive skewness if the gravel mode is dominant. Samples containing equal proportions of

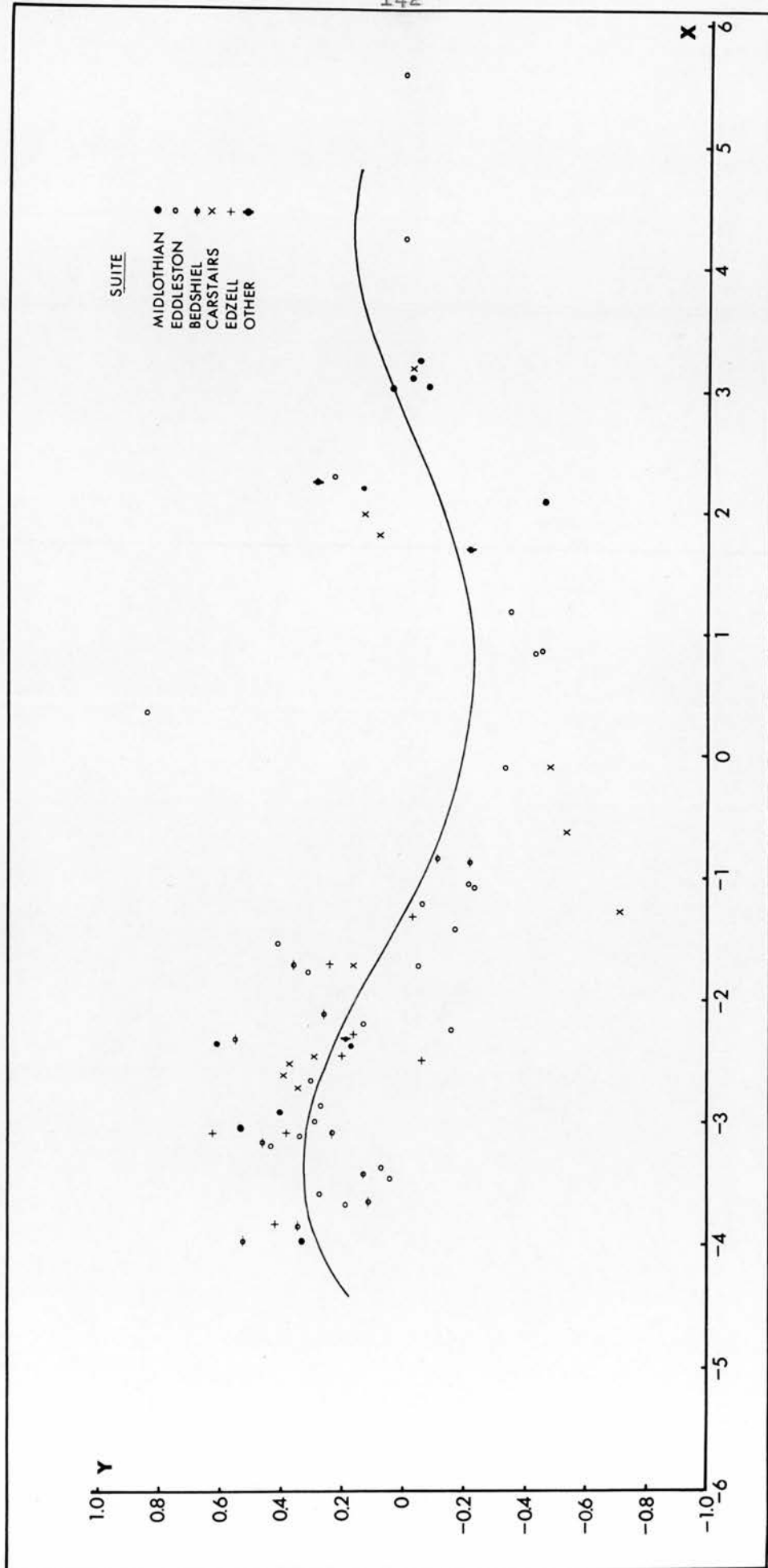


FIGURE 6.2a. All samples, differentiated by suite. Graphic Mean (ϕ units - X axis) versus Inclusive Graphic Skewness (Y axis). Fourth degree curve fitted

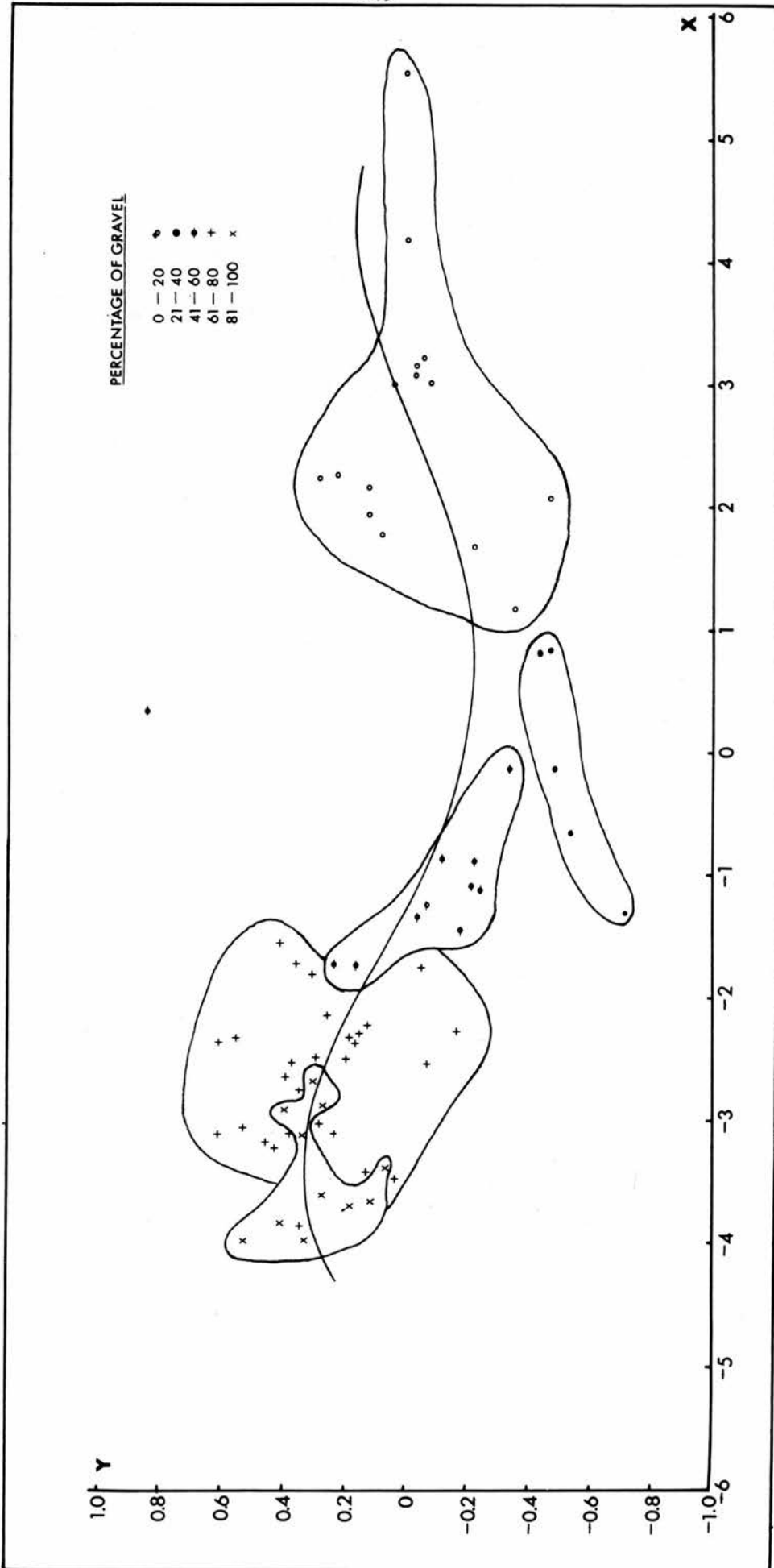


FIGURE 6.2b. All samples, differentiated by percentage gravel. Graphic Mean (ϕ units - X axis) versus Inclusive Graphic Skewness (Y axis). Fourth degree curve fitted

sand and gravel give rise to near-symmetrical size curves.

This ideal sequence is followed in the present results, and is brought out by the fourth degree curve fitted to Figures 6.2a and 6.2b. With reference to the percentage of gravel groups (Fig. 6.2b), the 61 to 80 per cent gravel group exhibits the highest overall skewness values, as might be expected from earlier theoretical considerations. The highest single skewness value of +0.84 occurred in a somewhat anomalous sample from Eddleston. Although this sample contained 46.2 per cent gravel, 25.8 per cent silt and clay fraction was present, and a pronounced positive skewness was expected.

Lowest skewness was found in the five samples containing 21 to 40 per cent gravel. Four of these were around -0.50, while the anomalous Carstairs sample had the lowest negative skewness of all, -0.71. Samples with graphic mean $+3\phi$ or greater were grouped round the zero skewness line, while samples containing 41 to 60 per cent gravel tended to group round -0.1 skewness.

Fourth degree curves drawn through the Midlothian, Eddleston and Carstairs samples support the above trends, however tentatively (Figs. 6.2c, 6.2d and 6.2f respectively). Maxima occur at about -3ϕ in each case and again at $+3.25\phi$, $+4.5\phi$ and $+2.5\phi$ respectively. The corresponding minima are $+0.6\phi$, $+1\phi$ and -0.2ϕ . Again, the curves drawn through the Midlothian and Carstairs samples can only be regarded as visual indicators of possible theoretical trends.

A second degree curve drawn through the Bedshiel esker samples indicates a maximum positive skewness at about -3ϕ , while the outwash

KEY to FIGURES 6.2c to 6.2g

X-axis: Graphic Mean (ϕ units)
 Y-axis: Inclusive Graphic Skewness

Percentage of Gravel in individual data points denoted as follows:

0	-	20% Gravel	-	1
21	-	40		2
41	-	60		3
61	-	80		4
81	-	100		5

Where curve fitted, degree of curve shown in top right-hand corner of Figure

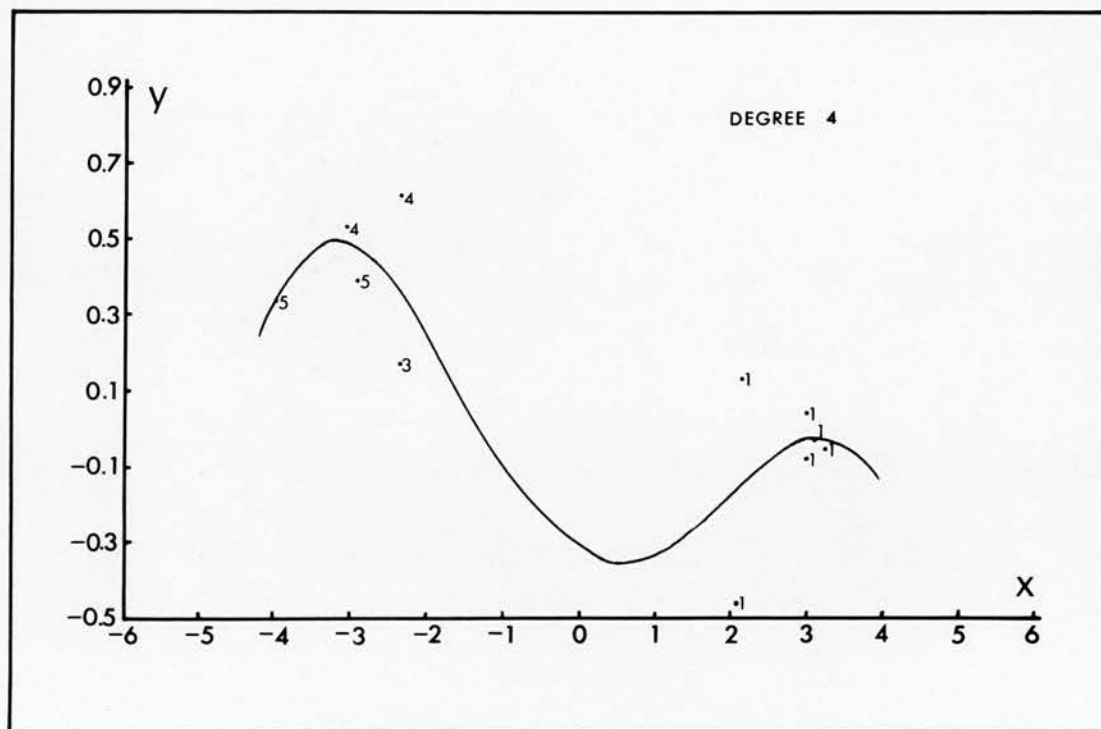


FIGURE 6.2c. Midlothian

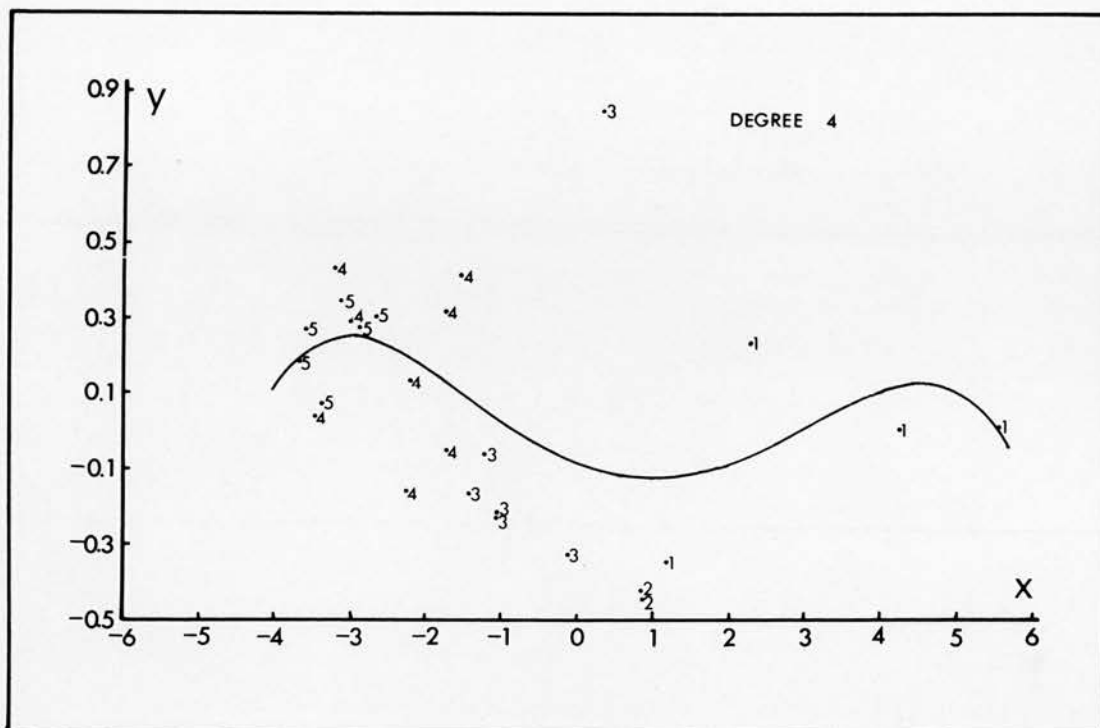


FIGURE 6.2d. Eddleston

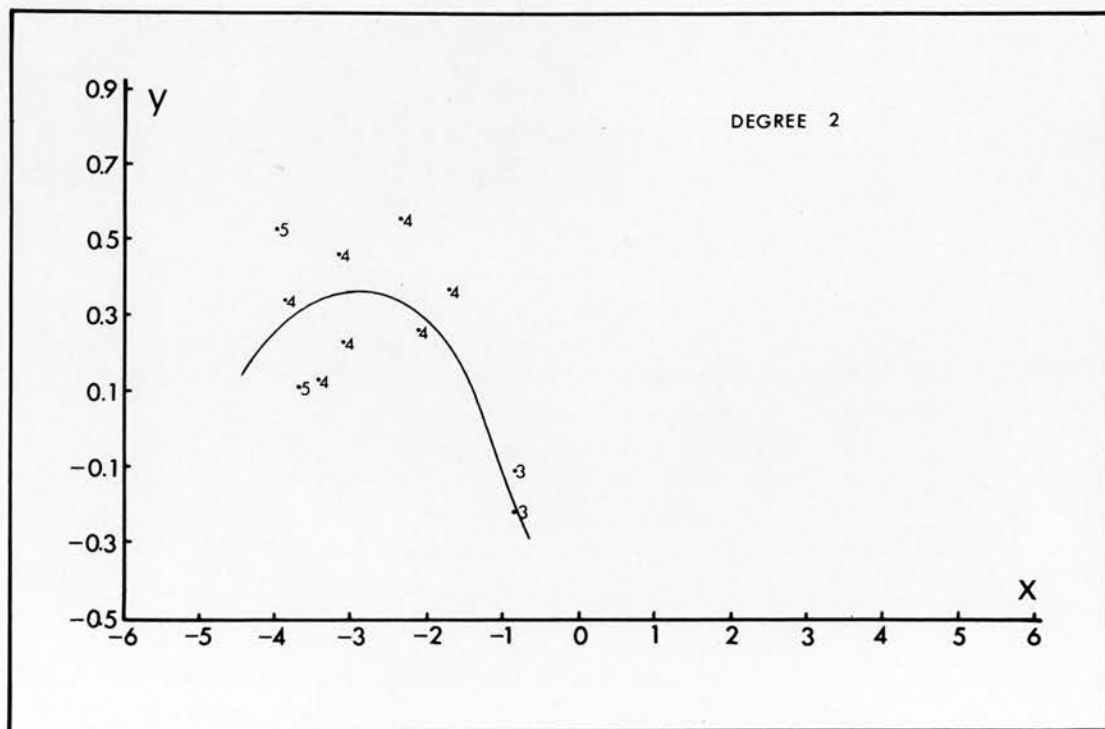


FIGURE 6.2e. Bedshiel

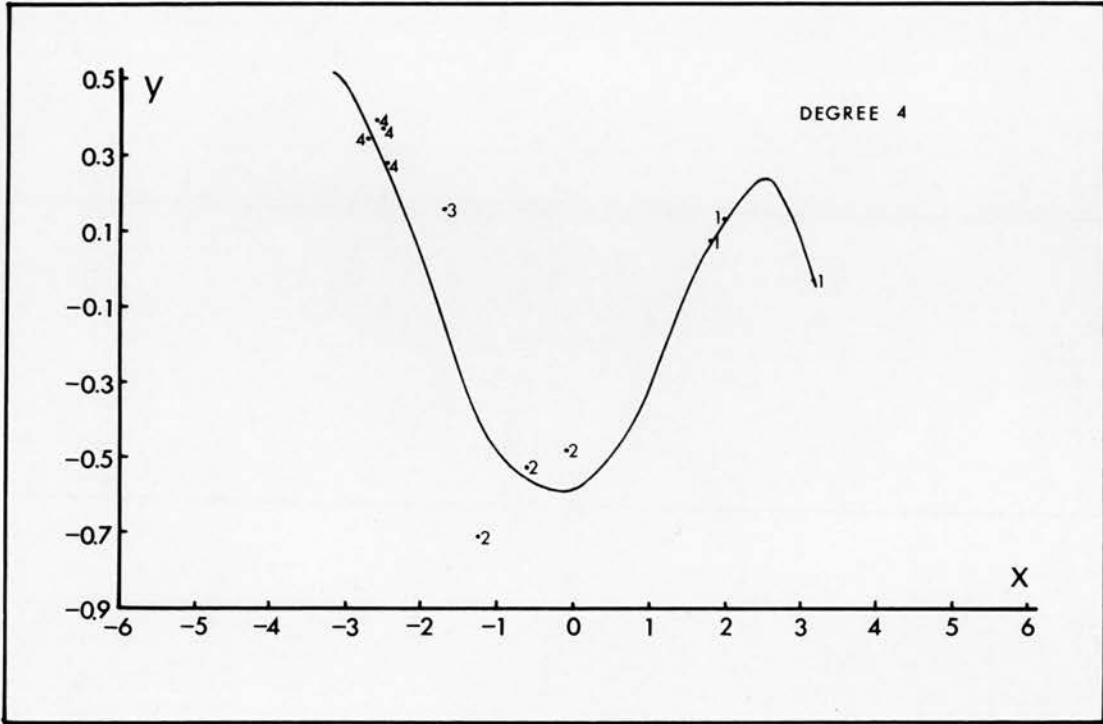


FIGURE 6.2f. Carstairs

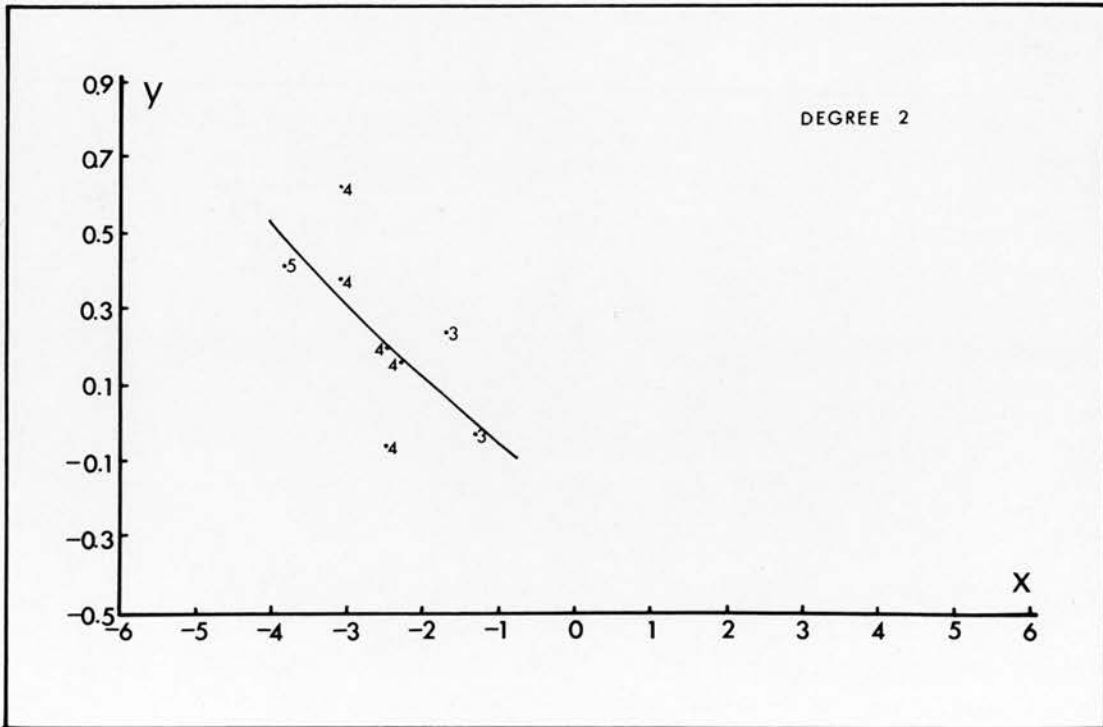


FIGURE 6.2g. Edzell

sample trend shows less positive skewness with smaller percentages of gravel. Only three noticeable groupings of samples occur. Four Midlothian samples containing 0 to 20 per cent gravel are grouped round zero skewness. Eddleston samples containing 81 to 100 per cent gravel tend to group round a skewness of +0.2, while the 61 to 80 per cent gravel samples from Carstairs average about +0.35 skewness.

GRAPHIC MEAN Vs. GRAPHIC KURTOSIS

The relationship between graphic mean and graphic kurtosis is complex. Pure modes, 100 per cent gravel or 100 per cent sand, give "normal" kurtosis, $K_G = 1.0$. Small amounts of more than 3 per cent of another mode increase the kurtosis value of the sample. However, if the two modes are in proportions of 25 per cent gravel to 75 per cent sand or 75 per cent gravel to 25 per cent sand, then the sediment tends to give a low kurtosis value, and becomes platykurtic.

The trend found in the present study seems to be U-shaped - a curve with peaks at the extremes of graphic mean size and a minimum value in the neighbourhood of -1.25ϕ (Figs. 6.3a and 6.3b). Study of Figure 6.3b, the percentage gravel plot, shows that the range of kurtosis values possible within any one percentage gravel class is large. The extreme range of values for samples containing over 80 per cent gravel is from $K_G = 0.93$ to $K_G = 1.63$, a range of 0.70. The corresponding range in the 61 - 80 per cent class is 0.84, in the 0 - 20 per cent class, 0.40. With one exception, the samples in the 41 - 60 per cent gravel class have low kurtosis values of less than 0.8.

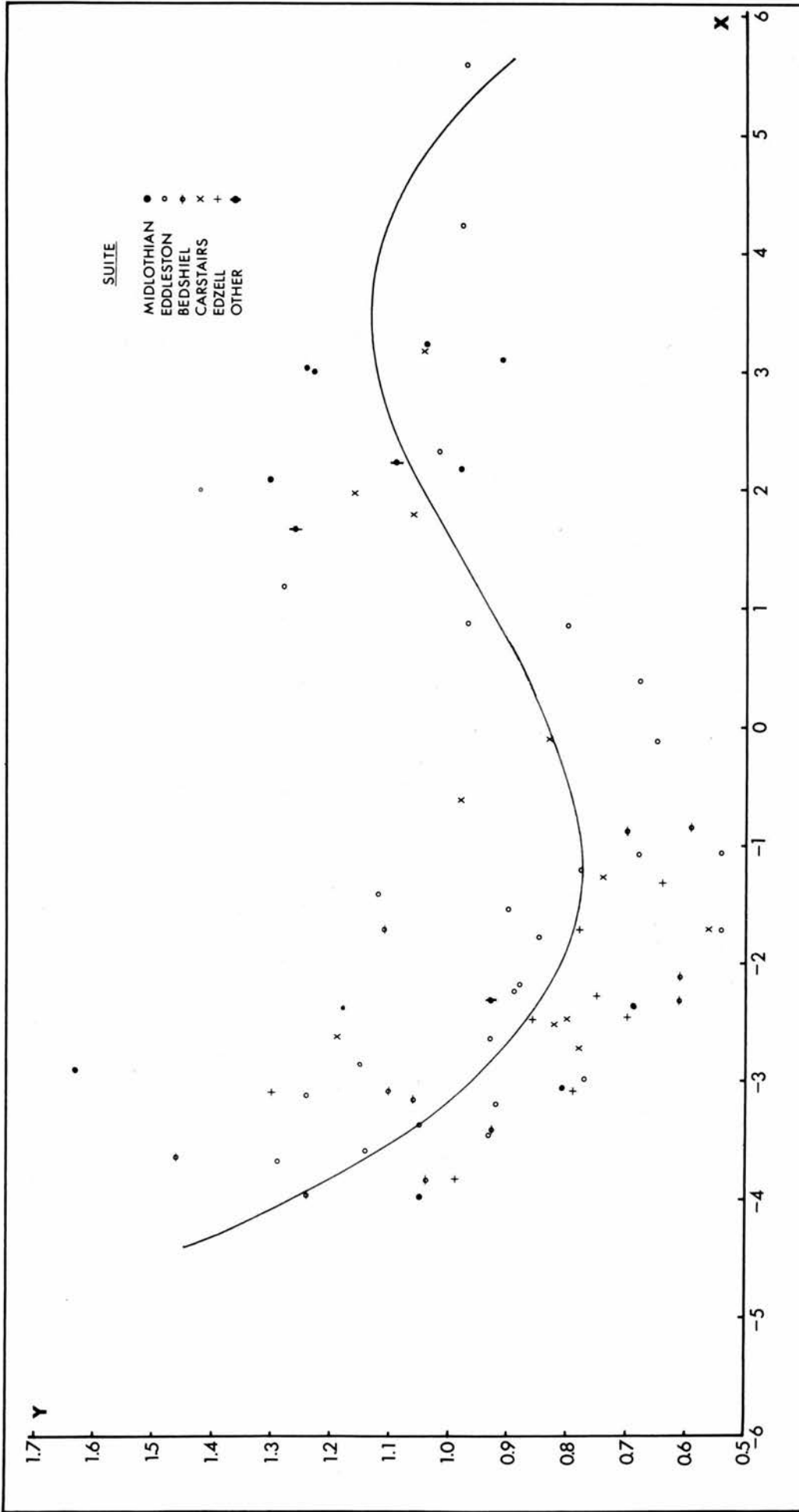


FIGURE 6.3a. All samples, differentiated by suite. Graphic Mean (ϕ units - X axis) versus Graphic Kurtosis (Y axis). Third degree curve fitted

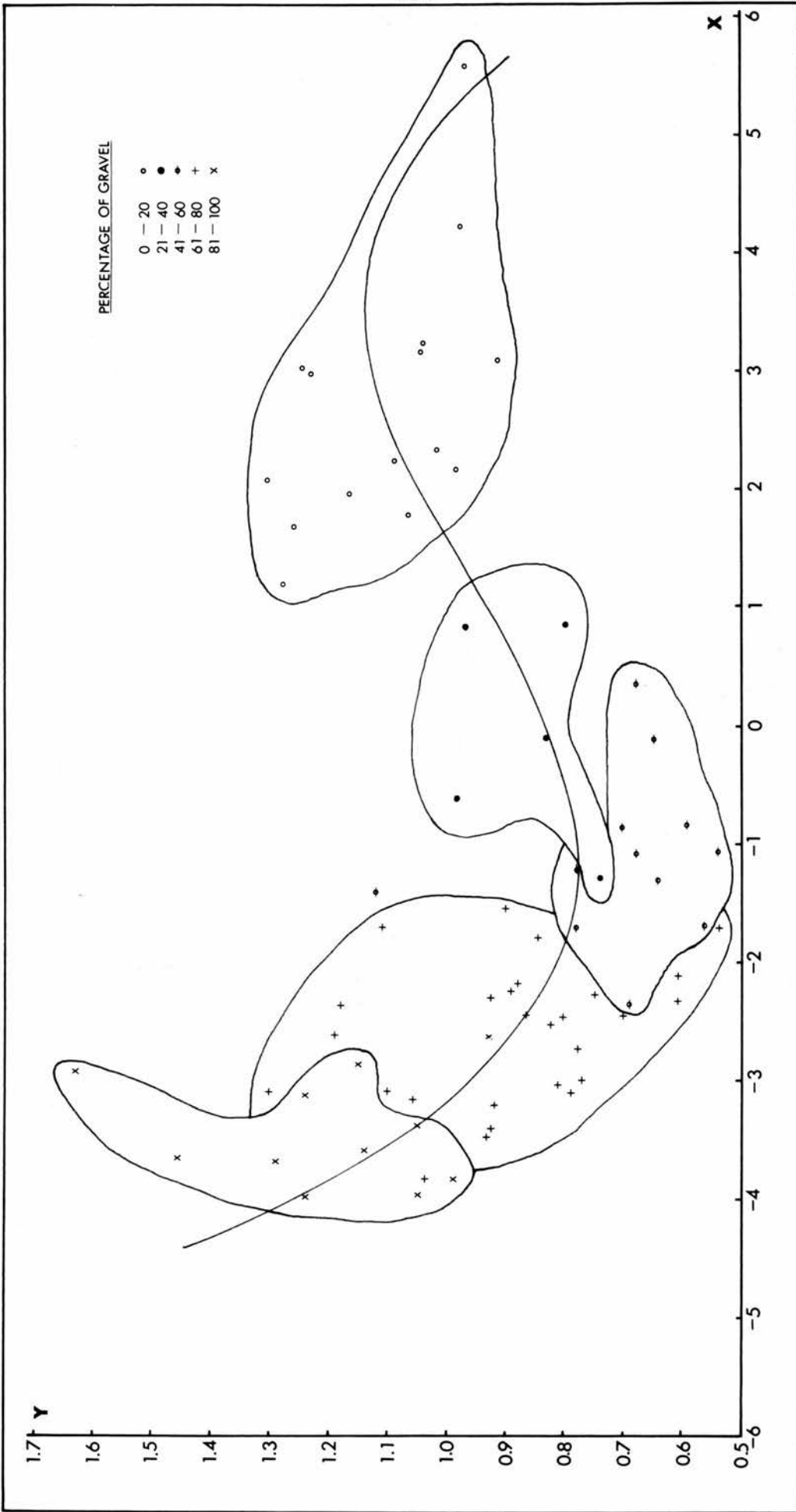


FIGURE 6.3b. All samples, differentiated by percentage gravel. Graphic Mean (ϕ units - X axis) versus Graphic Kurtosis (Y axis). Third degree curve fitted

KEY to FIGURES 6.3c to 6.3g

X-axis: Graphic Mean (ϕ units)
 Y-axis: Graphic Kurtosis

Percentage of Gravel in individual data points denoted as follows:

0 - 20% Gravel	- 1
21 - 40	2
41 - 60	3
61 - 80	4
81 - 100	5

Where curve fitted, degree of curve shown in top right-hand corner of Figure

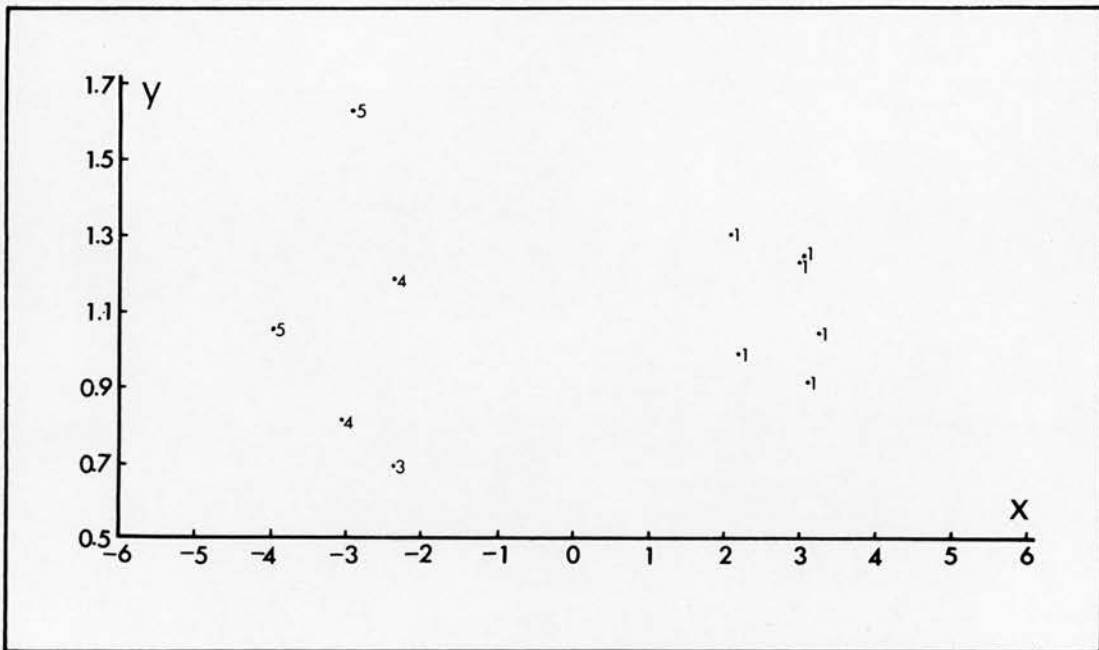


FIGURE 6.3c. Midlothian

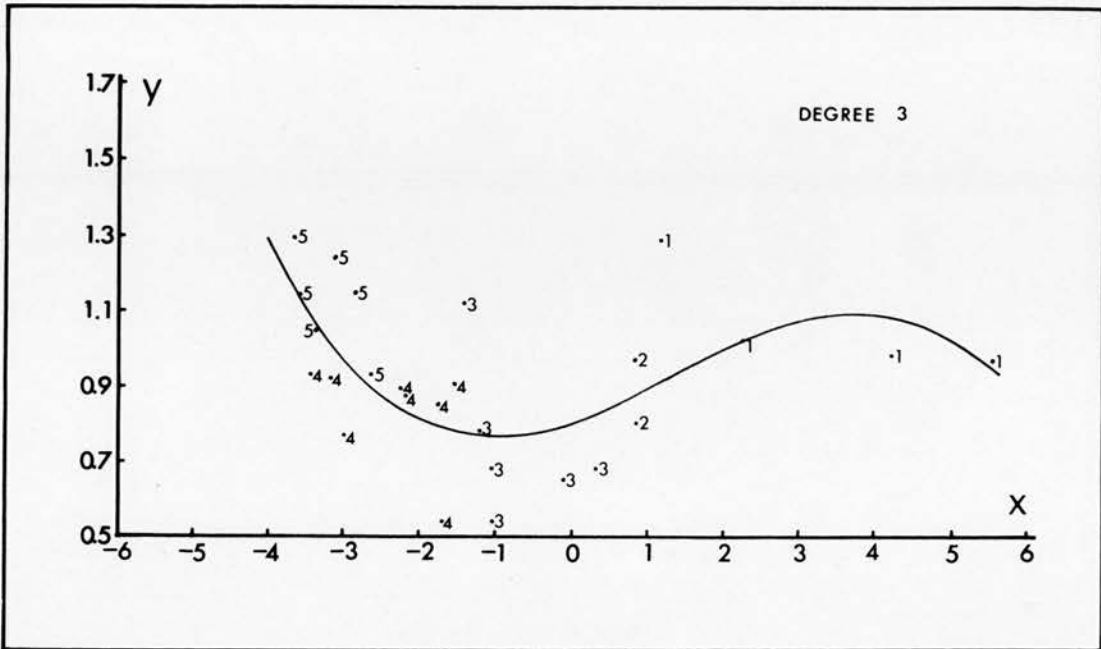


FIGURE 6.3d. Eddleston

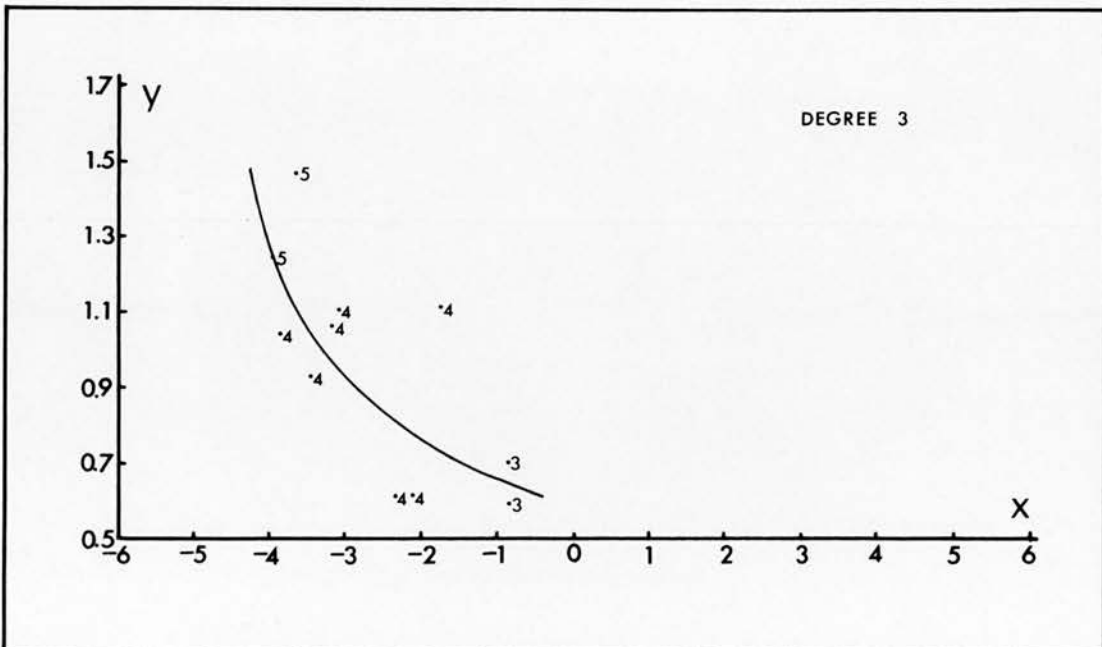


FIGURE 6.3e. Bedshiel

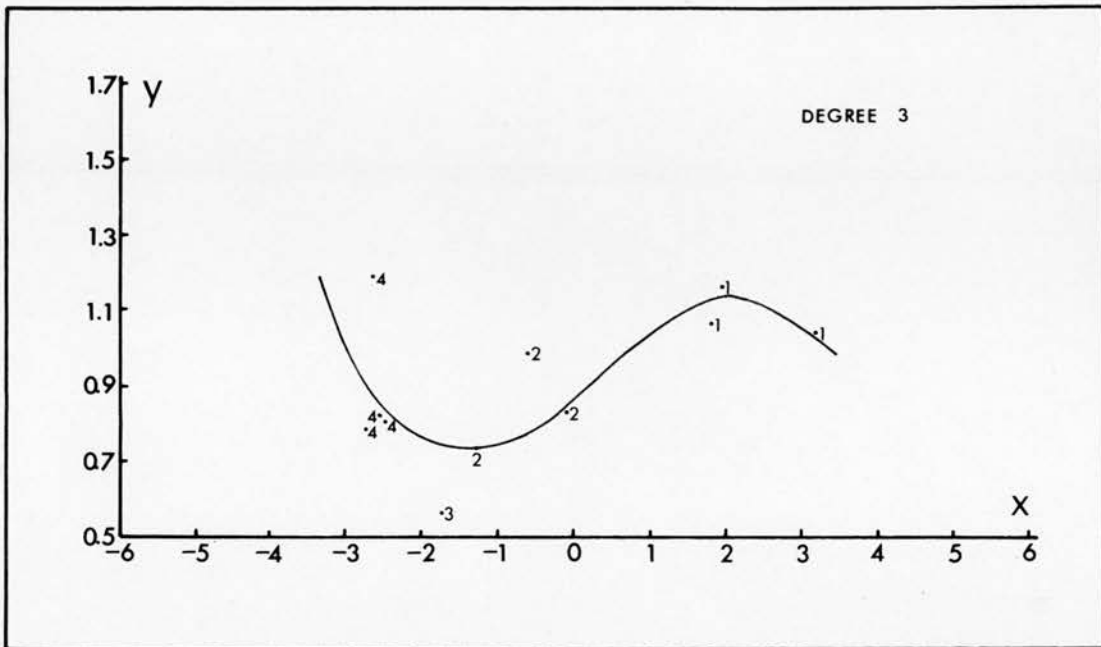


FIGURE 6.3f. Carstairs

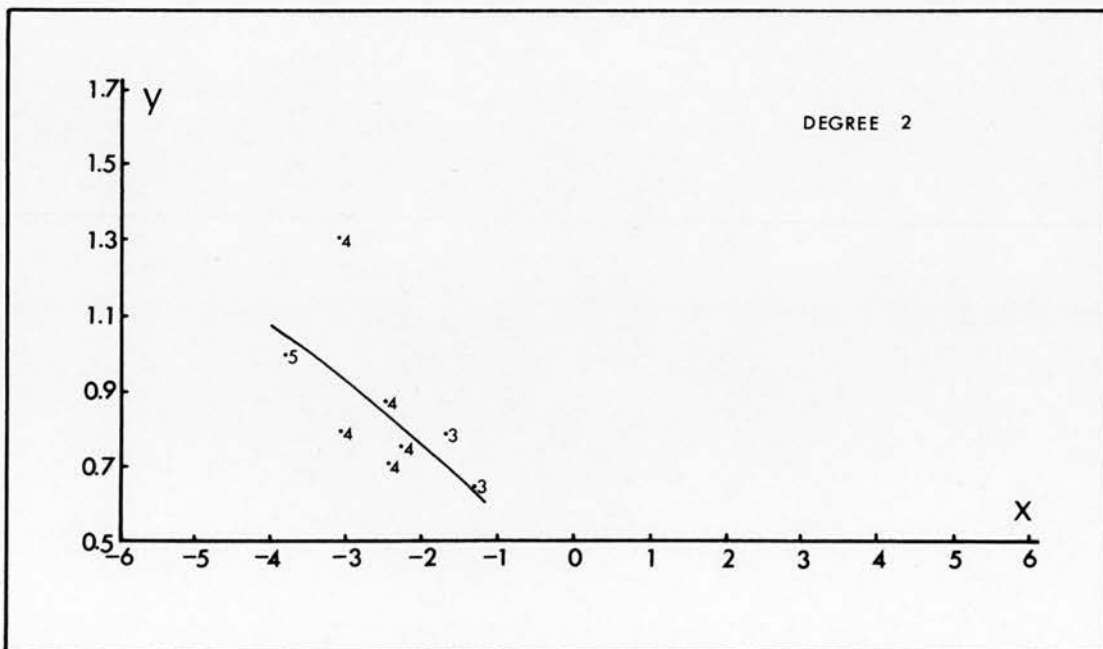


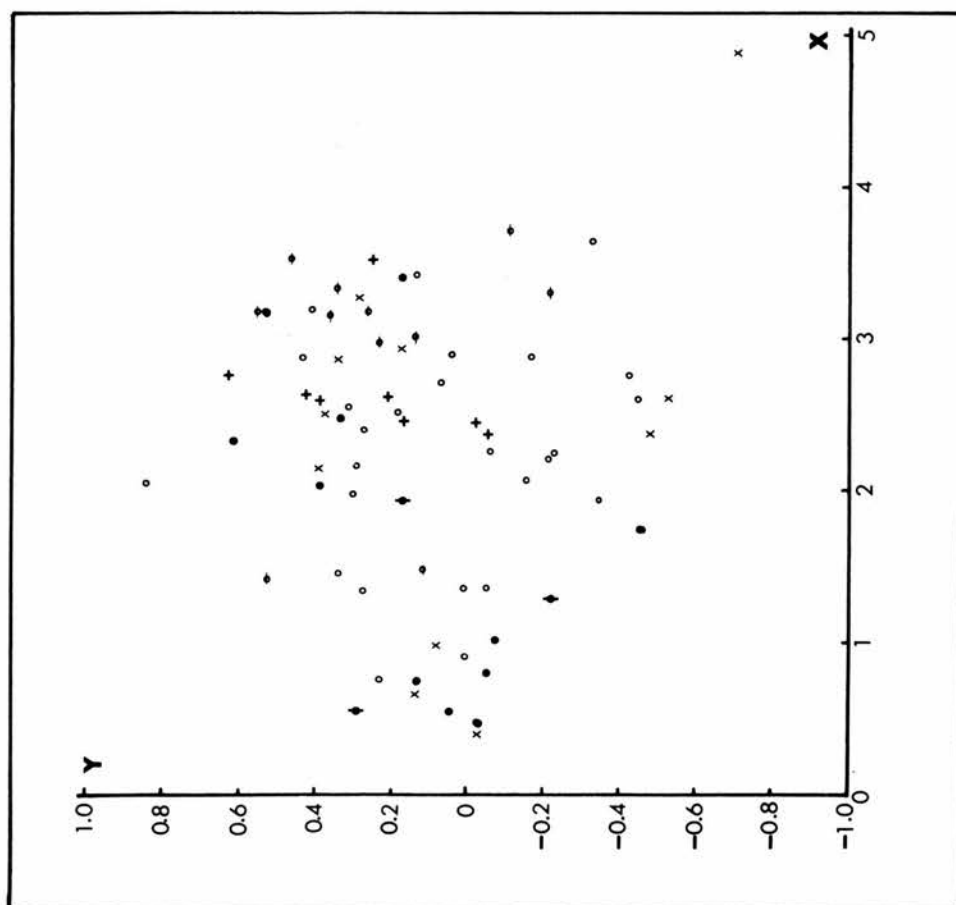
FIGURE 6.3g. Edzell

In general, the individual plots seem to follow the trend suggested (Figs. 6.3c to 6.3g). Samples in the largest percentage gravel class are clustered loosely round a kurtosis of 1.2 in the Eddleston kame plot (Fig. 6.3d), while 61 - 80 per cent gravel samples have kurtosis values close to 0.9. This follows closely the trend shown in Figure 6.3b, where the gravel class groups can be picked out with occasional anomalies. However, as can be seen from Figure 6.3a, a plot of mean size against kurtosis does not lead to any discernible separation of fluvioglacial landform types.

INCLUSIVE GRAPHIC STANDARD DEVIATION Vs. INCLUSIVE GRAPHIC SKEWNESS

As might be expected, as more complex measures are compared, the interrelationships between these measures of sediment characteristics become increasingly more intricate. In the case of standard deviation against skewness, there would appear to be a circular trend in the results plotted. This is more noticeable when the percentage gravel graph is studied (Fig. 6.4b). A circular succession can also be traced, by percentage of gravel, in all of the individual suite curves (Figs. 6.4c to 6.4f). The only exception is the Edzell outwash group of samples (Fig. 6.4g). The degree of circularity is of course due to the particular scales chosen, and "involute" would be a more accurate description of the distribution than "circular".

FIGURE 6.4a. All samples, differentiated by suite. Inclusive Graphic Standard Deviation (σ units - X axis) versus Inclusive Graphic Skewness (Y axis)



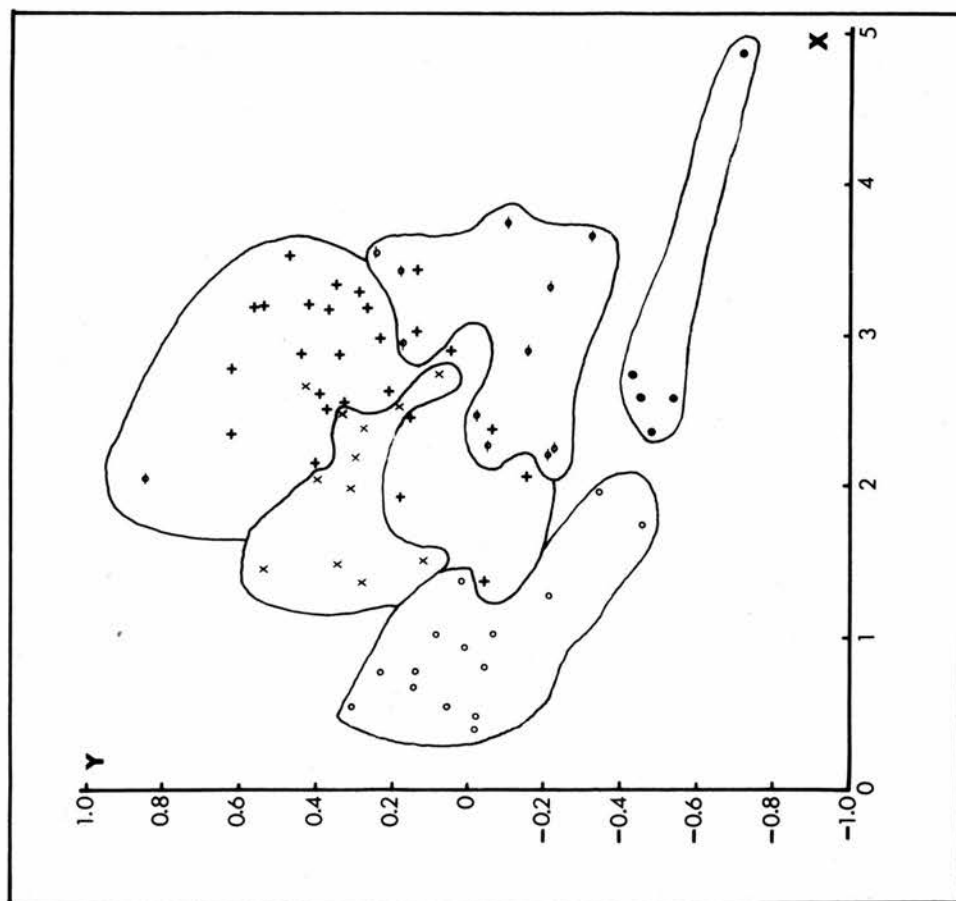
SUITE

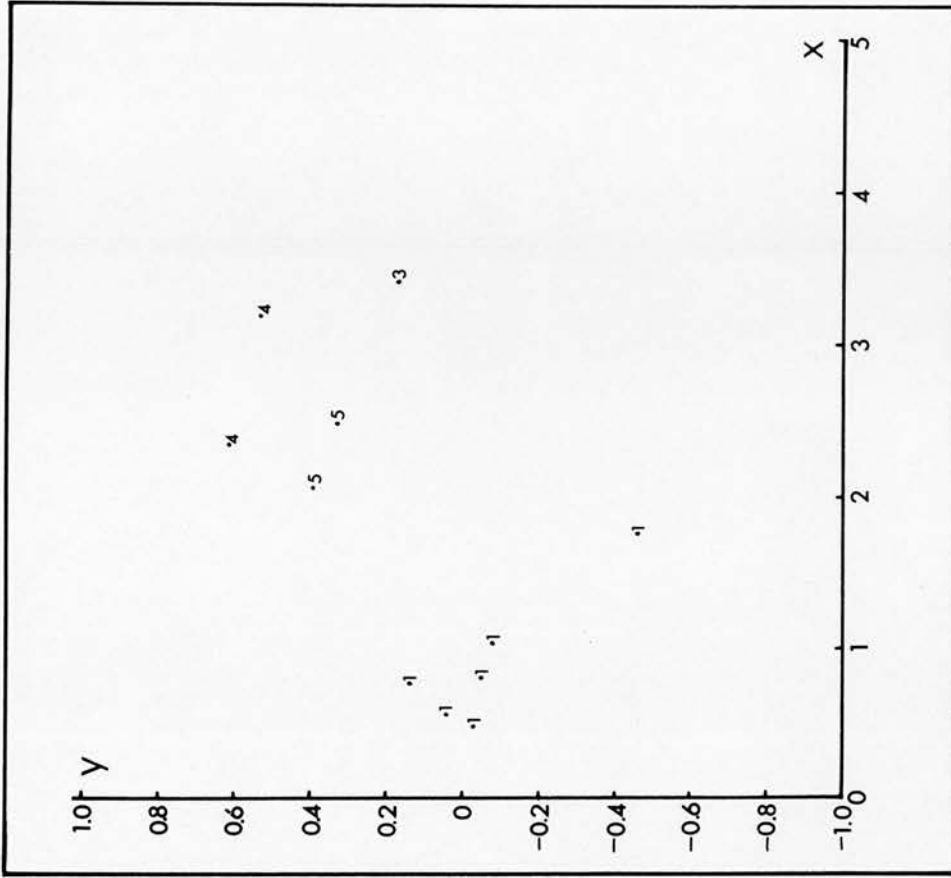
MIDLOTHIAN •
 EDDLESTON ○
 BEDSHIEL ◆
 CARSTAIRS x
 EDZELL +
 OTHER ◆

FIGURE 6.4b. All samples, differentiated by percentage gravel. Inclusive Graphic Standard Deviation (σ units - X axis) versus Inclusive Graphic Skewness (Y axis)

PERCENTAGE OF GRAVEL

0 -	20	°
21 -	40	•
41 -	60	•
61 -	80	+
81 -	100	x





KEY to FIGURES 6.4c to 6.4g

X-axis: Inclusive Graphic Standard Deviation (ϕ units)
 Y-axis: Inclusive Graphic Skewness

Percentage of Gravel in individual data points denoted as follows:

- 0 - 20% Gravel - 1
- 21 - 40 - 2
- 41 - 60 - 3
- 61 - 80 - 4
- 81 - 100 - 5

FIGURE 6.4c. Midlothian

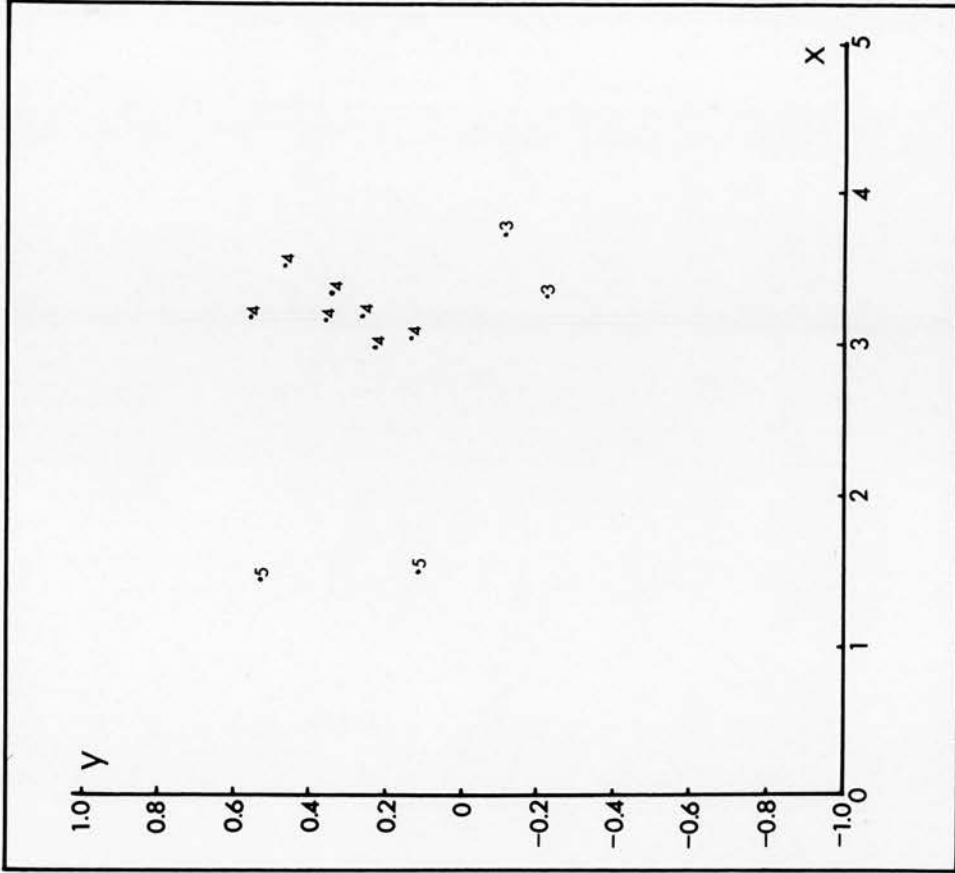


FIGURE 6.4e. Bedshiel

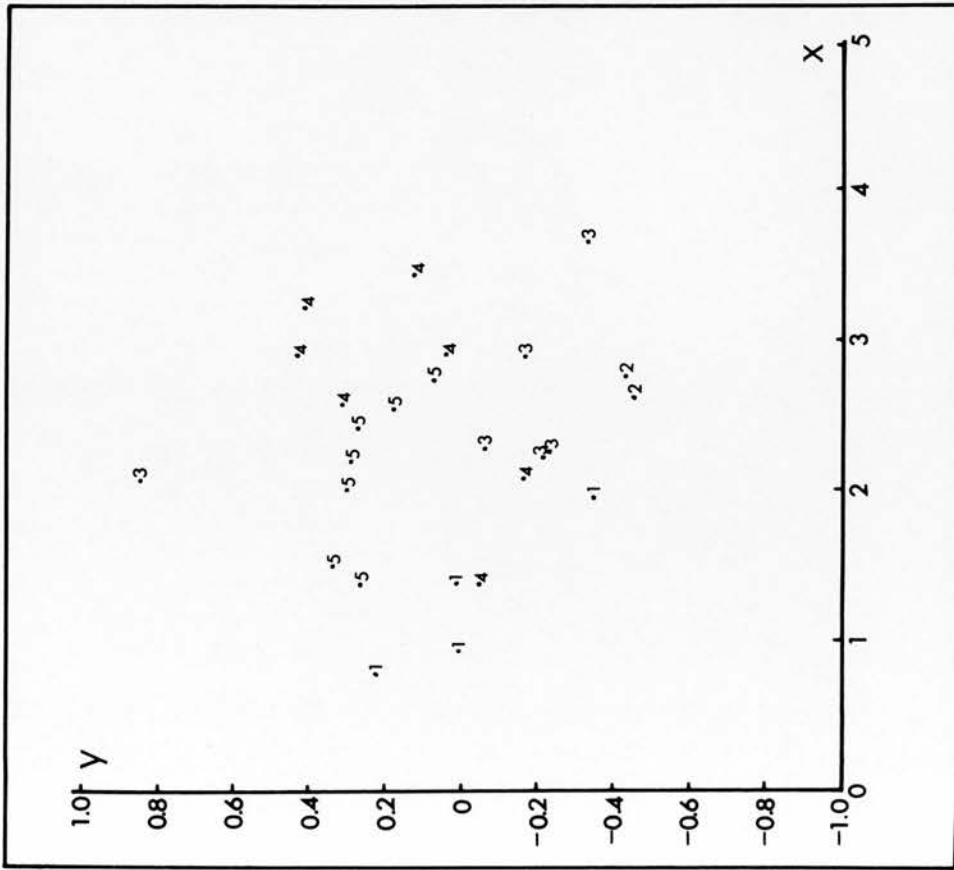


FIGURE 6.4d. Eddleston

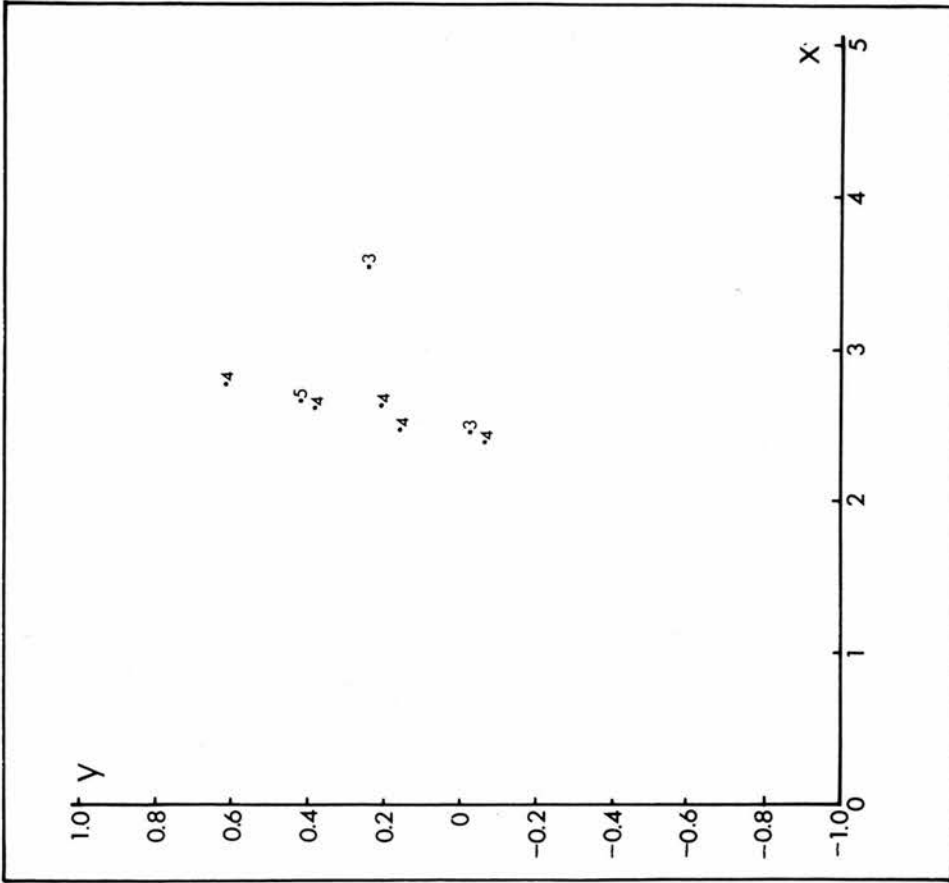


FIGURE 6.4g. Edzell

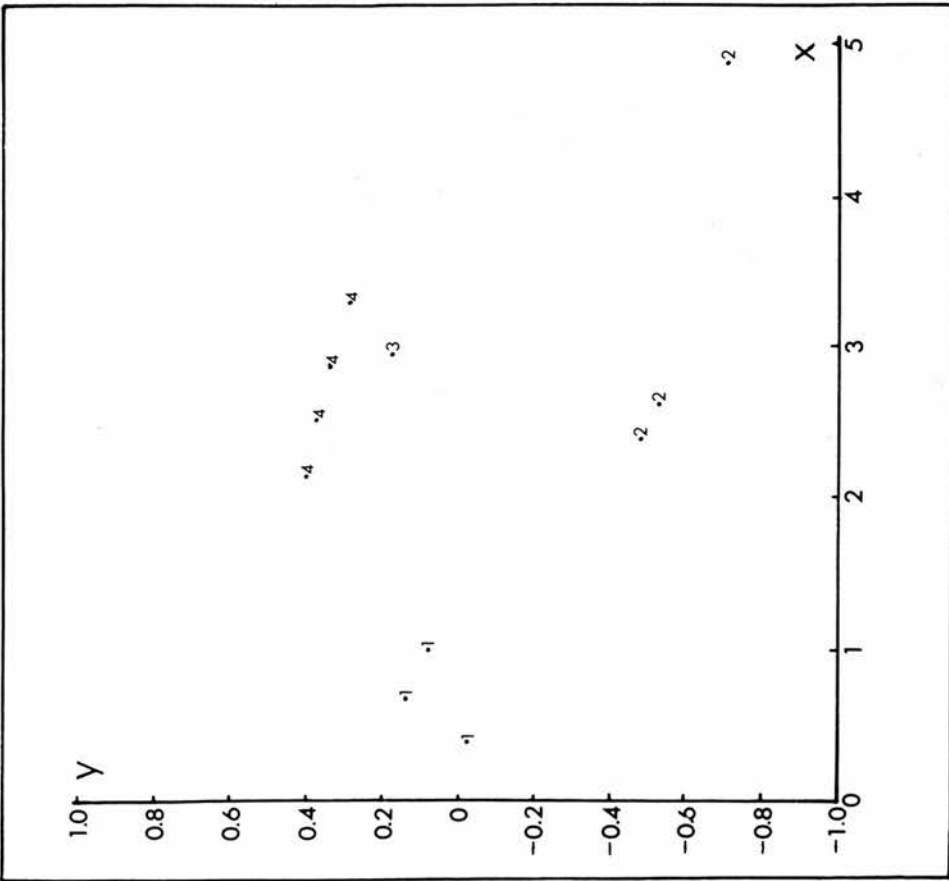


FIGURE 6.4f. Carstairs

Symmetrical curves, that is those with zero skewness, may be obtained in unimodal samples with good sorting. This is shown by the cluster of sand samples round the zero skewness mark. Samples containing equal mixtures of the two modes, which have the poorest possible sorting for any given suite of samples, ought also to have zero skewness. Again, samples containing 41 - 60 per cent gravel appear to be clustered, however loosely, around the line of zero skewness (Fig. 6.4b). Sand samples containing a "tail" of gravel are negatively skewed and have intermediate sorting values. Four of the five 21 - 40 per cent gravel samples are clustered in this position, with the anomalous Carstairs sample showing stronger negative skewness and an exaggerated apparent lack of sorting. Samples containing mainly gravel, but with a subordinate sand fraction, are found to have relatively strong positive skewness and exhibit an intermediate degree of sorting.

It was not meaningful to apply "Curvefit" to this particular data comparison as the program was not designed to deal with involute distributions. Therefore no curves have been fitted to this set of diagrams. However, the relatively high standard deviation of the Bedshiel esker sample is brought out, there being a noticeable clustering around a standard deviation of 3.25 units and a skewness ranging from +0.1 to +0.55 (Fig. 6.4e). This vertical grouping is even more noticeable with the outwash samples of Figure 6.4g. While standard deviation is approximately constant at 2.6 units, skewness ranges from -0.1 to +0.6. This would seem at first sight to indicate that skewness is a more sensitive measure

than standard deviation. Even though standard deviation, and hence degree of sorting, remains fairly constant in each of these sample groups, skewness varies considerably. The degree of asymmetry as measured by inclusive graphic skewness relies on the proportions of material in the tails of the distribution. In the cases quoted, the tail lies in the fine sand and silt fractions, and relatively slight variations in these fractions are picked out by the inclusive graphic skewness measure.

The involute nature of the distribution is brought out most clearly by the Midlothian kame outwash and Carstairs esker samples (Figs. 6.4c and 6.4f respectively). Five of the six Midlothian samples of less than 20 per cent gravel are clustered round zero skewness and standard deviation between 0.5 and 1.0 units. The sixth sample contains a much larger percentage of gravel than the others (10.6 per cent against the next highest of 1.8 per cent), has a correspondingly larger standard deviation (1.75 units), and is strongly negatively-skewed (-0.46).

Within the Carstairs esker suite, an even more striking succession appears in the samples containing between 70 and 80 per cent gravel (Table 6.2, Fig. 6.4f). With increasing content of gravel, standard deviation decreases and skewness rises. Without putting undue emphasis on these figures, it would seem that a plot of standard deviation against skewness might prove to be a sensitive indicator of changing conditions, reflected in changing gravel percentage. Closer study of the Bedshiel results underlines this trend, as percentage gravel rises more or less consistently with

increasing skewness in the samples containing between 40 and 80 per cent gravel (Table 6.3).

TABLE 6.2

Relation between gravel content, standard deviation and skewness,
Carstairs Esker samples

Sample No.	Percentage Gravel in Sample	Inclusive Graphic Standard Deviation	Inclusive Graphic Skewness
E 2.3	70.6	+3.27 ϕ units	+0.28
E 2.6	71.3	+2.88 ϕ units	+0.34
E 2.9	71.8	+2.51 ϕ units	+0.37
E 2.8	79.8	+2.15 ϕ units	+0.39

TABLE 6.3

Relation between gravel content, standard deviation and skewness,
Bedshiel Esker samples

Sample No.	Percentage Gravel in Sample	Inclusive Graphic Standard Deviation	Inclusive Graphic Skewness
E 1.2	45.6	+3.30 ϕ units	-0.22
E 1.4	47.6	+3.71 ϕ units	-0.11
E 1.1	60.1	+3.18 ϕ units	+0.26
E 1.3	75.5	+3.15 ϕ units	+0.36
E 1.7	77.1	+3.54 ϕ units	+0.46
E 1.9	78.0	+3.01 ϕ units	+0.13
E 1.5	78.2	+3.19 ϕ units	+0.55
E 1.11	78.3	+2.96 ϕ units	+0.23

With rise in percentage gravel, standard deviation tends to fall, though the fall is irregular in this case. Similar, though more confused, trends can be picked out within the other sample groups.

INCLUSIVE GRAPHIC STANDARD DEVIATION VS. GRAPHIC KURTOSIS

There is no clear relationship immediately obvious from the plot of standard deviation against kurtosis, but theoretical considerations clarify the picture. In general, poorest sorting is found in the bimodal mixtures with approximately equal amounts of the sand and gravel modes. These samples have the lowest kurtosis values, as can be seen from Figure 6.5b. Highest kurtosis is usually found where one mode dominates and the other mode is subordinate. These samples have moderate sorting. Best sorting corresponds, in the present case, to samples containing virtually no gravel, and these are clustered around the normal kurtosis mark, $K_G = 1.0$.

The trend can best be described as an inverted double V-shape, as can be seen by tracing the numbers on Figure 6.5b. From pure sand at 1, through sand with a small proportion of gravel (2) and sand with a substantial proportion of gravel (3), the low-kurtosis position of equal sand and gravel proportions is reached (4). As the proportion of gravel increases, kurtosis rises without substantial change in standard deviation (5). A position of gravel with small amounts of sand is reached (6), after which the trend is towards pure gravel samples of normal kurtosis (7). This type of succession

FIGURE 6.5a. All samples, differentiated by suite. Inclusive Graphic Standard Deviation (σ units - X axis) versus Graphic Kurtosis (Y axis)

SUITE

MIDLOTHIAN	•
EDDLESTON	◦
BEDSHIEL	◊
CARSTAIRS	x
EDZELL	+
OTHER	◆

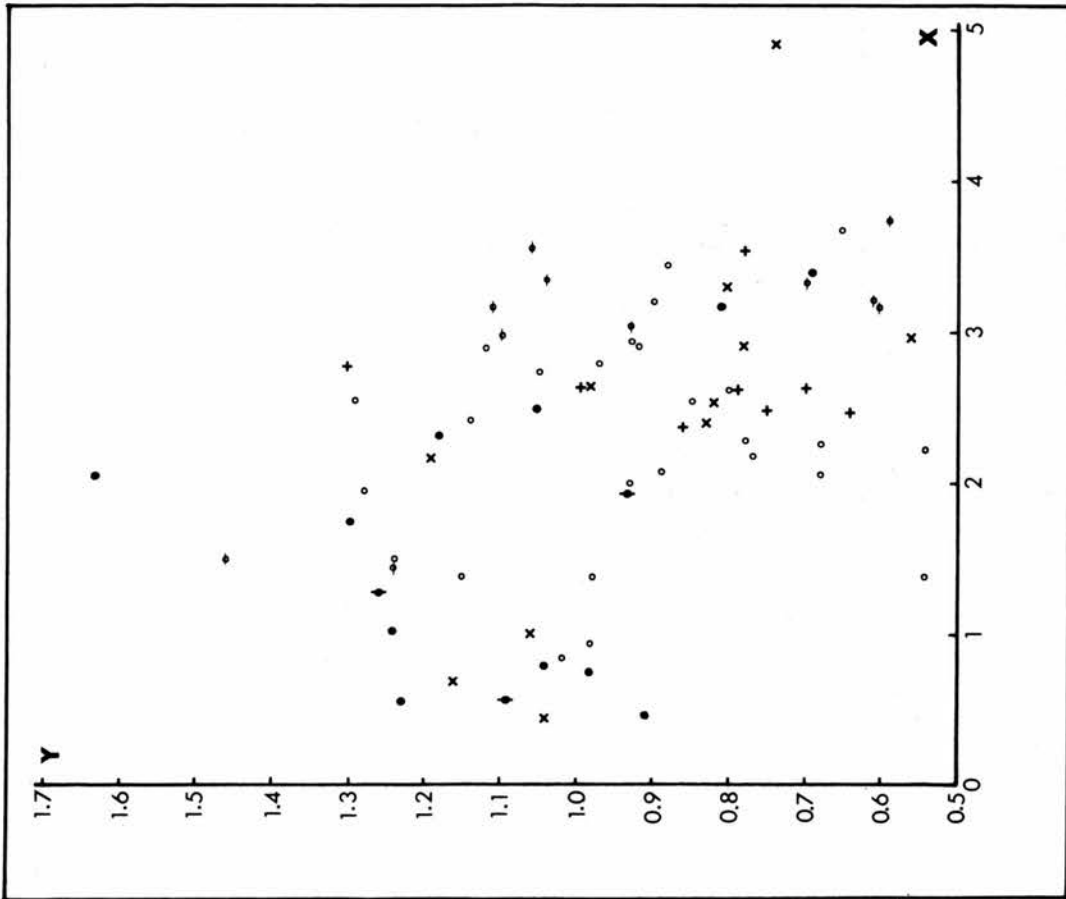
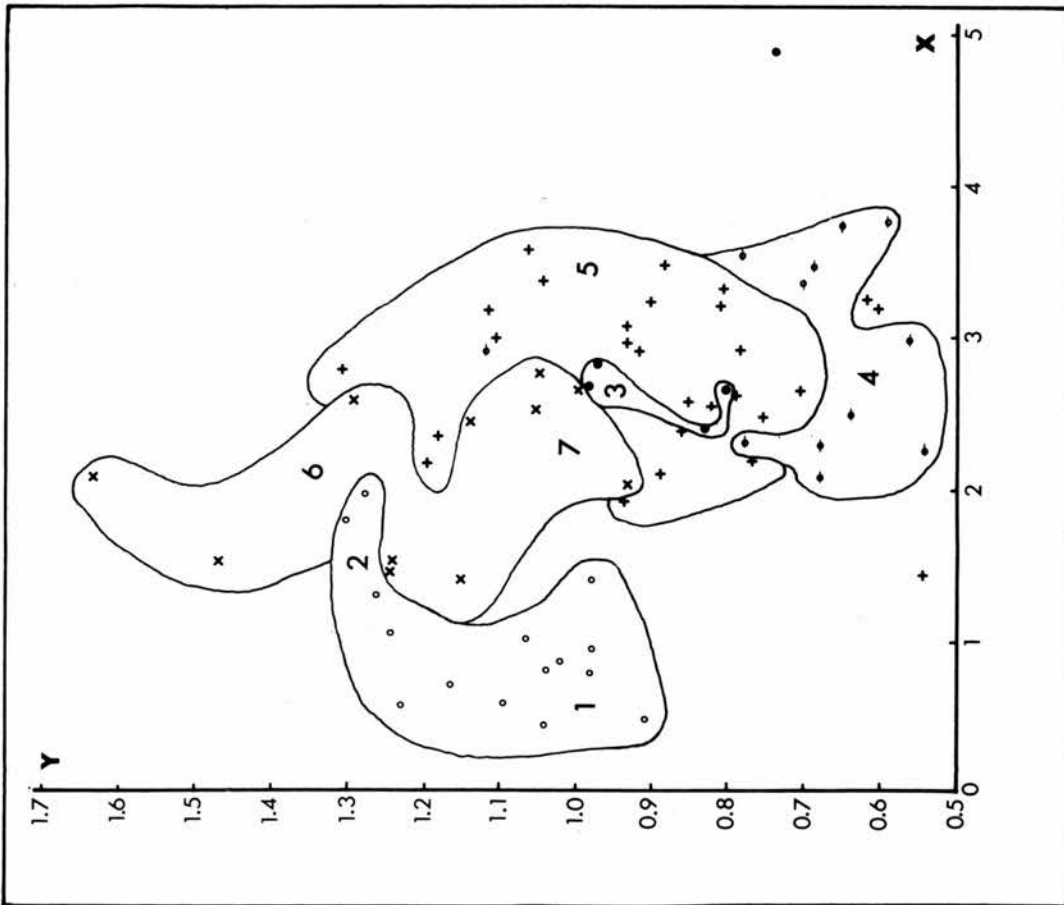
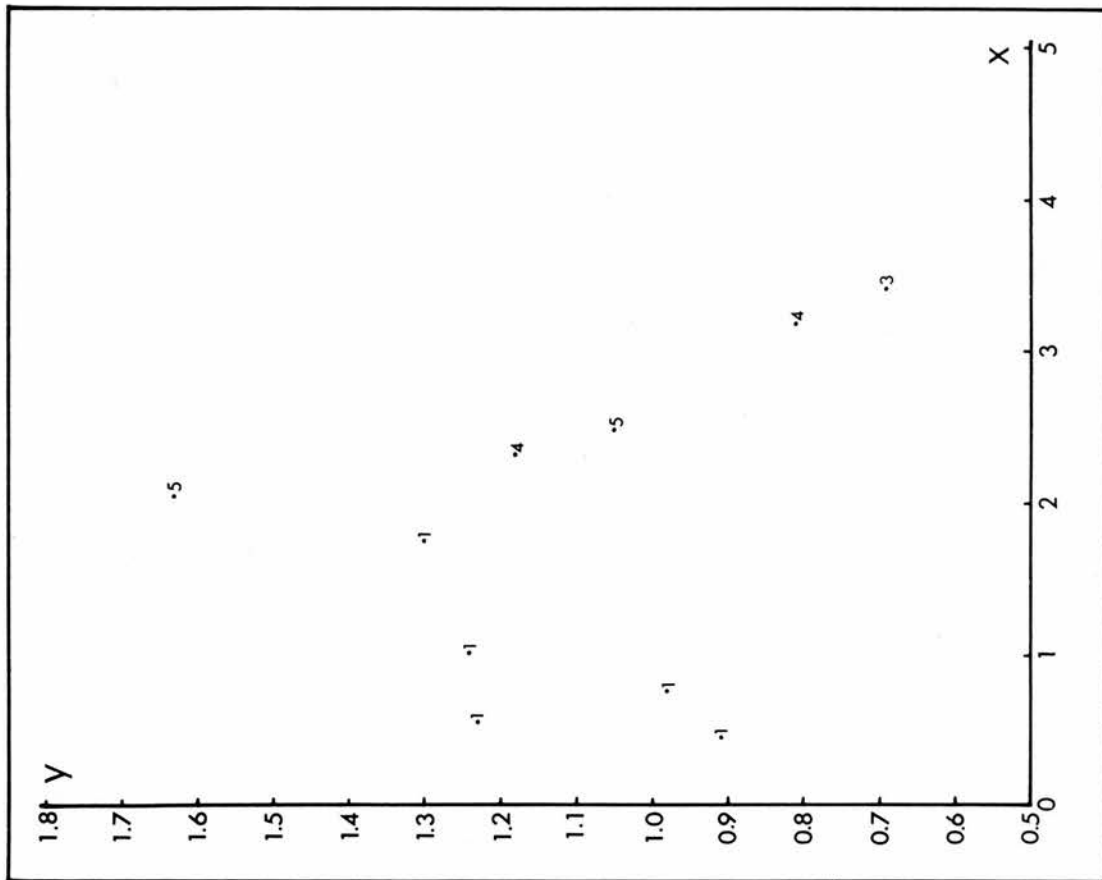


FIGURE 6.5b. All samples, differentiated by percentage gravel. Inclusive Graphic Standard Deviation (σ units - X axis) versus Graphic Kurtosis (Y axis)



PERCENTAGE OF GRAVEL

0	-	20	•
21	-	40	•
41	-	60	+
61	-	80	+
81	-	100	x



KEY to FIGURES 6.5c to 6.5g

X-axis: Inclusive Graphic Standard
Deviation (ϕ units)
Y-axis: Graphic Kurtosis

Percentage of Gravel in individual
data points denoted as follows:

- 0 - 20% Gravel - 1
- 21 - 40 - 2
- 41 - 60 - 3
- 61 - 80 - 4
- 81 - 100 - 5

FIGURE 6.5c. Midlothian

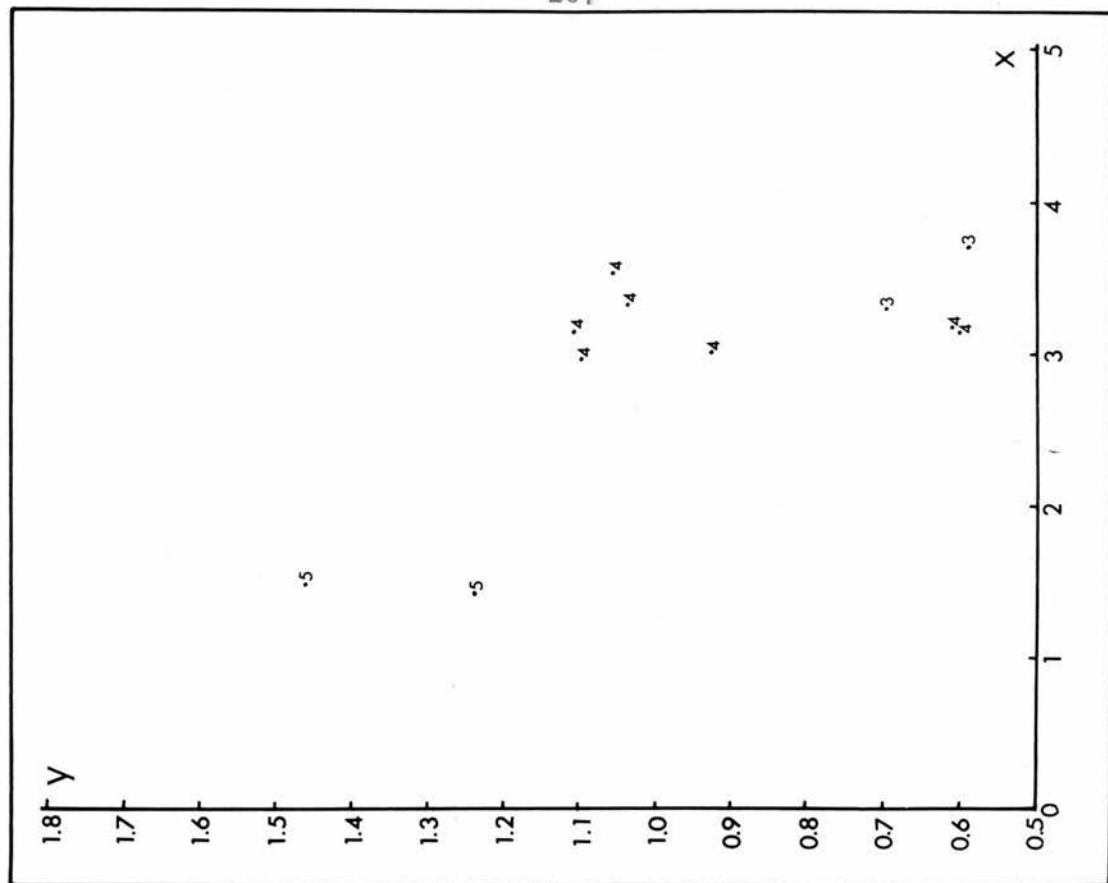


FIGURE 6.5d. Eddleston

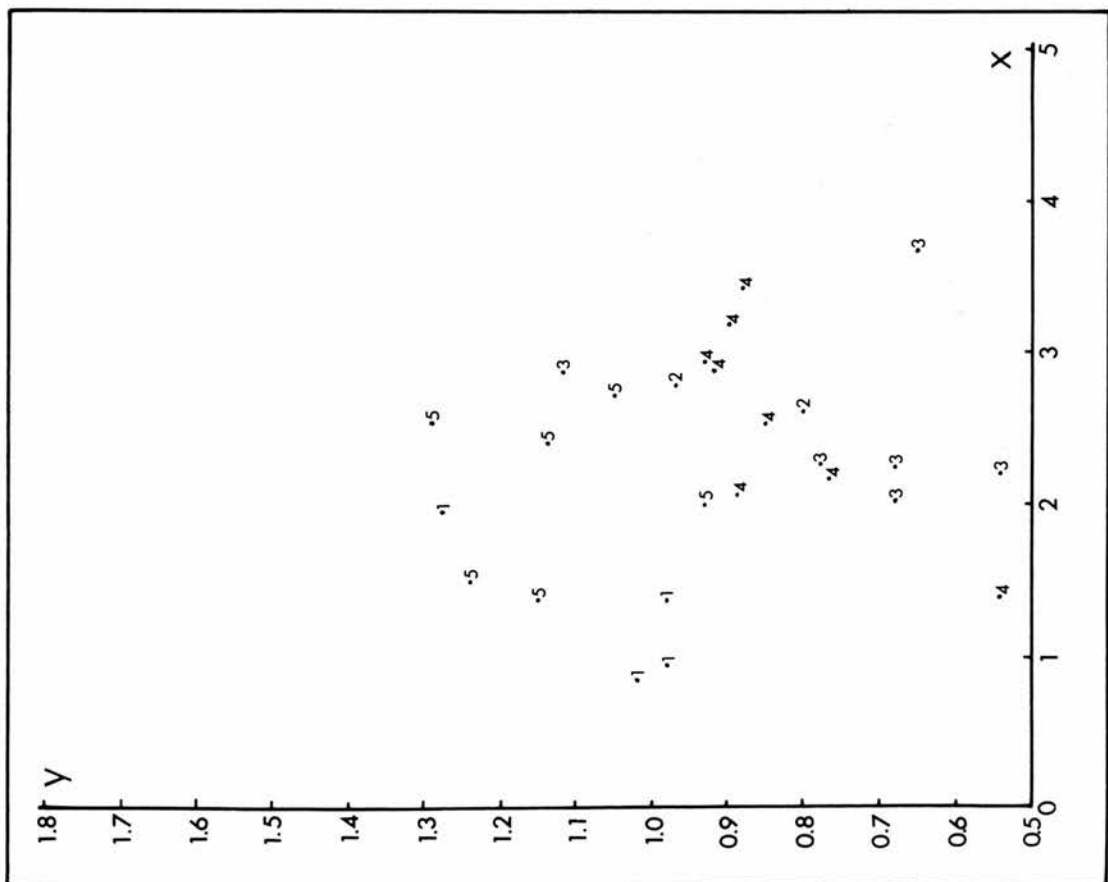


FIGURE 6.5e. Bedshiel

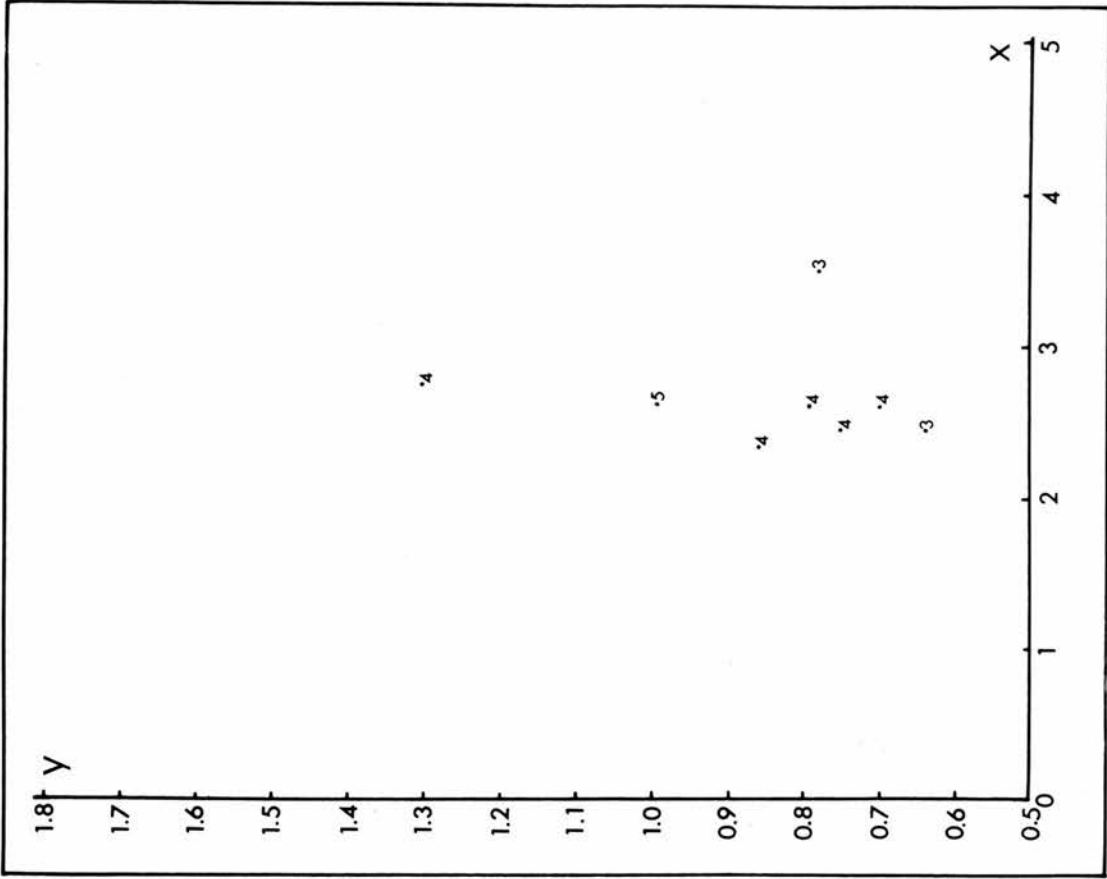


FIGURE 6.5g. Edzell

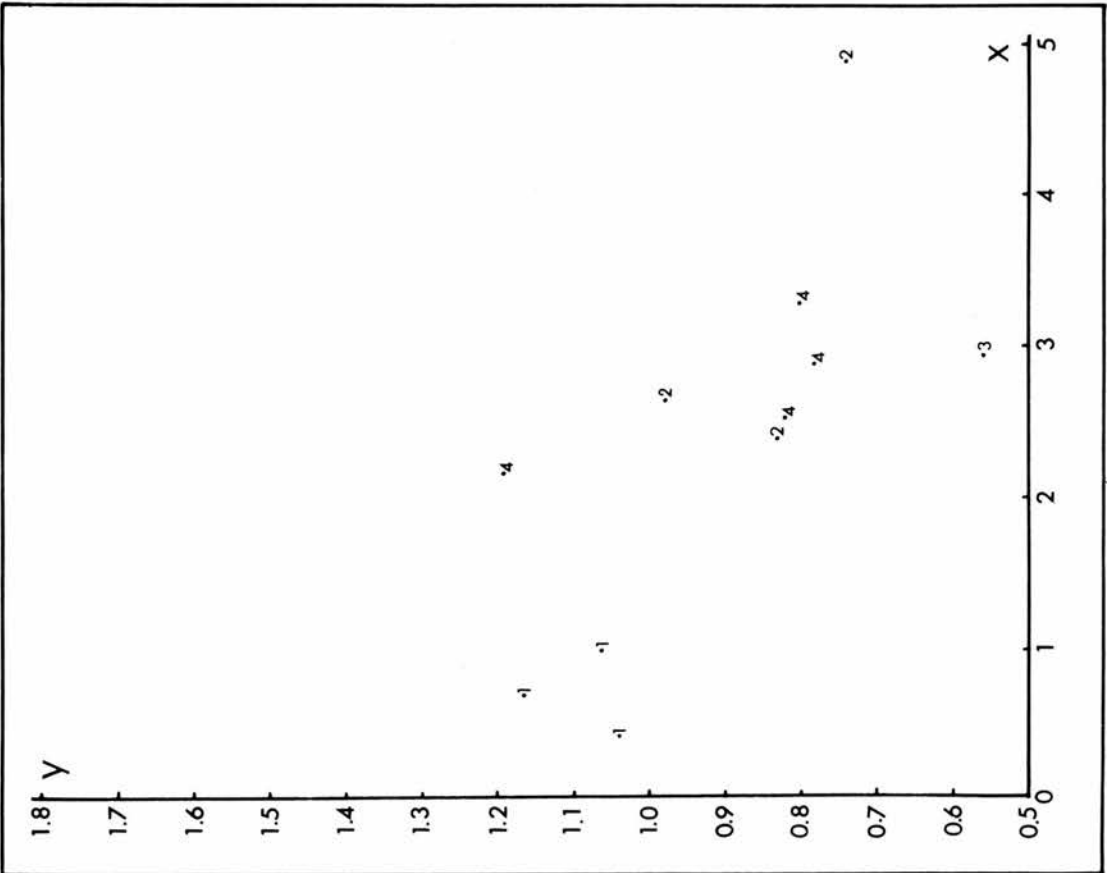


FIGURE 6.5f. Carstairs

can be traced through all separate plots except the outwash plot (Fig. 6.5g), but is rather complicated for meaningful interpretation to be made.

INCLUSIVE GRAPHIC SKEWNESS Vs. GRAPHIC KURTOSIS

Both skewness and kurtosis depend to a great extent on the proportions of the two modes present and are indicators of the degree of bimodality of a distribution. When compared, however, no clear pattern emerges. The numbers on Figure 6.6b trace out a roughly circular sequence which agrees to some extent with theoretical considerations, but variations from this sequence are too great for any weight to be attached to the succession of figures.

The pure sand mode has zero skewness and normal kurtosis (point 1 on Fig. 6.6b). The addition of a small amount of gravel to the pure sand mode produces a slight negative skewness, but a considerably higher kurtosis (2). Increasing amounts of gravel lower kurtosis to a minimum point where amounts of the two modes are approximately equal, and skewness is hence roughly zero (3). As the percentage of gravel in the sample increases, kurtosis gradually rises without significant change in skewness (4, 5, 6). Gravel samples with a small but significant sand fraction are extremely leptokurtic (6), while more pure gravel modes have kurtosis values of about 1.0 (7).

FIGURE 6.6a. All samples, differentiated by suite. Inclusive Graphic Skewness (X axis) versus Graphic Kurtosis (Y axis)

SUITE

- MIDLOTHIAN
- EDDLESTON
- ◊ BEDSHIEL
- x CARSTAIRS
- + EDZELL
- ◈ OTHER

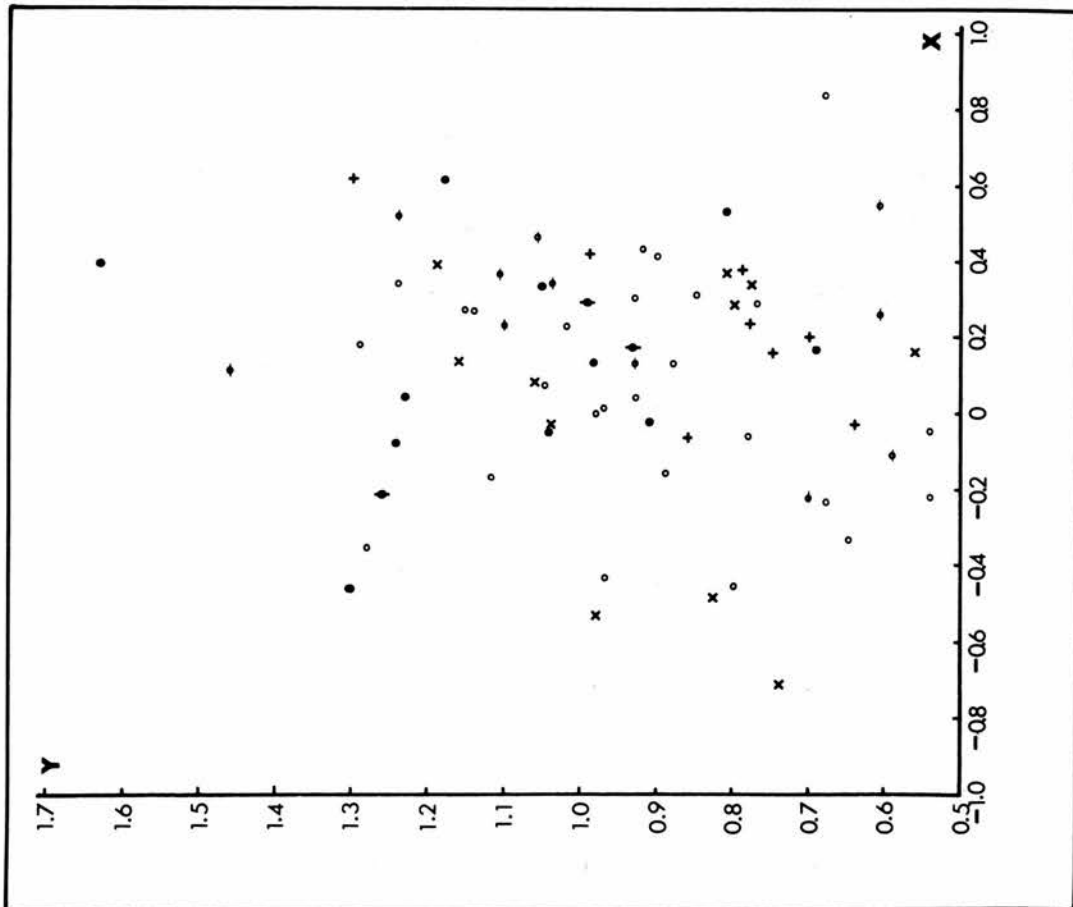
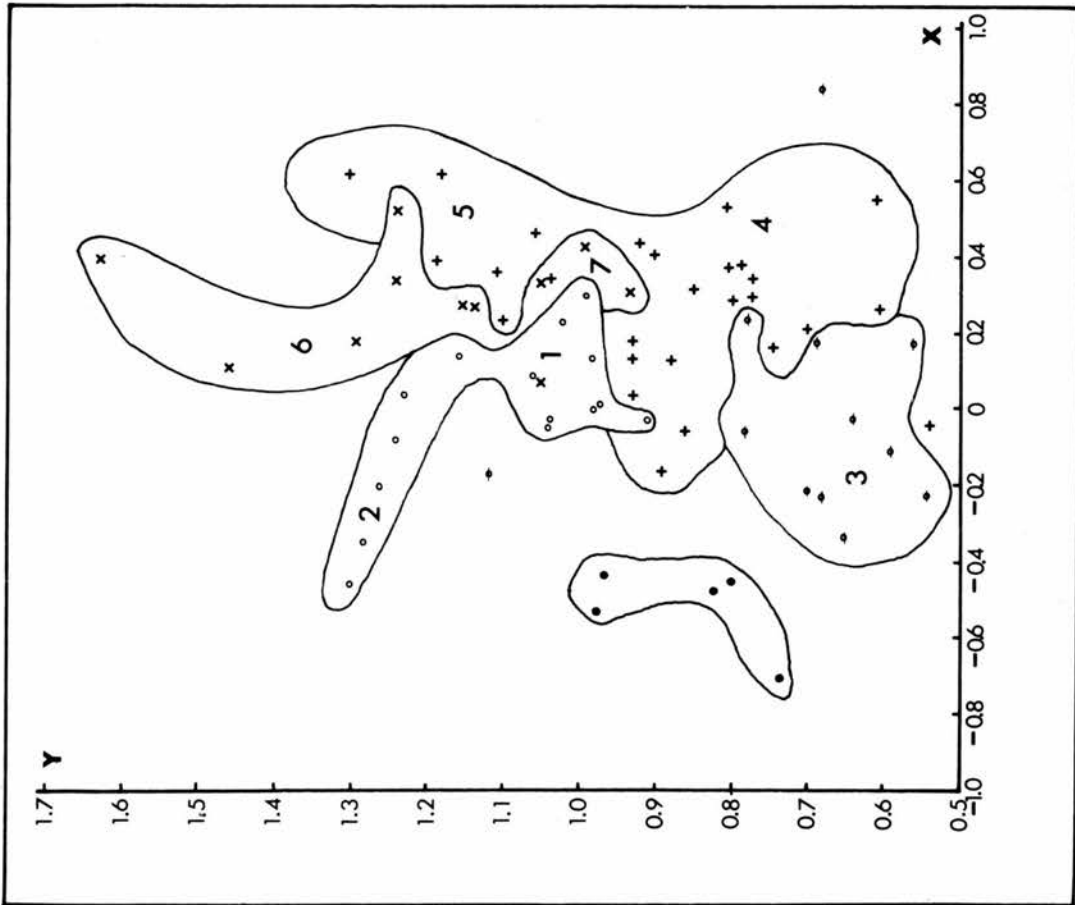
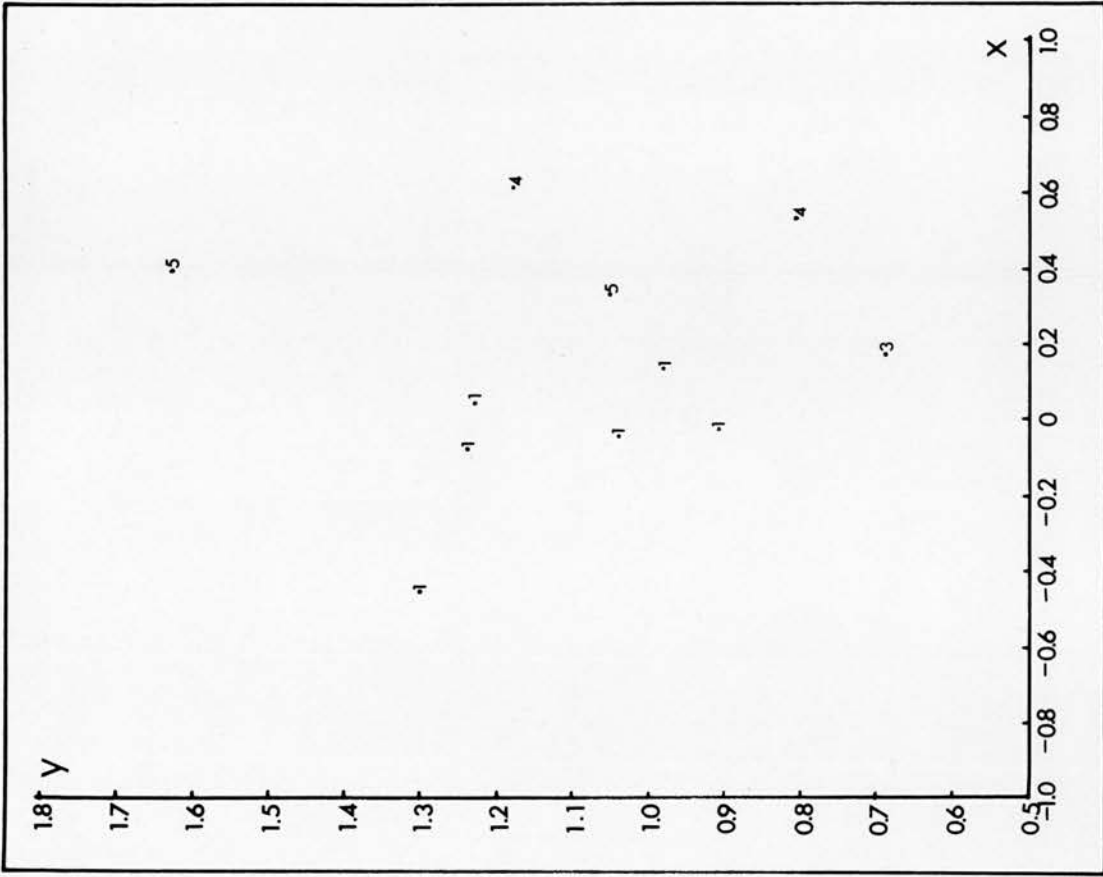


FIGURE 6.6b. All samples, differentiated by percentage gravel. Inclusive Graphic Skewness (X axis) versus Graphic Kurtosis (Y axis)

PERCENTAGE OF GRAVEL

- 0 - 20 °
- 21 - 40 •
- 41 - 60 ◊
- 61 - 80 +
- 81 - 100 x





KEY to FIGURES 6.6c to 6.6g

X-axis: Inclusive Graphic Skewness
 Y-axis: Graphic Kurtosis

Percentage of Gravel in individual data points denoted as follows:

- 0 - 20% Gravel - 1
- 21 - 40 - 2
- 41 - 60 - 3
- 61 - 80 - 4
- 81 - 100 - 5

FIGURE 6.6c. Midlothian

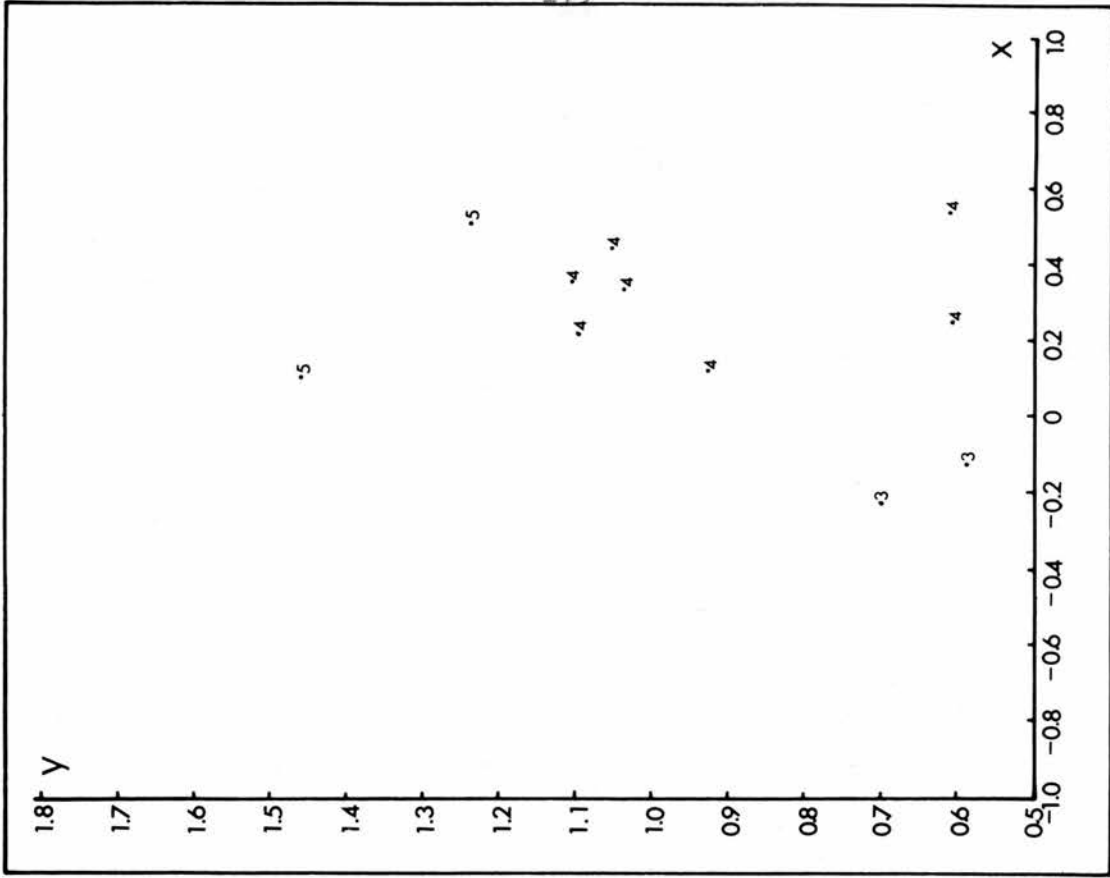


FIGURE 6.6d. Eddleston

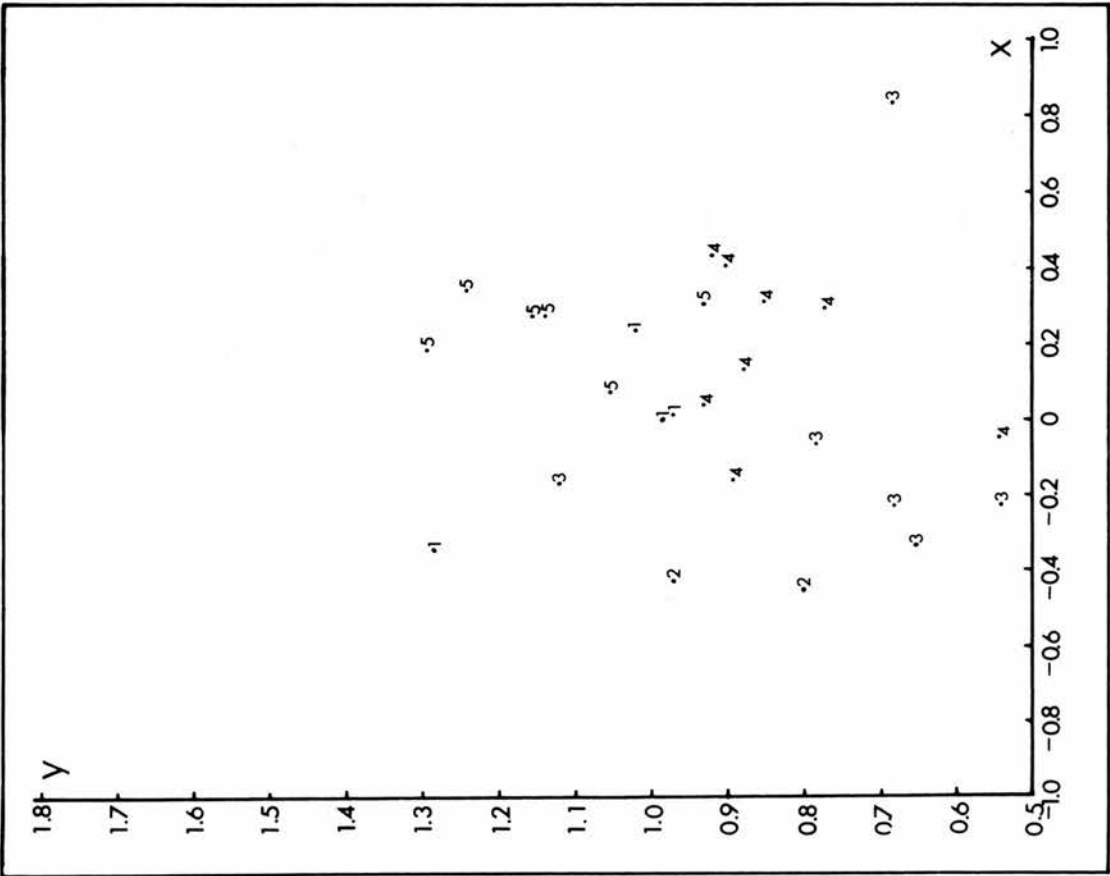


FIGURE 6.6e. Bedshiel

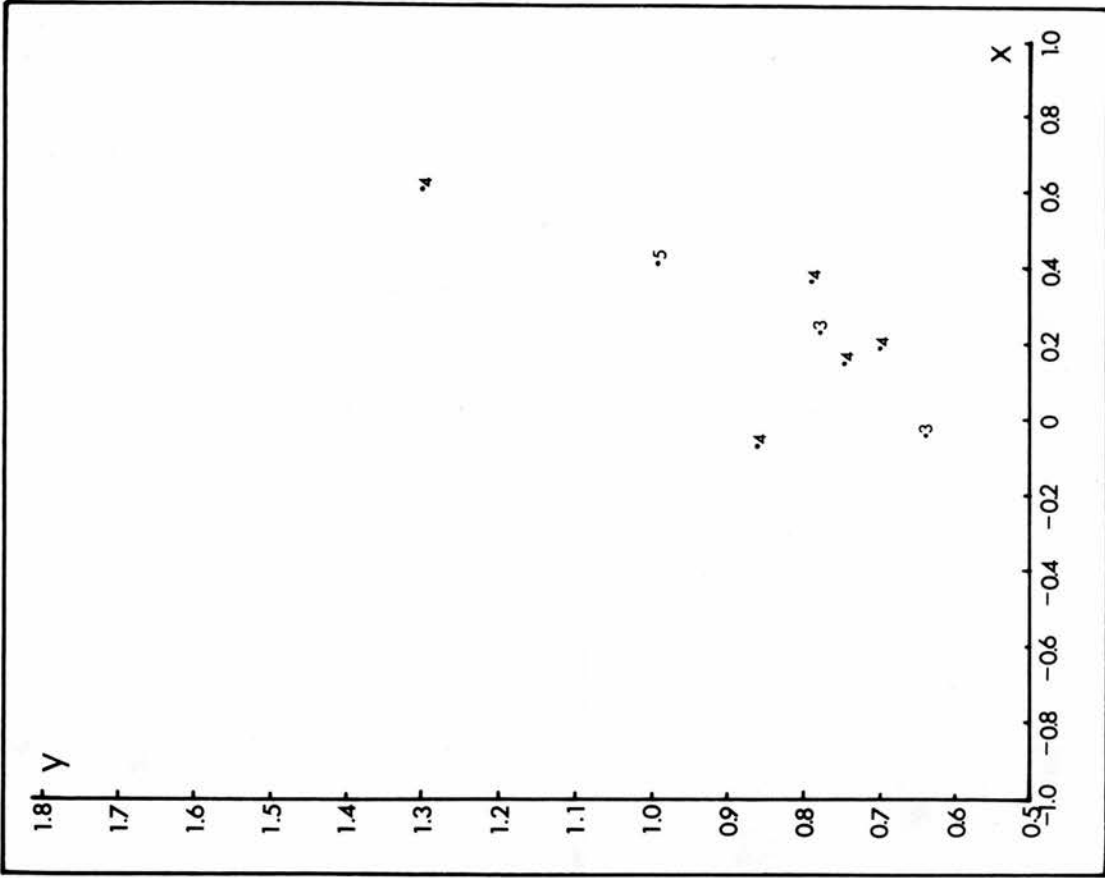


FIGURE 6.6g. Edzell

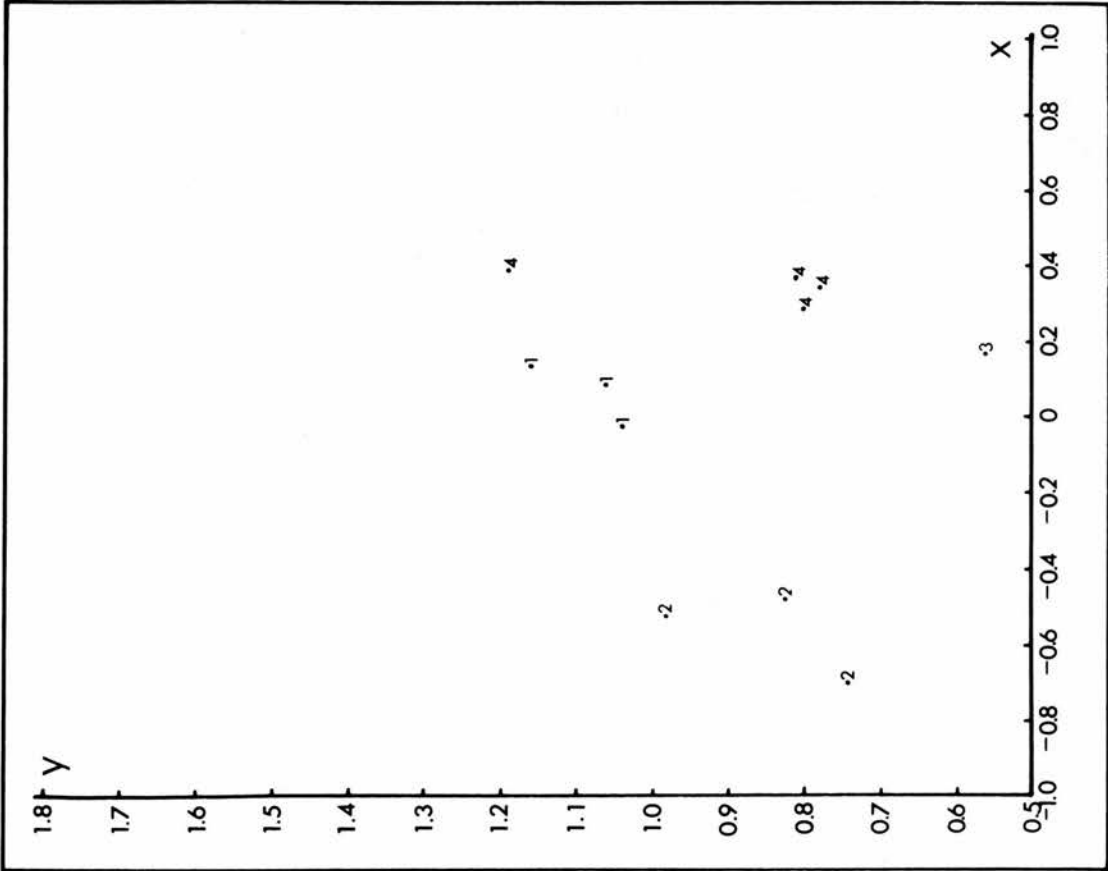


FIGURE 6.6f. Carstairs

As stated earlier, the amount of local variation present is sufficient to mask this theoretical trend. Samples containing 61 - 80 per cent gravel cover virtually the entire range of kurtosis values as well as having a wide range of skewness values. That such variation is due in large part to the different origins of the suites of features incorporated in Figures 6.6a and 6.6b seems self-evident. For example, there is a concentration of outwash samples in a position of low kurtosis of 0.70 to 0.80 and positive skewness of about +0.20 to +0.30 (Fig. 6.6g). The Bedshiel esker samples, as can be seen from Figure 6.6e, are divided into two groups, one clustered around kurtosis of about 1.10 and positive skewness of approximately +0.30 to +0.40, and another group of extremely low kurtosis and variable skewness. On the whole, however, the relationship between skewness and kurtosis shown by the various suites is diffuse and can best be described as "exhibiting an involute tendency."

SUMMARY

In summary, it would appear at first sight that the potentialities of this method of distinguishing between fluvioglacial landform types are limited. General principles emerge, however. The graphs of percentage gravel suggest that the successions developed in a fluvial environment are paralleled in fluvioglacial conditions of deposition. The similarity of curves fitted to the entire range of samples for each data comparison and the corresponding

Eddleston kame samples suggest that these curves are typical of fluvioglacial environments. The Eddleston group of samples is by far the largest group in the study, but only the Edzell outwash samples are consistently different in their trend as compared with the overall trend.

TABLE 6.4

Average parameter values of samples with over 40 per cent gravel

Suite	Percentage Gravel	G. Mean	I. G. S. D.	G. Skewness	G. Kurtosis
Midlothian	<u>76.76</u>	<u>-2.94</u>	+2.68 units	<u>+0.40</u>	<u>+1.07</u>
Eddleston	68.00	<u>-2.15</u>	<u>+2.41</u> units	<u>+0.13</u>	+0.90
Bedshiel	71.74	-2.64	<u>+2.93</u> units	+0.24	+0.95
Carstairs	69.95	-2.41	+2.75 units	+0.31	<u>+0.83</u>
Edzell	<u>67.59</u>	-2.54	+2.67 units	+0.24	+0.85

 = Highest value

_____ = Lowest value

Study of the average grain size measures of samples with more than 40 per cent gravel shows that the Midlothian samples have the highest overall mean size (Table 6.4). As the Midlothian gravel samples also exhibited the highest average percentage of gravel, this would seem logical. Midlothian gravel samples also show the highest average skewness and kurtosis of the five groups of samples. Standard deviation is intermediate however. It would perhaps be

Expected that samples with high standard deviation should have a correspondingly low kurtosis value, but this is not the case with these average sample values. Highest standard deviation is in fact shown by the Bedshiel esker samples, a fact which has been noted earlier. The Bedshiel samples have the second highest average gravel percentage, mean size and kurtosis, but have a relatively low average skewness.

Lowest average percentage of gravel is found in the Edzell outwash samples, and lowest average kurtosis is exhibited by the Carstairs suite of samples. Lowest average mean, standard deviation and skewness are all found in the Eddleston samples, which also average the second lowest gravel content at 68.0 per cent. Although Eddleston and Edzell samples average virtually identical gravel percentages, there is a relatively large difference in average graphic mean, -2.15ϕ and -2.54ϕ respectively. This could be explained in terms of depositional environment. Outwash gravels, presumably, are subject to more washing out of sand-sized particles during seasons of reduced meltwater flow. On the other hand, kame gravels, such as Eddleston, are buried more rapidly during formation. There is much less likelihood of periods of relative quiescence of flow washing out sand-sized particles. However, the outwash samples have a more positive average skewness than the Eddleston samples, indicating a stronger "tail" of fine material. The average fines fraction of the Edzell samples, 1.3 per cent, is much smaller than that of the Eddleston material, 3.3 per cent. This proves that the larger average skewness of the Edzell gravels is caused fundamentally

by a greater concentration of material in the larger pebble grades. The tail is in fact partly made up of the finer gravels.

The poorest-sorted samples are those taken from the Bedshiel esker. This could be a consequence of a certain amount of sorting downslope during postglacial slip. However, the second poorest sorting is found in the Carstairs esker gravel samples. These two suites also show intermediate gravel percentage, mean size and skewness. In other words, the esker samples analysed prove to be average apart from being more poorly sorted than the outwash kame deposits. One would perhaps expect outwash deposits to be better size-sorted than the more heterogeneous esker and kame deposits, but this is not apparent with the present range of samples. In most data comparisons, the outwash samples have appeared to be anomalous in terms of the broad trends followed by other samples.

The Eddleston kame samples show a relatively low average gravel percentage, and, as a group, have the lowest graphic mean value and hence smallest average grain size. They also show the best degree of sorting and have the least positive skewness. The relatively low sorting values may be connected with the relatively small graphic mean size. Kame samples would be expected to display a greater degree of heterogeneity than outwash samples and possibly also than esker samples. Although no strong conclusions can be drawn from the figures presented, the relatively poor degree of sorting encountered in esker samples may be of significance. A much larger number of samples from a wider variety of features would be necessary to test this.

CHAPTER 7. RESULTS OF THE MORPHOLOGICAL ANALYSIS

OF SELECTED PEBBLES

The purpose of pebble morphology study in the present work is parallel with that of the mechanical grain size analysis detailed in Chapter 6, namely to attempt to differentiate between environments of deposition of fluvioglacial landforms. As with grain size analysis, the only direct application to fluvioglacial gravel-sized particles thus far published is that of King and Buckley (1968).

The derivations of the parameters used - long axis length, sphericity and roundness - are set out in Chapter 3. The laboratory results are set down throughout this chapter with the necessary minimum of discussion. Fuller discussion will follow in succeeding chapters, in conjunction with inferences to be drawn from the results set down in Chapter 6.

SIZE ANALYSIS OF PEBBLES SELECTED - WHOLE SAMPLES

The pebbles selected from each sample were compared by calculating mean long axis length and standard deviation for each set of 100 pebbles. Mean and standard deviation were then plotted against each other. Every individual sample was plotted in Figure 7.1. These were then plotted as individual suites (Figs. 7.2a to 7.2e). The correlation coefficient was calculated for each set of figures, and regression lines were constructed of mean (independent variable) against standard deviation (dependent variable). 95 per cent confidence limits were drawn for Figure 7.1.

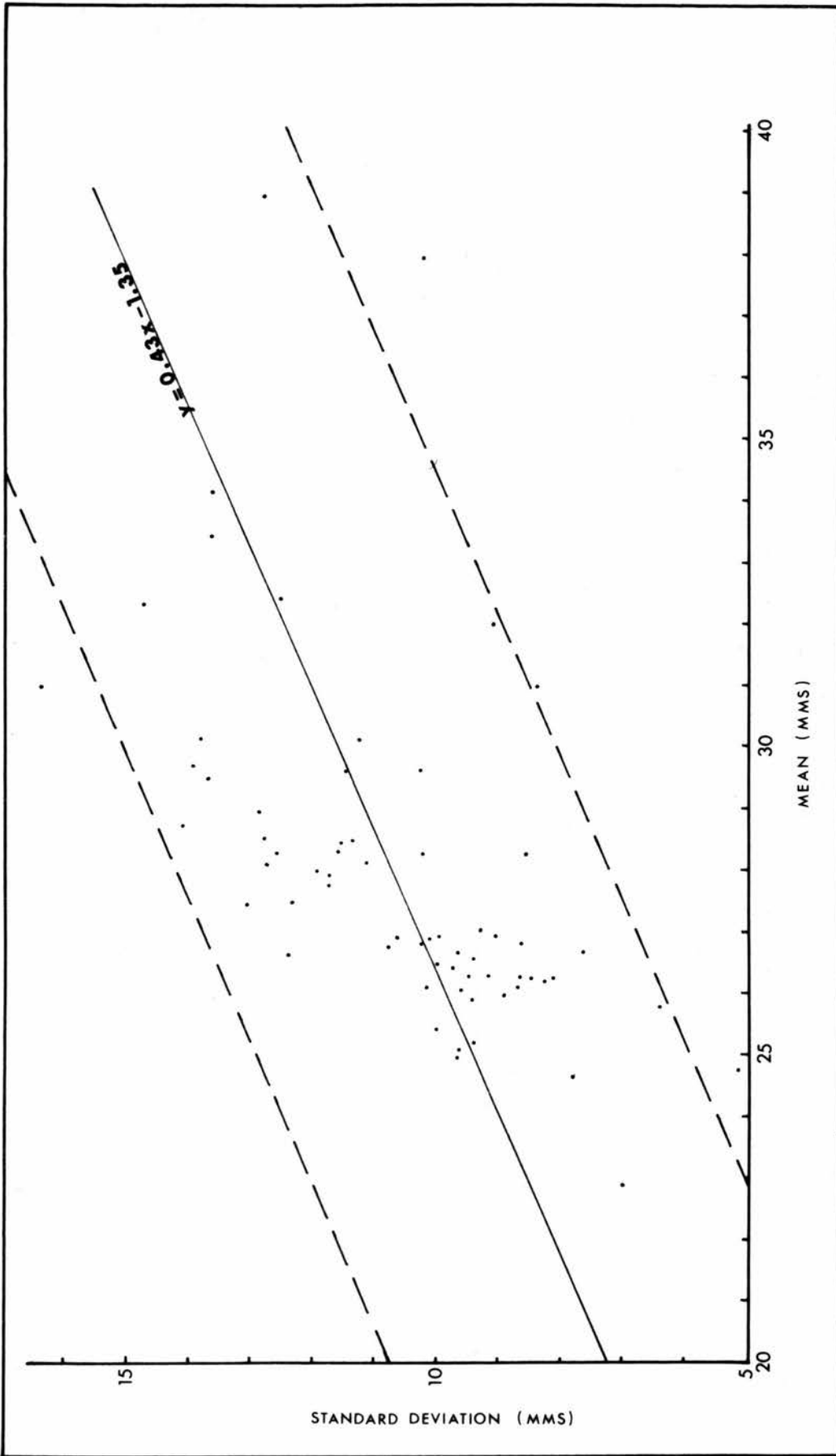


FIGURE 7.1. Long axis length of all samples. Mean versus standard deviation. Confidence limits at 95 per cent. $n=63$, $r=+0.56$

FIGURES 7.2a to 7.2e. Long axis length of individual suite samples. Mean versus standard deviation. For n and r see Table 7.1

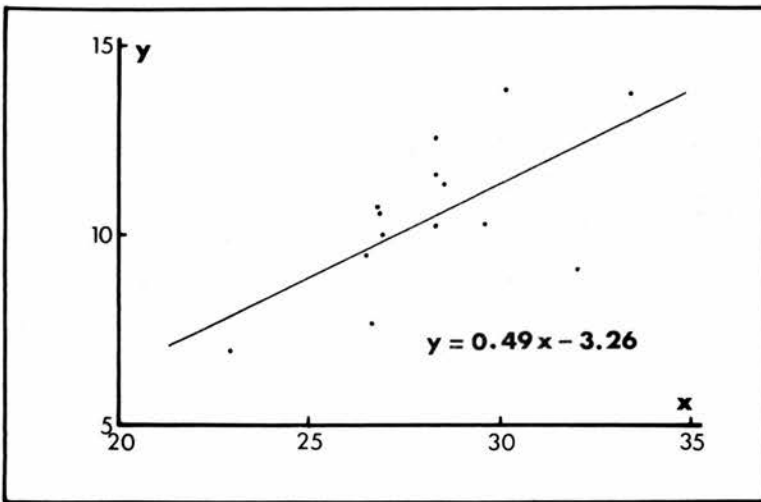


FIGURE 7.2a. Midlothian

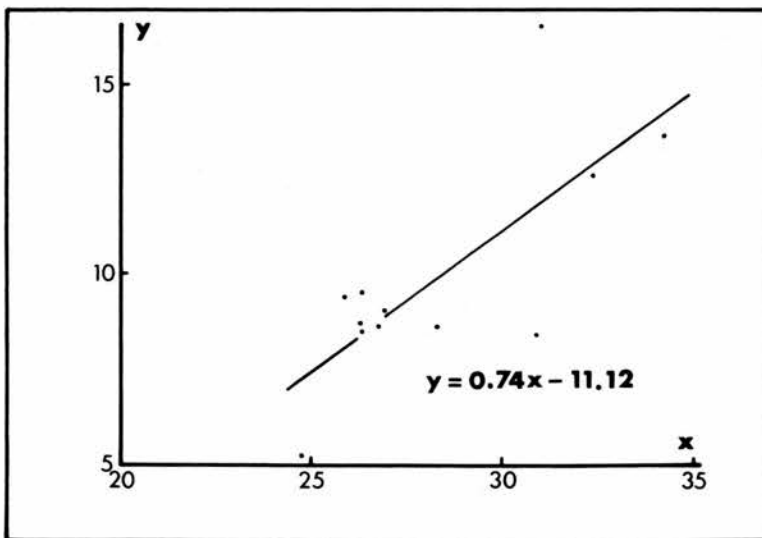


FIGURE 7.2b. Eddleston

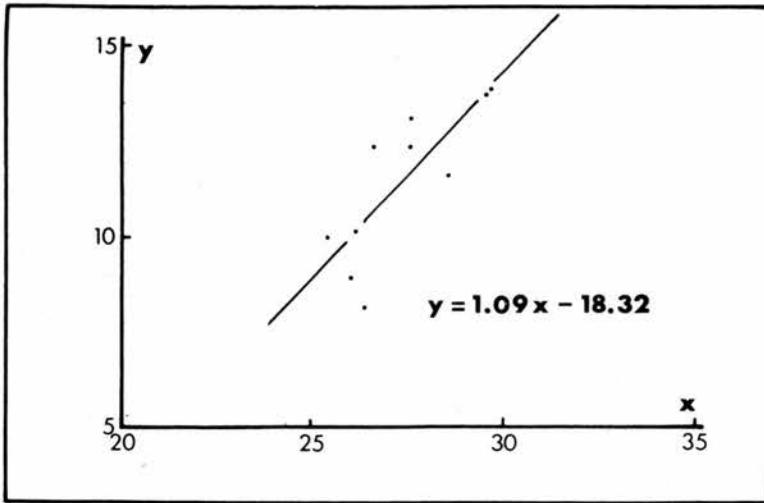


FIGURE 7.2c. Bedshiel

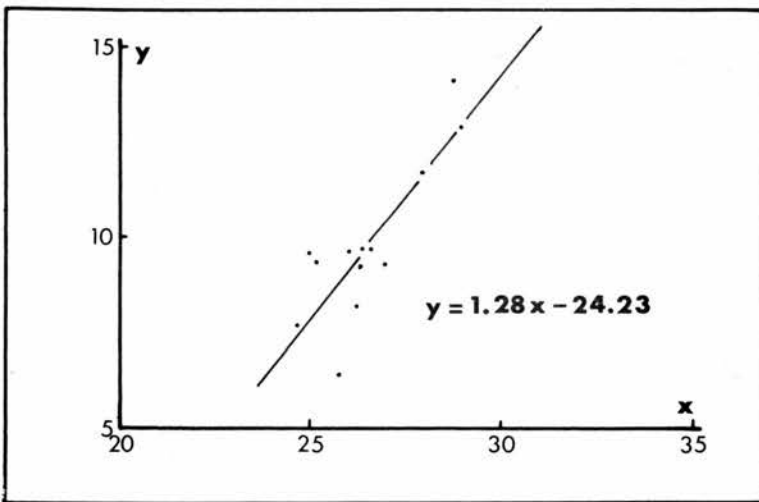


FIGURE 7.2d. Carstairs

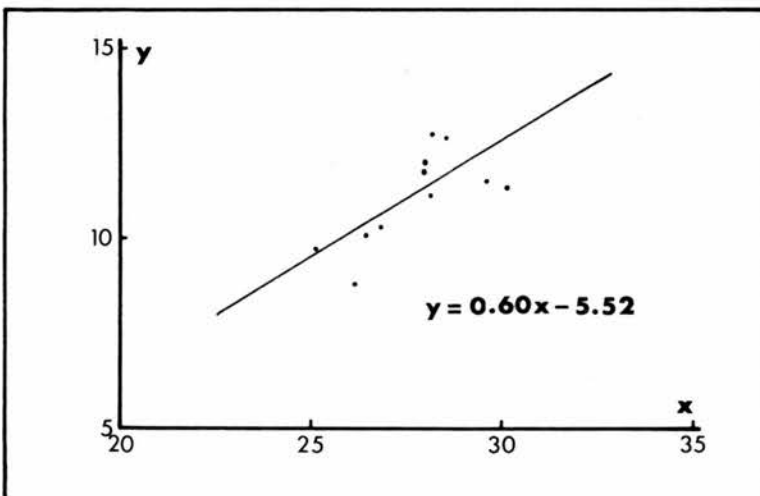


FIGURE 7.2e. Edzell

The relatively small number of data points on each of the Figures 7.2a to 7.2e immediately suggests that the construction of regression lines through these points is barely justified statistically. From similar considerations in the preceding chapter, a search of appropriate literature suggested that ten points would be an acceptable minimum on which to base a regression line. A certain degree of latitude was suggested by one example of only eight data comparisons (Griffiths, 1967, p.444).

The total number of samples of 100 pebbles obtained in the present study was 63. This was made up of 10 samples from the first Bedshiel esker sample run, 13 from the Carstairs esker suite, 14 from Midlothian, 12 from Eddleston, 11 from the Edzell outwash, plus one sample from the gorge of the River North Esk and two samples from south of the Midlothian sequence, Castlelaw and Ladyurd. The 10 samples of 50 sandstones plus 50 greywackes obtained from the Bedshiel esker second sample run were not included as these were in no way representative of average lithological proportions of pebbles within the size limits considered.

Regression lines drawn through these groups of samples must be regarded merely as indicators of possible trend. They should not be regarded as rigorous statistical proofs of trend. Study of the significance of the correlations obtained partly bears this out.

Considering the samples with poorest correlation and best correlation between mean long axis length and standard deviation, the Midlothian sequence and Carstairs sequence show correlations of +0.64 and +0.83 respectively.

The correlation coefficient can be tested to see if a chance correlation of this magnitude is likely. This can be done by employing Student's *t*, using the following formula:

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}},$$

where *r* is the correlation coefficient, *n* the number of pairs of data studied, and where there are (*n* - 2) degrees of freedom.

The Midlothian group of samples give a 1.5 per cent probability that the distribution could have occurred by chance, a probability which is well within the usual 5 per cent level of significance. The corresponding figure for the Carstairs samples is a probability of less than 0.1 per cent that the distribution is chance, an extremely significant probability. Other relevant values are set out in Table 7.1, Bessel's correction for small *n* having been applied.

TABLE 7.1

Results of correlation significance test

Suite	No. of samples (<i>n</i>)	<i>r</i>	<i>t</i> value	Significance (%)
All samples	63	+0.56	5.323	«0.1
Midlothian	14	+0.64	2.849	1.5
Eddleston	13	+0.75	3.751	«0.5
Bedshiel(1)	10	+0.81	3.907	0.5
Carstairs	13	+0.83	4.974	«0.1
Edzell	11	+0.69	2.835	2

Degrees of freedom = *n* - 2

The lowest significance (2 per cent) arises from the lower number of Edzell outwash samples taken, but still lies well within normally-acceptable limits. With this in mind, it would seem that these regression lines may be regarded as fairly certain indicators of trend, although the relatively small number of points on the individual suite graphs requires that any interpretation be treated with caution.

In all cases, however, a sharply rising trend is indicated. With respect to the plot combining all samples, the correlation between mean long axis length and standard deviation is +0.56. According to the correlation significance test, this value is significant at beyond the 0.1 per cent level (Table 7.1). In other words, it is more than 99.9 per cent certain that this figure of +0.56 is not a chance correlation between the 63 pairs of long axis mean and standard deviation figures.

The equation of the regression line is $y = 0.43x - 1.35$ (Fig. 7.1). This shows a positive gradient of about 24° , indicating a steady rise in standard deviation with increasing mean long axis length. The gradient figure of 24° is a function of the scales on both axes, which are the same throughout the present examples, and has therefore no inherent quantitative significance. According to the equation, a sample with mean long axis length of 25 millimetres would be expected to have a standard deviation of around 9.4 millimetres. A rise in mean long axis length to 30 millimetres corresponds to a rise in standard deviation to about 11.6 millimetres. The larger the average pebble size becomes, the more varied individual pebble sizes become.

It can be seen from Figure 7.1 that the only two samples with mean pebble long axis length approaching 40 millimetres have considerably lower standard deviations than would be expected from the calculated equation. From Figure 7.1, these samples have mean long axis lengths of 37.9 and 38.9 millimetres and standard deviations of 10.3 and 12.8 millimetres respectively. This contrasts with the expected values of 15.1 and 15.5 millimetres respectively, suggesting that the relationship between long axis length and standard deviation is not in fact a first-degree straight line, but is a second-degree curve. However, such an assumption based on two out of 63 points is certainly not justified. Further, the two samples mentioned are from Castlelaw Pit, West Linton and Ladyurd Pit and were not included in any of the suites of deposits examined. They could well be anomalous in themselves, but in any case lie within the 95 per cent confidence limits.

It is assumed, therefore, that the relationship between mean long axis length and standard deviation is best described by a straight line. In a similar study in Baffin Island, King and Buckley (1968) investigated this relationship among glacial deposits. They found a correlation of +0.93 between mean and standard deviation, corresponding to a straight line relationship of equation $y = 0.57x - 2.26$. This gradient, +0.57, corresponds to an angle of rise of about 30° on the diagram and shows a gradual rise in standard deviation with increase in mean long axis length. The rate of rise is slightly greater than that found in the present study.

This greater rise could be due to the fact that their study covered a much wider range of mean stone sizes, up to an average long axis length of 1100 millimetres. The very high correlation coefficient found by King and Buckley seems remarkable in view of this very wide range of mean stone length and in view of the relatively wide variety of features studied, but even a considerably lower correlation would still be indicative of a straight-line trend.

The 95 per cent confidence limits on Figure 7.1 seem broad in the context of the scatter of points on that diagram. This apparent width has to be viewed in the context both of the correlation significance test mentioned earlier in the present chapter and of a much wider range of mean long axis length values, such as that obtained by King and Buckley in their 1968 paper. When considered with these points in mind, the wide confidence limits and the apparent clustering of data points due to the relatively small range of mean long axis lengths involved need not be regarded as a deterrent to further analysis.

Turning to the individual suites of samples, the first immediately noticeable fact is that the two sets of esker samples show higher correlation between long axis length and standard deviation than the other three suites. Highest value of all, +0.83, was obtained from the Carstairs group of samples. The first run of Bedshiel samples showed a correlation of +0.81. A gradual lowering of correlation value is seen through Eddleston samples (+0.75) and Edzell samples (+0.69) to Midlothian samples (+0.64) (Table 7.1).

The question arises as to whether these differences may be the result of the type of field sampling employed in such different fluvioglacial deposits. From discussion of sampling method in Chapter 2, it can be repeated that samples taken were "average" samples from available exposures, taken from the approximate centre of gravel sedimentation units. Thus all outwash and kame samples and Carstairs esker samples are essentially similar in method of extraction. It was more difficult to judge in the field whether or not samples taken from the Bedshiel esker were "average" for each location, as only very small exposures could be examined. The nature of the second group of Bedshiel esker samples, taken from depths of one metre down from the esker crest, ensured as far as possible that the material sampled represented the latter phases of deposition at each site and could therefore be compared for possible trend along the length of the esker. The assumption that similar sedimentation units were used is implicit. Thus bias caused by different sampling methods was eliminated as far as possible.

Variations in mean long axis length and related standard deviation are much more likely to be due to inherent differences in environments of deposition. Such factors as distance of travel of material from source to landform, distance from head of landform suite to site, and the effects of transport on different rock types must obviously be investigated and standardisations made. These factors will be discussed later. The main aim of the present section of this chapter is to discuss the possible implications of the study of mean long axis length versus standard deviation in fluvioglacial landforms in

terms of its value as a simple diagnostic technique.

The degree of correlation between mean long axis length and standard deviation in the samples under consideration is only indirectly related to the gradient of the line equation. The Carstairs samples exhibit the greatest line gradient. The equation is $y = 1.28x - 24.23$, corresponding to a line at an angle of 52° with the mean long axis length axis (Fig. 7.2d). This would seem to indicate that the Carstairs esker samples show the worst size sorting of the groups of pebbles selected. Any increase in mean long axis length is accompanied by an increase in standard deviation 1.28 times greater. This trend is extremely steep, and would possibly not be expected to occur in samples of much larger mean long axis length. For example, a sample of mean long axis 100 millimetres would be expected to have a standard deviation of about 104 millimetres according to this equation. While this is by no means impossible, it seems unlikely that sufficient numbers of large boulders would be selected from the matrix of pebble-sized particles. Selection of stones could not be undertaken by the means used in the present study as the sample required would be impracticably large. Similarly, any grid scheme of sampling the particles in situ would be weighted in favour of the larger-sized particles, and samples obtained thus could not be regarded as either truly random or representative. Only samples considering each pebble as an equal individual occurrence can be classed as representative.

In their 1968 article, King and Buckley in fact found 4 samples of 50 stones with standard deviation greater than mean long axis length, out of a total of 93 samples. One of these, from an ice-marginal

delta, had a mean long axis length of about 90 millimetres and standard deviation of around 170 millimetres. They do not detail their method of selection of stones, other than describing them as "... random samples."

Samples from the Carstairs esker system were expected to exhibit a higher standard deviation than those from other suites as a larger number of cobbles was present in the Carstairs deposits. Goodlet (1964) and McLellan (1967a) both noted large boulders more than 1 metre across, while rounded boulders up to 2 metres x 1 metre x 1 metre were noted by the writer in road excavations about 1 kilometre north-east of Carstairs in July 1969. Bedding was contorted in places and generally confused. Boulders 1 metre x $\frac{1}{2}$ metre x $\frac{1}{2}$ metre were common. Most were rounded, but occasional very angular boulders were encountered.

It is worth noting that both esker sample suites yield regression lines with gradients of 1.00 or greater. On the other hand, the Eddleston samples give a regression line gradient of 0.74, Edzell outwash 0.60 and Midlothian 0.49. Allowing for the caution with which these regression lines must be regarded, it seems as if some form of grouping emerges. For this size of pebble, approximately 20 to 64 millimetres long axis length, esker samples would appear to show poorest sorting for size. That is, they show the greatest increase in standard deviation per unit increase in mean long axis length. The Eddleston kame samples are intermediate in degree of size sorting, and the Edzell outwash samples show better size sorting for these particular gravel grades. The more complicated Midlothian

sequence can be regarded as intermediate between kame and outwash for the present purpose, but a significant proportion of the samples were obtained from true outwash deposits.

At this juncture, comparison with results obtained in Chapter 6 reveals a very similar conclusion. Both methods attempted to investigate degree of sorting. In Chapter 6, mechanical analysis of whole samples yielded statistical "measures of moment." The present results arose from the size analysis of 100 pebbles selected from each sample, standard deviation being used in the more common statistical sense. These two tests, involving completely different data from the same samples, gave very similar conclusions. The implications of this will be discussed as appropriate in a later chapter.

The conclusions reached from the present set of data must be regarded as tentative in view of the present relatively limited information. There is also insufficient evidence to suggest that the order of gradients shown by the different suite regression lines are unique for the individual landform types, or even for the individual landforms. Some variation would be expected if the number of data points on the individual plots were increased. Whether this variation would be sufficient to disturb the patterns described above remains to be proved.

To allow for differences in average size, King and Buckley calculated the relative standard deviation by dividing the mean by the standard deviation of each sample. This is not applicable to the present case as the differences in mean long axis lengths of the groups of samples are not statistically significant (Table 7.2).

TABLE 7.2

Mean, standard deviation and relative standard deviation of samples

Sample suite	Mean (mms)	Standard deviation (mms)	Relative standard deviation
Midlothian	28.20	10.30	2.73
Eddleston	28.32	9.32	3.04
Bedshiel(1)	27.25	11.36	2.40
Carstairs	26.50	9.50	2.79
Edzell	27.69	10.94	2.53

Highest relative standard deviation is shown by the Eddleston group of samples, while the Bedshiel(1) suite exhibits lowest relative standard deviation. Theoretically, relative standard deviation should be a reliable indicator of relative degree of sorting. Samples with relatively high average long axis length and relatively low average standard deviation, such as Eddleston, would be assumed to be better sorted than samples of lower mean long axis length and higher average standard deviation, such as Bedshiel(1).

The Carstairs samples, judged to have shown poorest degree of size sorting on the basis of regression line gradient, show an intermediate value for relative standard deviation in Table 7.2.

These samples show the lowest mean long axis length and lowest average standard deviation of all the suites considered. This explains the intermediate relative standard deviation value and suggests that the regression line analysis, depending as it does on

all individual data points, is perhaps more relevant to the present work than relative standard deviation. Relative standard deviation depends on only two values, the average mean and standard deviation of suites of samples. The differences between the mean long axis lengths and average standard deviations of the present groups of samples are very small, and certainly statistically insignificant. It must therefore be concluded that the relative standard deviation test is too crude for use with the data obtained during the present study. The regression line gradient test therefore remains the best indicator of relative degree of sorting between the various fluvio-glacial landform suites.

SIZE ANALYSIS OF PEBBLES SELECTED - INDIVIDUAL ROCK TYPES

The results obtained above from mixed lithologies can be compared with corresponding mean long axis length against standard deviation plots of individual rock type samples.

The only two pebble types found in large numbers in most of the deposits studied were sandstones and greywackes. Sandstones were of two main types, Old Red Sandstone of Devonian age and Calciferous Sandstone of Lower Carboniferous age. Both tended to disintegrate when rubbed, the major difference being that Old Red pebbles were in general larger-grained than Calciferous pebbles. It was assumed that these could both be classified as "soft" rocks, and would behave approximately similarly during transport. Greywackes, on the other hand, were regarded as "hard" rocks, and the relatively small range

of constituent pebble sizes was not regarded as being a significant factor in determining rates of pebble wearing.

In total, 48 sandstone samples were obtained as follows:- 10 from Bedshiel esker (first run of samples), 10 from Bedshiel esker (second run), 14 from the Midlothian area, 13 from Carstairs suite, and one from Castlelaw pit.

The 46 greywacke samples included 10 from Bedshiel esker (first run), 10 from Bedshiel esker (second run), 12 from the Eddleston valley deposits, 13 from Carstairs suite, and one from Ladyurd pit.

Pebbles of various Lower Old Red Sandstone volcanic rocks were found throughout the Midlothian and Carstairs suites of deposits. These ranged in type from felsites, through rhyolites, trachytes and andesites, to basalts. When counted collectively within individual 100-pebble samples, these formed sufficient numbers to allow meaningful long axis versus standard deviation calculations. Only 29 volcanic pebbles were found throughout the entire Bedshiel esker first run of samples. Of the Eddleston kame samples, significant numbers of volcanic pebbles were found in samples taken from the northernmost site of commercial workings. The five samples of 100 pebbles from Cowieslinn pit together contributed only 15 pebbles, the distribution being, 0, 1, 4, 4 and 6. The four remaining samples from the Eddleston valley deposits contained individually 0, 1, 1 and 2 volcanic pebbles. The Castlelaw pit and Ladyurd pit samples yielded 39 and 11 volcanic pebbles respectively.

A total of 33 volcanic pebble samples were considered. These comprised 14 from Midlothian area samples, 13 from Carstairs eskers, 4 from Eddleston valley gravels (3 from individual samples taken at

Site 6 plus the grouped sample of 15 from Site 7, Cowieslinn pit), together with one each from Castlelaw pit and Ladyurd pit. The Bedshiel esker volcanic pebbles were not included in any calculations as the distance between sites was relatively large.

The high positive correlations found when considering entire samples are mirrored in the sandstone, greywacke and volcanic pebble samples (Table 7.3).

TABLE 7.3

Mean pebble long axis vs. standard deviation - all comparisons

Sample group	Correlation coefficient			
	All pebbles	Sandstones	Greywackes	Volcanics
All samples	+0.56	+0.84	+0.81	+0.70
Midlothian	+0.64	+0.84	-	+0.77
Eddleston	+0.75	-	+0.77	-
Bedshiel(1)	+0.81	+0.93	+0.79	-
Bedshiel(2)	-	+0.88	+0.85	--
Carstairs	+0.83	+0.88	+0.90	+0.80
Edzell	+0.69	-	-	-

The correlation values for the individual rock types are higher than the corresponding mixed lithology correlation in all but two cases. Greywacke correlation for the Bedshiel first run of samples is 0.02 lower than the "whole sample" correlation, and the Carstairs

volcanic pebbles show a correlation figure 0.03 lower than the whole sample correlation. Generally speaking, the lower whole sample correlation coefficients, for example All samples and Midlothian samples, are increased dramatically, whereas the higher whole sample correlation figures are barely improved on.

It is noticeable that the sandstone correlation figures tend to be higher than those of greywacke or volcanic pebbles. This reflects the relative ease with which sandstone pebbles are worn down. Variations in size of pebble when freed from bedrock are more quickly reduced during transport of sandstone pebbles.

Regression lines for long axis versus standard deviation of the various rock types are shown in Figures 7.3, 7.4 and 7.5. Figure 7.3 shows that all sandstone regression lines have remarkably similar gradients. With regard to greywacke regression lines, Figure 7.4 shows that the three esker regression lines have virtually identical gradients. The Eddleston kame regression line is much less steep. Little inference can be made from the volcanic pebble regression lines, as drawn in Figure 7.5, but that through the Midlothian kame/outwash samples is notably less steep in gradient than that drawn through the esker samples of the Carstairs suite of deposits.

From these results, it appears initially that "soft" rock types such as sandstone are less suitable for studies of environment of deposition in the fluvio-glacial environment than "hard" rocks such as greywackes or rocks of volcanic origin. These harder rocks exhibit similar trends to the mixed lithology studies in that esker samples appear to be poorer sorted for size than either kame samples (Eddleston) or kame/outwash samples (Midlothian).

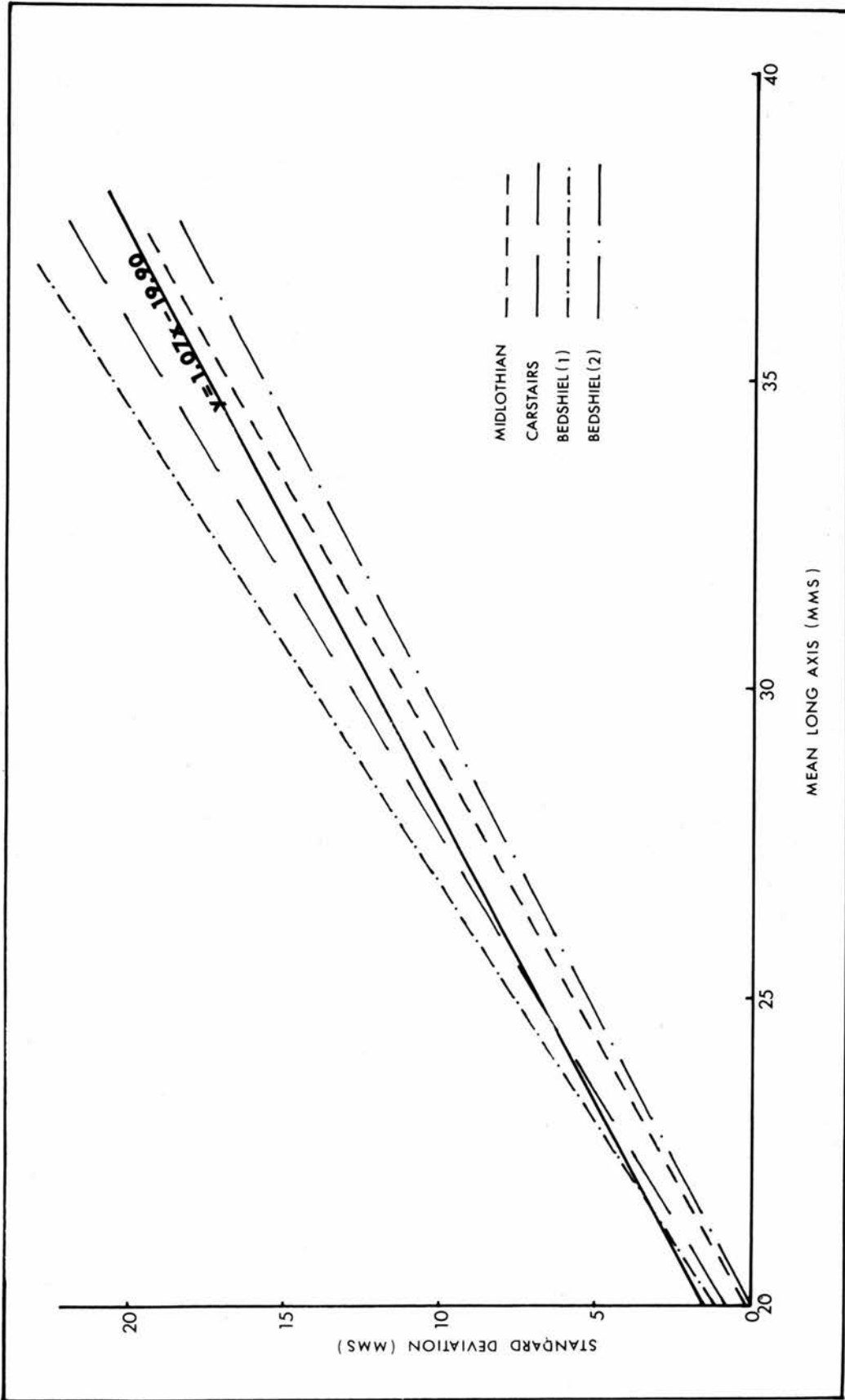


FIGURE 7.3. Long axis mean versus standard deviation of sandstone pebbles. Individual suite regression lines shown relative to grouped regression line (solid line - equation given)

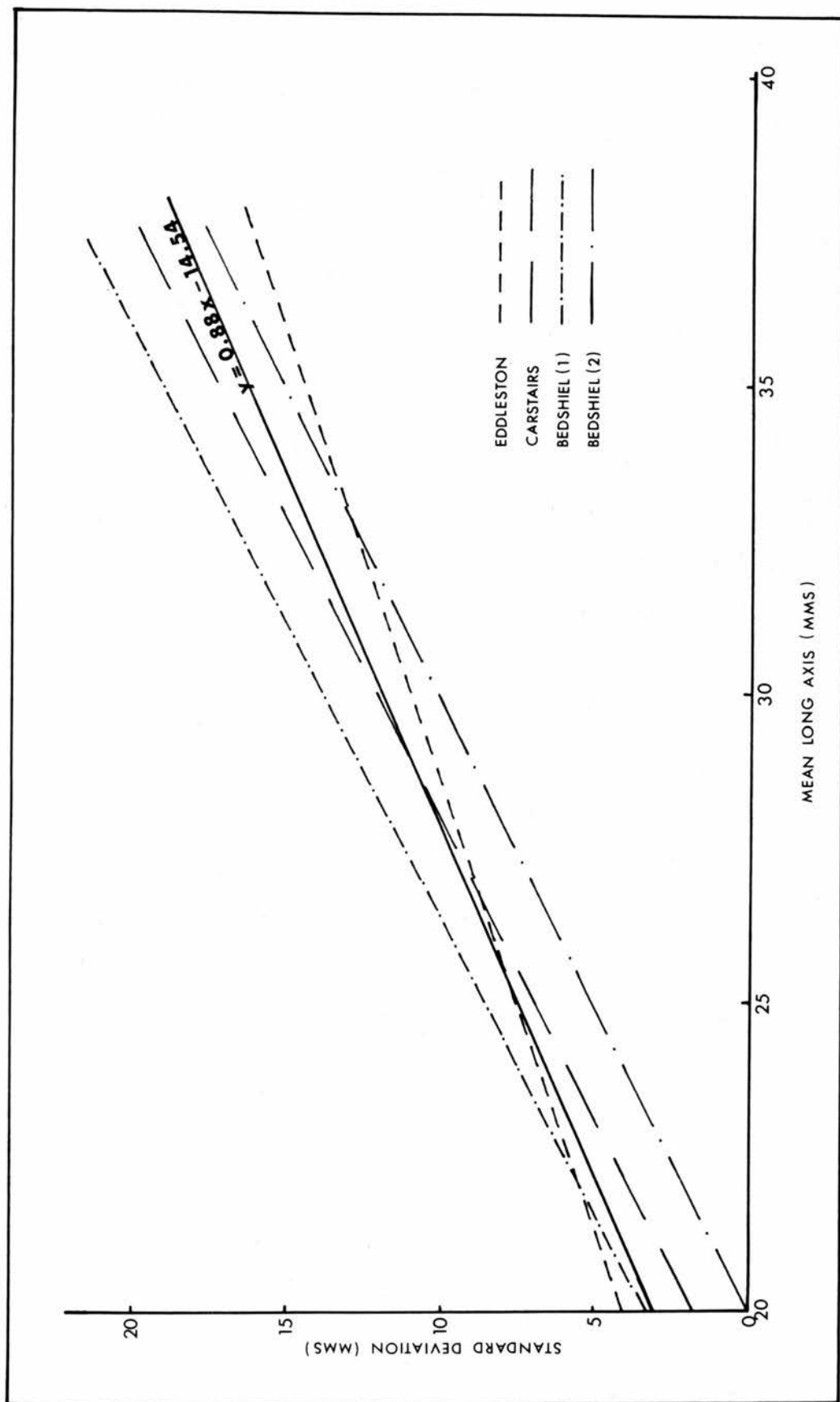


FIGURE 7.4. Long axis mean versus standard deviation of greywacke pebbles. Individual suite regression lines shown relative to grouped regression line (solid line - equation given)

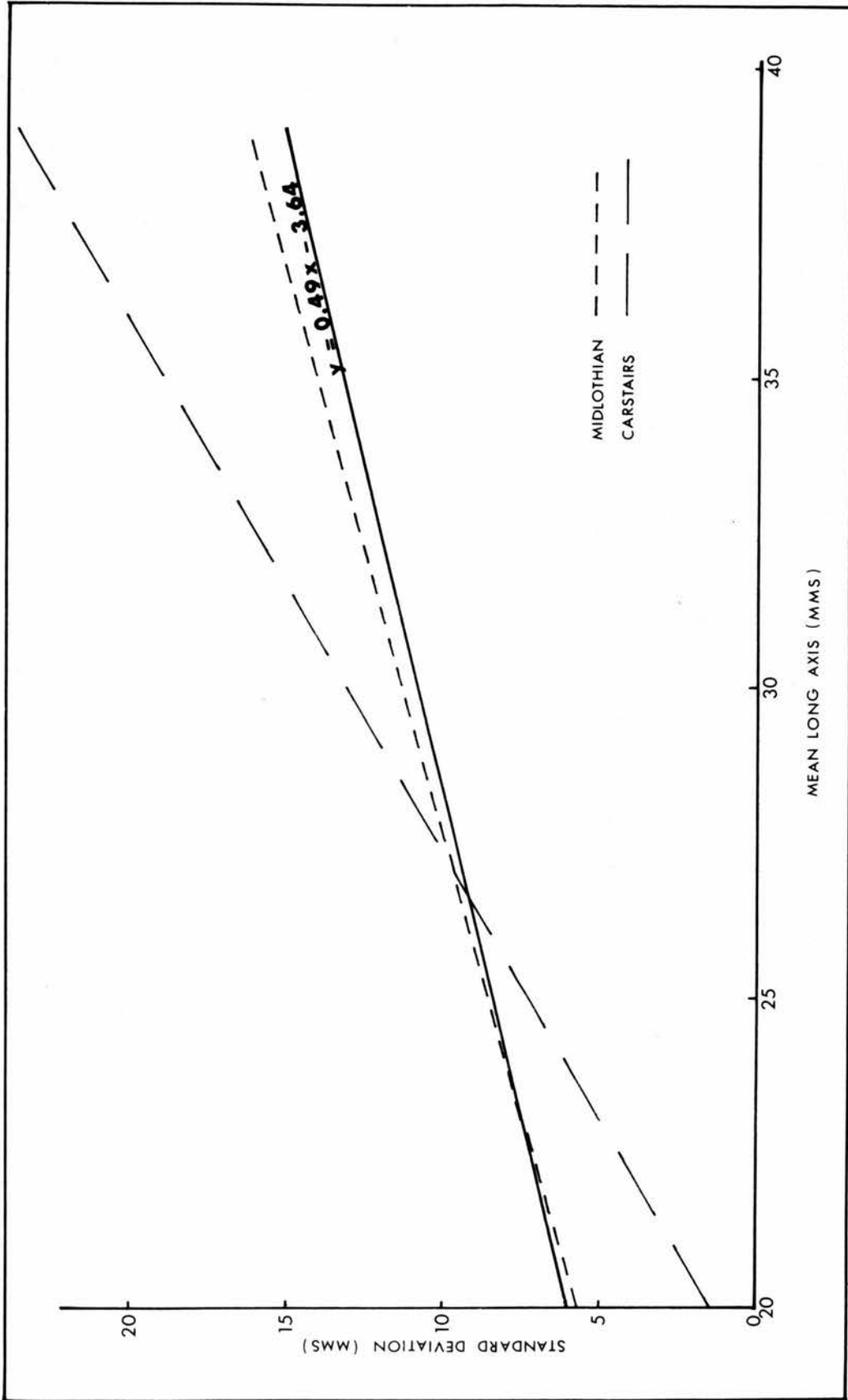


FIGURE 7.5. Long axis mean versus standard deviation of volcanic pebbles. Individual suite regression lines shown relative to grouped regression line (solid line - equation given)

SIZE ANALYSIS OF PEBBLES SELECTED - SORTING BY SIZE WITHIN SUITES

Thus far, mean long axis lengths of individual samples within suites have been considered. When all pebbles selected from each suite are plotted together, it becomes more difficult to distinguish between the individual landforms. Figure 7.6 shows a semi-logarithmic plot of total numbers of pebbles selected from each suite, divided into 5 millimetre classes. The logarithmic rise in number of particles with decrease in size is clearly shown. Quantitative analysis of these curves seems unlikely to produce worthwhile evidence.

Partly because of this exponential-type distribution, studies of grouped mean against standard deviation would also seem unlikely to produce fresh evidence. The rapid decrease in number of particles with increase in size makes data comparison difficult. An attempt at weighting the various numbers in successive classes produced no significant improvement in results obtained.

ROUNDNESS

Average roundness values of mixed lithologies would seem to have little relevance to an overall estimation of the value of measures of roundness as an environment differentiation technique. Within single suites, as demonstrated by the Bedshiel esker investigation detailed in Chapter 5, variations in percentages of the different rock types present throughout any one suite of deposits

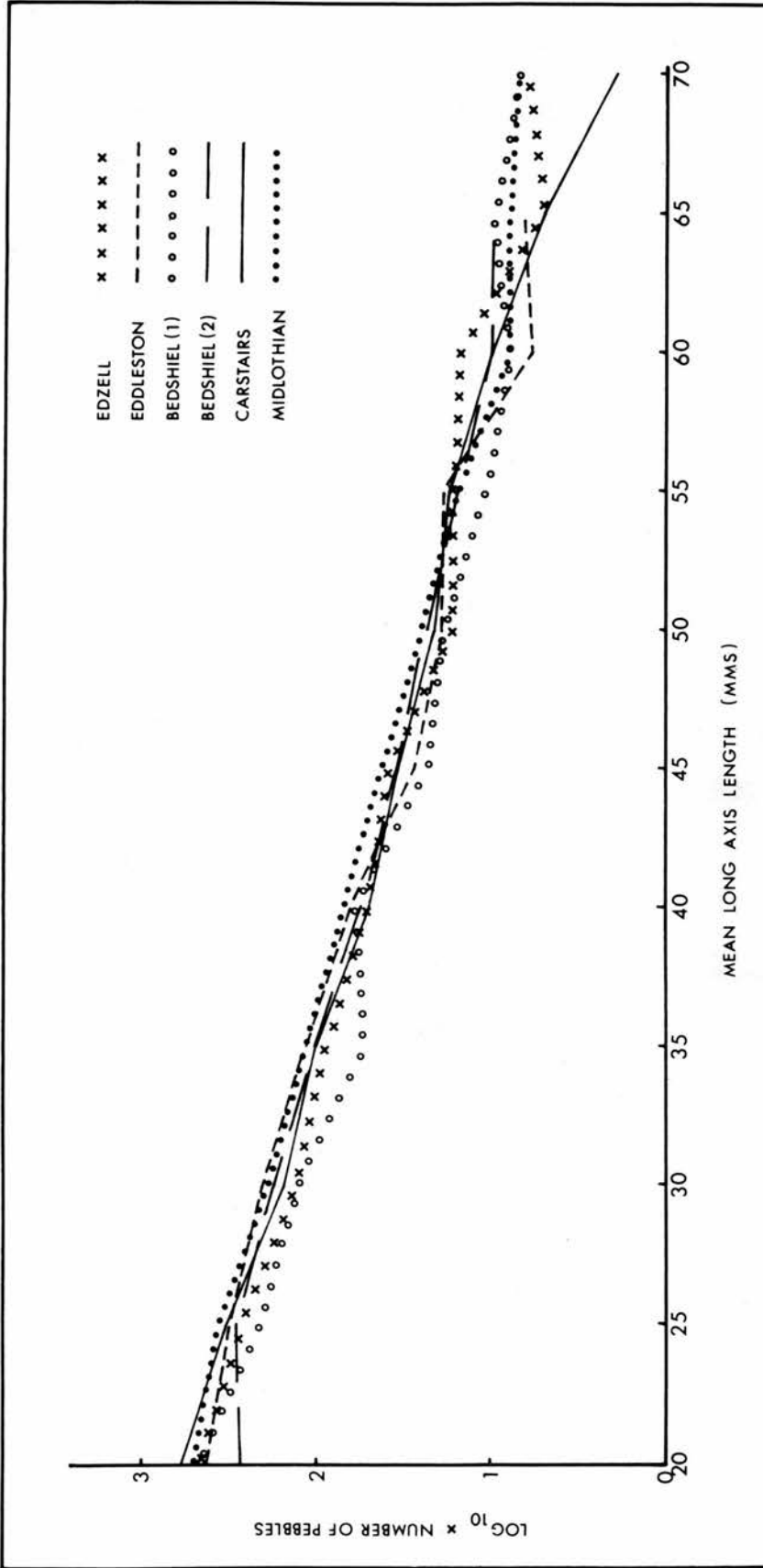


FIGURE 7.6. Semi-logarithmic plot of total numbers of pebbles selected from each suite, divided into five-millimetre classes

would tend to mask significant trends in average roundness value.

The correlation coefficients of mean against standard deviation of roundness for the three rock types considered are set out in Table 7.4. In all cases there is a considerable difference, within the same suite of deposits, between sandstone correlation on the one hand and greywacke and volcanic correlations on the other. The greywacke and volcanic correlations are markedly more positive in all cases but one. This tends to suggest at first sight that any relationship between mean and standard deviation of roundness samples is merely coincidental.

TABLE 7.4

Correlation between mean and standard deviation of roundness samples

Sample group	Correlation coefficients		
	Sandstone	Greywacke	Volcanic
All samples	-0.02	+0.27	+0.54
Midlothian	-0.28	-	+0.25
Eddleston	-	+0.53	-
Bedshiel(1)	+0.58	-0.42	-
Bedshiel(2)	+0.11	+0.42	-
Carstairs	-0.21	+0.46	+0.44

Theoretically, increasing distance of travel from source would be accompanied by an increase in roundness. This increase in roundness

would be reflected by an increasing uniformity of roundness values within pebble size classes, due in part to natural sorting within the suite of deposits. A negative gradient for mean versus standard deviation would seem to be indicated. Further, it would be expected that groups of pebbles of similar origin and roughly similar size found at any one site would exhibit a roughly similar mean against standard deviation ratio. The difference between the mean versus standard deviation correlation values of the two Bedshiel esker sandstone and greywacke sample groups suggests strongly that local variations effectively mask any overall trend. It seems that use of this particular technique for environment differentiation would not seem to be warranted on the basis of the present results.

SPHERICITY

As with roundness, average sphericity values of mixed lithologies must be treated with caution. Correlation coefficients of mean sphericity against standard deviation for the individual rock types investigated are set out in Table 7.5.

Again, as with the roundness correlation values, there is a complete disparity between sandstone mean against standard deviation correlation and the greywacke and volcanic figures for the same suite. As before, this cannot be attributed to factors such as distance of travel owing to the substantial correlation coefficient difference between Bedshiel first group of samples and Bedshiel second group for both sandstone and greywacke pebbles.

TABLE 7.5

Correlation between mean and standard deviation of sphericity samples

Sample group	Correlation coefficients		
	Sandstone	Greywacke	Volcanic
All Samples	+0.16	+0.09	-0.24
Midlothian	-0.06	-	-0.20
Eddleston	-	+0.21	-
Bedshiel(1)	-0.89	+0.05	-
Bedshiel(2)	+0.17	+0.61	-
Carstairs	-0.61	-0.04	-0.19

The most remarkable figures obtained are the correlations of -0.89 and -0.61 for Bedshiel (first run) and Carstairs sandstone samples respectively, together with the Bedshiel (second run) figure for greywacke of +0.61. It would seem difficult to explain such high correlation values as purely coincidental (although the change of sign of the two 0.61 correlations might indicate chance correlations). In the normal course of events, lower sphericity values would indicate greater distances of travel from source. Combined with greater degree of sorting, it would seem logical that lower mean sphericity values would be accompanied by lower group standard deviations. A positive gradient for a mean against standard deviation regression line would seem to be indicated. This would make the high negative values mentioned above seem extremely anomalous.

It must be concluded from the evidence presented that, as with roundness values, study of mean against standard deviation of sphericity values does not lead to a greater understanding of environments and modes of deposition.

CHAPTER 8A. RELIABILITY OF SAMPLE

The question of reliability of sample is difficult to resolve for material from the confused fluvioglacial environment. How reliable, for example, is the sample of 100 pebbles with respect to the overall sedimentary characteristics of the field sample, that is, with respect to the sedimentary parameters calculated from the cumulative size curve? This can be resolved by comparing results from the two relevant investigations, as will be done later in the current chapter.

How reliable, in turn, is the sieved sample in estimating sedimentary parameters for the entire deposit at that site? Again, this is bound up in the major problem of study of fluvioglacial deposits, namely that the relatively wide within-site variation may in fact be greater than between-site variation. How can this last point be resolved satisfactorily, apart from simply increasing the numbers of samples involved? Within-site versus between-site variance will be looked at immediately.

A third factor in reliability of sample is the question of the effect of the varying numbers of pebbles in the individual rock type investigations of Chapter 7. It is suggested that this need not be considered further as the worked data included in every case a correction for "best estimate" made via the mean and standard deviation calculations. This was in the form of the standard Bessel Correction.

WITHIN-SITE/BETWEEN-SITE VARIANCE

Samples taken from Site 6 (United Quarries Eddleston) and Site 7 (Cowieslinn Pit) can be studied to indicate within-site variation in the Eddleston kame deposits. As these sites are approximately 1.5 kilometres apart, it might be expected that multiple sampling at the two sites would indicate trends of constituent material proportions and pebble morphology. The location of these two sites is shown in Figure 1.3.

At Site 6 an attempt was made to obtain a representative sample from a suitable pit face. As explained in Chapter 2, a stratified grid sampling method was employed (Fig.8A.1). A suitable vertical face, measuring approximately 10 metres long by 3 metres high and oriented north-south, was chosen and a total of 12 samples extracted for mechanical grain size analysis. The height of the face was limited as it would have been difficult to obtain samples from all parts of a higher vertical face. The sample locations, shown by crosses on Figure 8A.1, were determined by drawing a grid over a field sketch, as shown in Figure 8A.2, and selecting sample points from the mid-point of the rectangular units formed by the grid. Sample points were selected so as to yield equal numbers of samples in all horizontal grid strata as well as equal numbers in all vertical grid strata. Channel samples were not used as it was the intention to cover the entire face without abstracting an unmanageable amount of material. The samples were numbered consecutively downwards through each vertical stratum, and from left to right

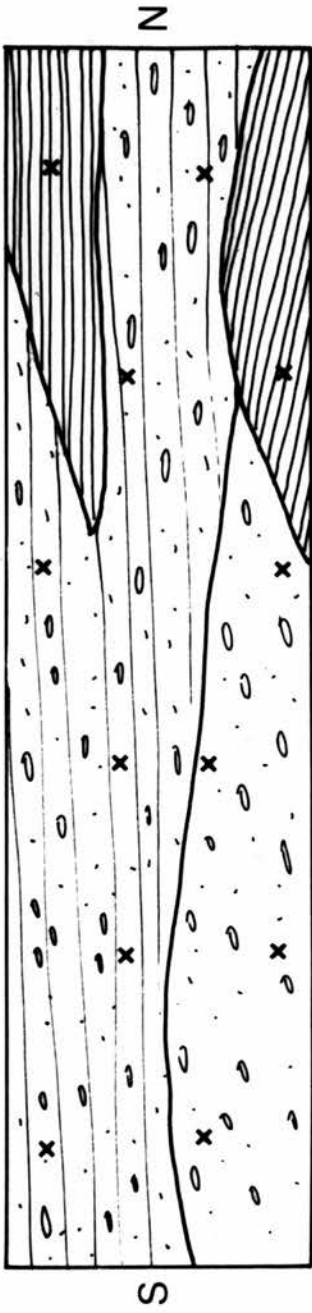


FIGURE 8A.1. Generalized sketch of bedding conditions at Site 6.
Crosses indicate sample locations

41/43/16		65/31/4		27/65/8
	46/28/26	68/25/7	86/13/2	
67/32/1		89/9/1		65/32/3
	89/11/0	67/33/0	0/9/91	

FIGURE 8A.2. Gravel, sand and fines percentages of Site 6 samples

as the face was viewed. Three samples 6.2, 6.4 and 6.12, were subsequently selected at random from those samples containing a sufficient proportion of gravels for pebble morphology study.

Site 6 (approximate location NT 239531) is at the northern end of the Eddleston valley, and towards the northern extremities of the Eddleston fluvioglacial suite of deposits. The pit is situated more or less on the break of slope between the higher ground towards the southwest and northeast and the valley of the Eddleston water itself. A series of low hummocks can be seen, stretching from southwest to northeast, towards the major fluvioglacial deposition of the Mount Lothian area. The pit itself contains sections of up to 8 or 9 metres of very disturbed sediments, as can be seen from Figure 8A.1. The selected face is typical of conditions throughout the pit, with gravels in a coarse sandy matrix predominating. Bedding is confused in many exposures, with occasional lenses of clayey sand being found among the gravels. Puckering and faulting of beds is common. Further confusing factors are the existence of a thick crust of material in the top half-metre of deposition and heavy staining throughout the upper gravel layers. This blue-black staining extends some way down from the top of the deposits, both crust and staining presumably being due to leaching.

Site 7, Cowieslinn Pit, is located at NT 238516. This is well within the area of massive fluvioglacial deposition which took place in the relatively narrow Eddleston valley. As this pit is more or less continuous with Nether Falla Pit (Site 8), the original topography of this area has been substantially altered. Within the pit, however,

gravel predominates, beds characteristically dipping 20° to 30° towards the valley floor a short distance to the east. The fluvio-glacial material is up to 10 metres thick, and beds of sand are common. Apparently undisturbed ground immediately to west and south of the pit shows the typical hummocky terrain configuration of kame and kettle deposition.

In contrast to Site 6, a much larger face was selected from Site 7 (Fig. 8A.3). The face selected was 30 metres long by 3 metres high, and 8 samples were selected as in the previous case, in a "stratified-grid" manner (Figs. 8A.3 and 8A.4). In this case 5 of the 8 samples were processed for pebble morphology characteristics.

The comparison of sample values from the two sites can be divided into three parts. Firstly, percentages of the various sizes of constituent materials can be looked at. Secondly, the cumulative curves of size percentages can be compared, and thirdly, pebble morphology differences can be investigated.

COMPARISON OF PERCENTAGES OF SIZES OF MATERIAL

The varying percentages of gravel, sand and fines can be effectively shown on one textural diagram (Fig. 8A.5). No clear set grouping emerges from this diagram. However, the relatively low percentages of fines in samples from Site 7 are clearly indicated. This is supported by average gravel/sand/fines content figures for all samples from each site. Within Site 6, average figures are as follows:- gravel 59.26 per cent; sand 27.53 per cent; fines 13.21

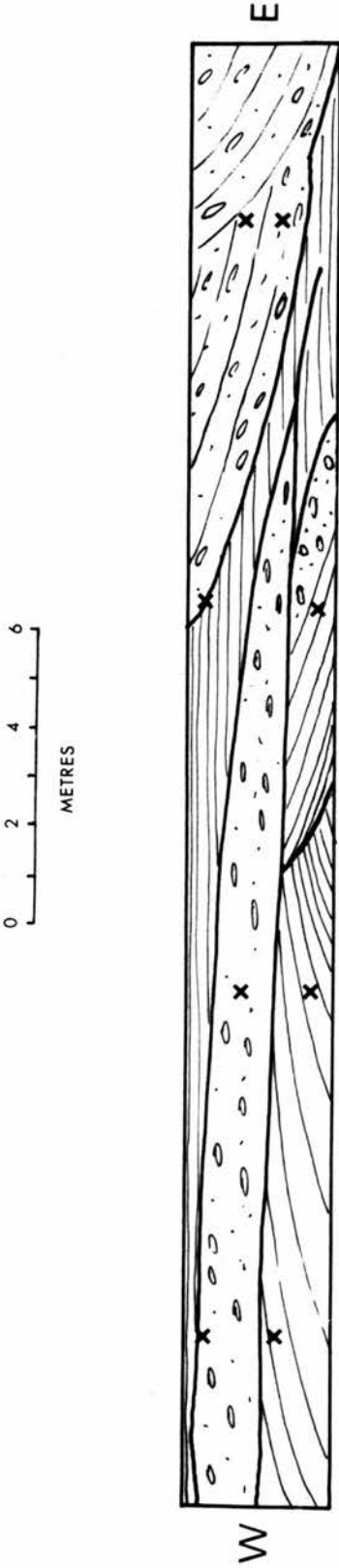


FIGURE 8A.3. Generalized sketch of bedding conditions at Site 7.
Crosses indicate sample locations

78 / 22 / 0	80 / 19 / 0	44 / 56 / 0
23 / 67 / 10	0 / 94 / 5	76 / 23 / 0

FIGURE 8A.4. Gravel, sand and fines percentages of Site 7 samples

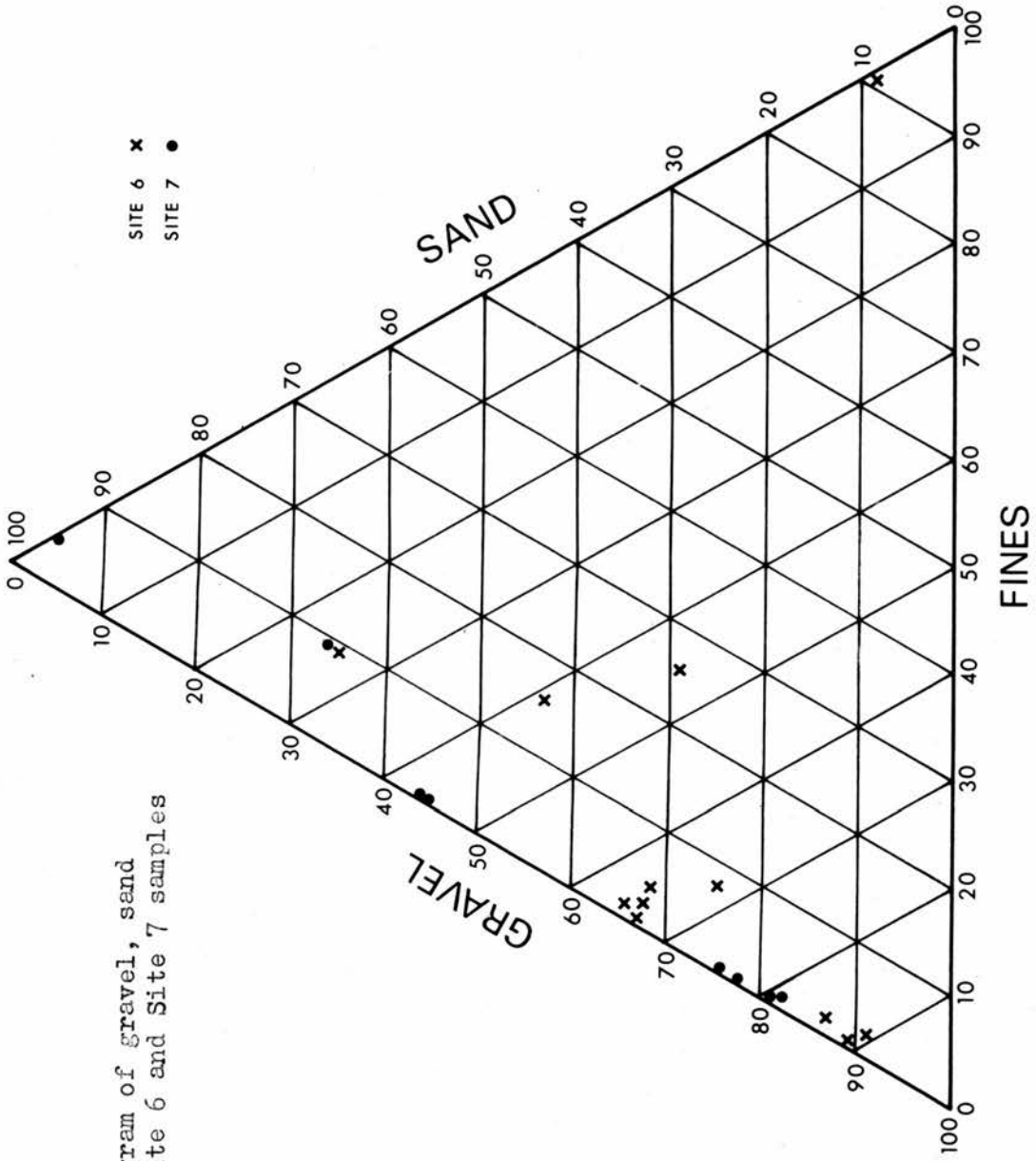


FIGURE 8A.5. Textural diagram of gravel, sand and fines percentages of Site 6 and Site 7 samples

per cent. This contrasts with the average figures from Site 7 samples:- gravel 53.27 per cent; sand 44.53 per cent; fines 2.20 per cent. Although average gravel content is similar, the average sand content of Site 7 samples is 17 per cent higher than that of Site 6, while the average sample from Site 7 has 11 per cent less fines than that from Site 6. The combination of higher sand content and less fines content suggests that Site 7 samples have been subjected to greater washing, and consequently would be expected to exhibit a greater degree of sorting.

COMPARISON OF CUMULATIVE CURVE CHARACTERISTICS

The cumulative curve, probability ordinate characteristics of samples from both Site 6 and Site 7 are shown diagrammatically in Figure 8A.6. Averages for the various groups are shown by a horizontal line across the appropriate column (Fig. 8A.6). The relative importance of the fines fraction is shown by the more positive graphic mean, indicating a smaller average size for the Site 6 samples despite a slightly higher overall gravel percentage. There is little difference in the range of ϕ sizes covered by the graphic mean values of both groups of samples, with the obvious exception of sample 6.10 (graphic mean +5.57 ϕ). This sample was found to have a fines content of 90.49 per cent. Even allowing for this anomalously high value, the other 11 samples from Site 6 have an average fines content of 6.19 per cent, approximately three times the average Site 7 fines content. The Site 6 samples are clustered

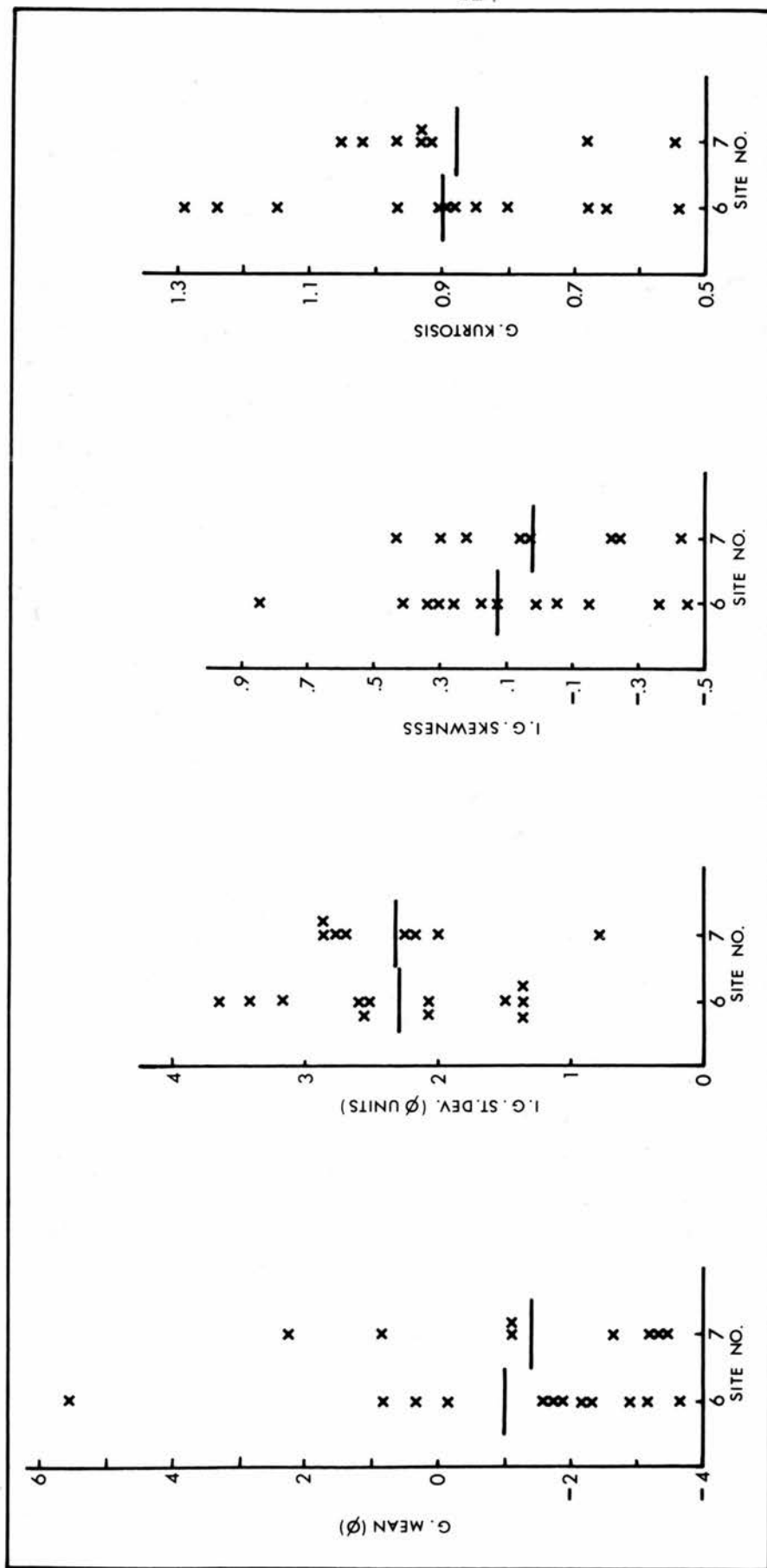


FIGURE 8A.6. Comparison of cumulative curve statistics of Site 6 and Site 7 samples. Averages shown by horizontal lines

round a graphic mean of -2ϕ , while the Site 7 samples show one small cluster at around -3.3ϕ . There is, however, no clear differential grouping between the two groups of samples.

With regard to inclusive graphic standard deviation, it might be expected that samples from Site 7 would show lower overall values, owing to the lower fines percentages and the higher overall sand content. That this is not the case is shown by Figure 8A.6. The average values are virtually identical. There are three samples from Site 6 (samples 6.1, 6.5 and 6.7) with high standard deviations, together with one low standard deviation value from Site 7 (sample 7.4), but this is not sufficient evidence of a significant between-site variation. Similar conditions of sorting, and by implication deposition, are indicated.

The inclusive graphic skewness plot shows a broadly similar spread of values, with one exception, sample 6.3 (Fig. 8A.6). This sample contained 46 per cent gravel, 28 per cent sand and 26 per cent fines, and a strong positive skewness, indicating a tail of finer sediments, arises. The average skewness of Site 6 samples is distinctly more positive, reflecting the overall higher fines content. This has already been noted in terms of the slightly more positive graphic mean average of samples from Site 6. As before, it would be difficult to justify this difference statistically. The Student's *t* test gives a *t* value of 0.78 which, with 18 degrees of freedom ($n_x + n_y - 2$), does not approach even the 75 per cent level of significance.

Referring again to Figure 8A.6, the graphic kurtosis spreads of values for the two groups of samples indicate a similar range. Mean values are virtually identical. This reinforces the general conclusion to be reached from the study of cumulative curve characteristics in this instance, namely that for these two sites the between-site variation in sample values is not sufficient to overcome the masking effect of within-site variance. Differences between the two sites can be noted, but these are not statistically significant.

COMPARISON OF PEBBLE MORPHOLOGIES

Mean long axis length of all pebbles in each sample and mean long axis length, sphericity and roundness of greywacke pebbles can be considered. The relatively small numbers of samples from each site (three from Site 6 and five from Site 7) make it unlikely that any firm conclusions will be drawn from the relevant plots (Fig.8A.7).

Both mean long axis plots show two samples from Site 7 (samples 7.7 and 7.8) to have a much higher average than the other samples. As the same rock type is being considered within each site, and as bedrock can be considered to be reasonably uniform in this area, this would seem to indicate a shorter distance of travel to Site 7 than to Site 6.

The mean sphericity plot shows no significant differentiation, but the three Site 6 samples have a notably low average roundness when compared with the Site 7 samples. This indicates a greater

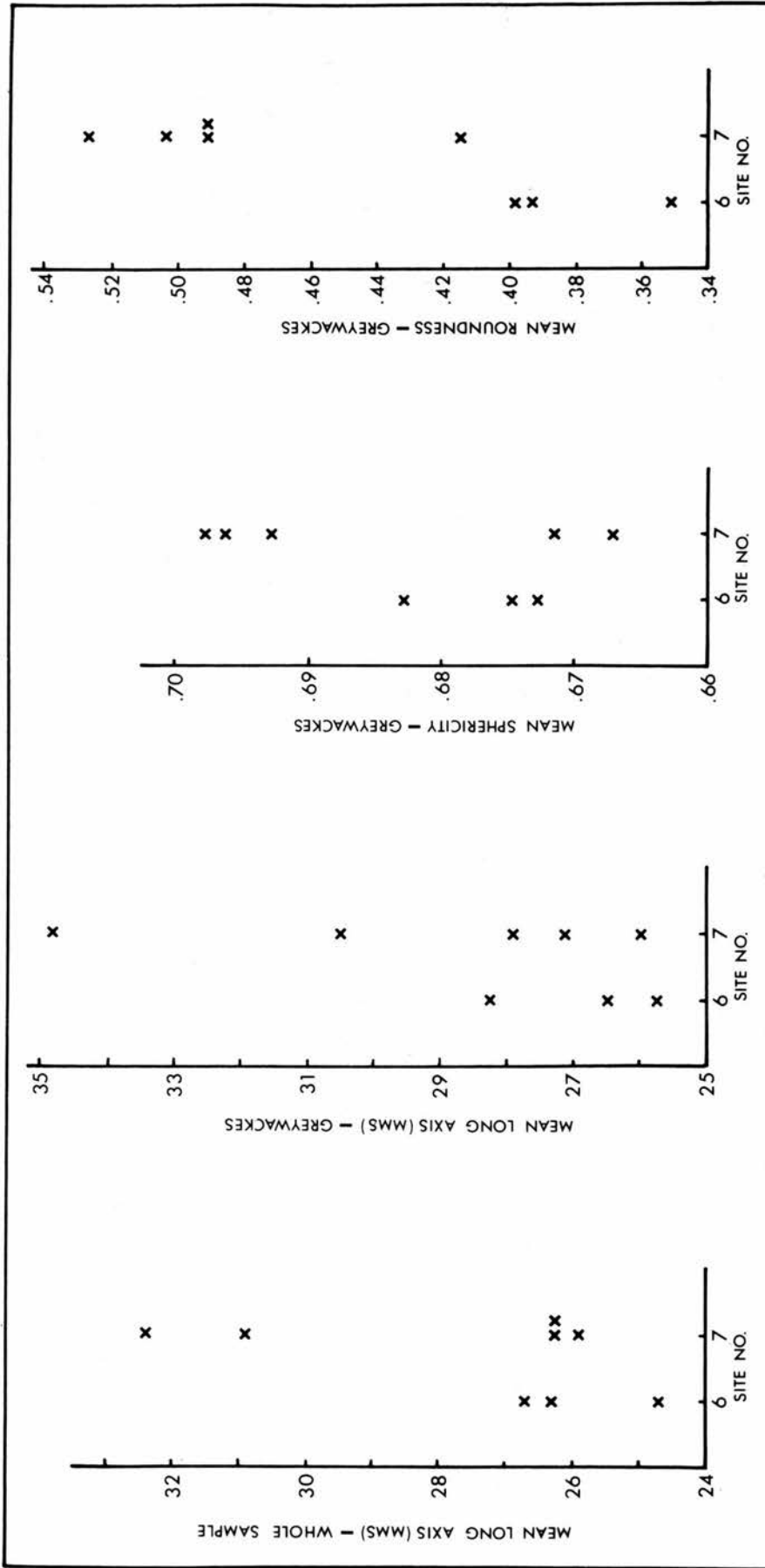


FIGURE 8A.7. Comparison of pebble morphology statistics of samples selected from Site 6 and Site 7

distance of travel of greywacke pebbles to Site 7 than to Site 6, in direct contrast to the inference made from the long axis length plots. These two contrasting hypotheses suggest, as with the cumulative curve statistics, that within-site variation is so wide as to cause a high degree of overlap of measured values between sites in the present case. The fact that there are fewer greywacke pebbles present in Site 6 samples (30, 28 and 21 as against 38, 53, 55, 52 and 47) does not seem to have affected the results to a significant degree, except possibly in the case of roundness. It seems unlikely that the relative difficulty in determining the boundary between greywackes and shales in hand specimen in the Eddleston valley deposits is of importance, as the pebble morphology average values in this instance do not differ significantly between greywacke pebbles on the one hand and mixed lithologies on the other.

The only conclusion to be drawn from the above considerations is that the probability of being able to detect short-distance variation within fluvio-glacial landform suites by relatively intense sampling of suitable faces is low. The nature of fluvio-glacial deposition is such that within-site variation effectively masks between-site variance over distances of at least 1.5 kilometres.

CHAPTER 8B. COMPARISON OF WHOLE-SAMPLE CUMULATIVE CURVE
STATISTICS WITH PEBBLE MORPHOLOGY STATISTICS

In the present section, a direct comparison of the results of Chapters 6 and 7 will be attempted. The significance of these results, and any obvious parallels between the results of the two studies, will be considered and analysed subsequently.

PRELIMINARY CONSIDERATIONS

It is difficult to compare directly whole-sample cumulative curve statistics with pebble morphology statistics for a number of reasons. Firstly, there is the fundamental difference in method of selection of material. On the one hand, the entire sample is used to find the cumulative curve and associated measures of moment, while on the other hand pebble morphology study involves the selection of a small number of particles from one particular size grade from within the original sample. Other size grades almost certainly will have different morphological properties. For example, sand-sized particles will not have the same shape as gravel-sized particles from the same sample. The differences in morphological properties between different material size classes are due to fundamental relations with the transporting and depositing medium. Conditions of deposition are not similar for sand deposition compared with gravel deposition, for example.

There is also the related question of the great degree of fluctuation of strength of depositing medium within relatively short

time periods which is a characteristic of fluvioglacial deposition. It can be argued that conditions of fluvioglacial deposition are not strictly comparable with conditions of fluvial deposition except in the case of glacial outwash, owing to the modifying effect of pressure gradients within the decaying ice mass. A predictive model of fluvioglacial deposition has not yet been developed.

In the samples to be considered, however, the sample of 100 pebbles has been drawn from a sample classed in the field as "gravel", and some degree of comparability might perhaps be expected.

A second factor to be considered in a direct comparison of cumulative curve and pebble morphology statistics is the different mean versus standard deviation relationship.

This relationship is crucial to any study of relative degrees of sorting. Within the pebble sizes considered in Chapter 7, the relationship between mean long axis length and standard deviation seems to be linear (see Figures 7.1 and 7.2). The corresponding relationship in Chapter 6 was found to be non-linear (see Figures 6.1a and 6.1b). A third degree curve was fitted, covering all size grades from gravels down to fine sands. This third degree curve agreed with theoretical considerations put forward by Folk and Ward (1957). Even within the gravel-sized samples, a strongly non-linear trend can be seen. Any comparison of mean versus standard deviation figures for the two different techniques would have to consider this linear/non-linear relationship.

A third point to note is the absence of skewness and kurtosis figures in the pebble morphology statistics. It was decided that

these were unlikely to be of value in pebble morphology studies owing to the relatively small number of constituent particles, to the relatively small range of sizes of particles with respect to the complete sediment range, and to the different behaviour of gravels under transport when compared with sands, silts and clays. It could be argued that this applies equally well to mean and standard deviation, but it is apparent from earlier considerations that the more complex the measure, the less likely it is to be of significance.

The fourth point to note regarding the difficulty of comparing the cumulative curve statistics with the pebble morphology statistics is that there is little obvious significance found at first sight in the sphericity and roundness values set down throughout Chapter 7. This is perhaps surprising as these are well-documented behavioural parameters, at least in the fluvial environment. Sphericity and roundness values of mixed lithologies are not considered significant owing largely to the effect of the varying proportions of the different rock types. For that reason alone, there is no justification in including these here. The individual lithology values also cannot be considered as there is no obvious comparison with the sieved sample.

In any attempted comparison of the results of Chapters 6 and 7, it is obvious that only those samples which can be classed as "gravel" should be compared. The comparison will obviously exclude those samples which have not had 100 pebbles selected from them for pebble morphology analysis. The classification of a "gravel" deposit in field section, or after mechanical sieving analysis, is less easy to define. Any definition must be stated in terms of a qualifying

percentage of gravel in the sample, just as, for example, any soil containing at least 35 per cent clay separate can be classed as a "clay" (Buckman and Brady, 1967, p.46). On this principle, the results tabulated below suggest that any sample containing more than approximately 45 per cent gravel mode can be classed as a "gravel" (Table 8B.1).

TABLE 8B.1

Percentages of gravel in samples having graphic mean of -1.50ϕ to -0.50ϕ

Sample No.	Percentage gravel	Graphic mean (ϕ units)
E1.2	45.62	-0.88
E1.4	47.60	-0.85
E2.4	24.05	-0.63
E2.10	39.70	-1.28
01.11	52.89	-1.32
7.6	44.00	-1.08
7.7	44.33	-1.08
8.3	53.75	-1.43
9.2	51.89	-1.23
Average values	44.89 per cent	-1.09 ϕ

According to the Wentworth grade scale, "gravel" includes particles larger than 2 millimetres (-1ϕ) diameter. It would there-

forms seem logical to class as "gravel" any sample having a graphic mean of about -1ϕ or greater, that is, more negative in terms of the phi scale. When the samples having a graphic mean value between -1.50ϕ and -0.50ϕ are considered, the average gravel percentage is as shown in Table 8B.1.

These figures suggest a gravel content of about 45 per cent corresponding to a sample graphic mean value of about -1ϕ .

In fact, the main criterion for selection of sample for pebble morphology study was the presence of at least 100 pebbles of the required size. Three samples were included in the pebble morphology study which had relatively low gravel percentages. They were sample E2.2, which contained 30.28 per cent gravel and had a graphic mean value of -0.10ϕ ; sample E2.4, 24.05 per cent gravel and -0.63ϕ graphic mean; and sample E2.10, 39.70 per cent gravel and -1.28ϕ graphic mean. These were the only three samples included which contained less than 40 per cent gravel, and they can not be described as true "gravel" samples. Their field identification supports this. Sample E2.2 was described as a stony layer within the sand pit at Site 1 (Carstairs). Sample E2.4 was taken from a bed of small gravels in a predominantly sandy section, while sample E2.10 was from a sandy bed containing gravels. All other samples quoted in Table 8B.1 were described in some way as being from gravel beds or lenses.

A last question of comparability arises from the small number of duplicate samples taken. Five of these were from within the Carstairs suite of deposits and three were taken from the Edzell outwash deposits. It seems logical at this stage to look at the comparison between the

two sets of 100 pebbles from the same sample before comparing the pebble morphology results with the cumulative curve statistics. The question has to be asked as to whether or not subsequent comparisons, as indicated in the previous sentence, would be invalidated if it were found that the two sets of pebbles from any one sample site were either significantly different in the statistical sense or were found to cover a large part of the between-sample range of variability for the relevant suite of samples. The duplicate sample values are set out in Table 8B.2.

Only in one case, samples E2.6 and E2.6(2), are the mean long axis lengths widely different, while the only widely different standard deviation values are those of samples E2.6 and E2.6(2) and samples O1.5 and O1.5(2).

The figures shown in the difference columns of Table 8B.2 compare with extreme differences of 5.02 millimetres long axis mean and 4.11 millimetres standard deviation for all Edzell samples, and extreme values differing by 4.22 millimetres long axis mean and 7.45 millimetres standard deviation for the Carstairs group of samples. These figures suggest that the variation within individual duplicate samples is sufficiently small in most cases to allow their inclusion in the overall comparison.

Including the duplicate samples, there are 48 samples for which both cumulative curve statistics and pebble morphology data are available. These comprise 4 samples from the Midlothian deposits, 10 each from Edzell and Bedshiel esker first run of samples, 11 from Edzell outwash and 13 from the Carstairs esker system. The small number of Midlothian samples arises from the relatively small number of pits

at which gravel beds could be identified. Representative field samples were not attempted at some pits, although samples were hand-sieved in the field for subsequent pebble morphology study.

TABLE 8B.2

Comparison of mean long axis length and standard deviation of duplicate samples

Sample no.	Mean long axis length (mms)	Difference	Standard deviation (mms)	Difference
01.5	28.08	2.00	12.76	4.07
01.5(2)	26.08		8.69	
01.7	27.94	0.56	11.93	0.87
01.7(2)	28.50		12.80	
01.8	30.10	1.98	11.25	0.10
01.8(2)	28.12		11.15	
E2.3	26.38	1.52	9.75	1.98
E2.3(2)	27.90		11.73	
E2.6	28.69	2.71	14.09	4.46
E2.6(2)	25.98		9.63	
E2.7	26.29	0.10	9.17	0.98
E2.7(2)	26.10		8.19	
E2.8	24.96	0.30	9.55	1.81
E2.8(2)	24.66		7.74	
E2.9	26.97	0.33	9.30	0.35
E2.9(2)	26.64		9.65	

As stated earlier in this section, direct comparison between the two different techniques as applied to the same sample is difficult. A direct quantitative expression of comparison, at least within individual samples, would seem to be unjustified owing to the fundamental differences in the two techniques involved. The most fruitful line of enquiry would seem to lie in a qualitative comparison of orders of magnitude and degrees of difference for each suite of samples, considering results from the two techniques in parallel, but separately. For example, degree of sorting of individual samples can be inferred from both sets of results. Comparison of the separate inferences on changes in sorting from sample to sample may reveal areas of agreement, or disagreement as the case may be.

The sampling results described in Chapters 6 and 7 may be compared sample by sample. This would seem to offer little of significance other than an estimate of degree of duplication of results, which has intrinsic value. A suite by suite comparison would seem to be of greater value. Such a comparison would seem to depend mainly on mean and standard deviation values, while recalling the basic difficulty of a non-linear mean versus standard deviation relationship with regard to the cumulative curve on the one hand and a linear mean versus standard deviation relation of a selected portion of the whole sample on the other. Skewness and kurtosis values may not be of great value owing to considerations associated with pebble morphology statistics. Factors such as the relatively small number of constituent particles, the relatively small range of

sizes of particles with respect to the complete sediment range, and the increasing difficulty of interpretation of more complex measures would seem to exclude skewness and kurtosis values from any comparison.

Finally, sphericity and roundness values of mixed lithologies have little direct value, while the corresponding values for single lithologies can not be compared directly with the mixed-lithology whole sample cumulative curve.

RELATIONSHIP WITH PERCENTAGE GRAVEL CONTENT

The simplest test of comparison is of the relationship between the percentage of gravel in the original sample and graphic mean and mean long axis length. This has been done for each of the four suites containing a sufficient number of common samples. Correlation coefficients have been calculated and set down as in Table 8B.3.

TABLE 8B.3

Suite correlation coefficients between percentage gravel in sample (independent variable) and graphic mean and mean long axis length (dependent variables)

Suite	Percentage gravel vs. graphic mean	Percentage gravel vs. mean long axis length
Eddleston	+0.87	-0.25
Bedshiel	+0.82	+0.36
Carstairs	+0.96	-0.21
Edzell	+0.95	+0.32

The negative sign of the graphic mean was ignored in the calculations as the negative sign is merely a mathematical device used in the phi scale. A larger graphic mean number (ignoring sign) implies a larger average particle size in the gravel sample.

Table 8B.3 brings out the strong relationship between gravel content and graphic mean, as would be expected as these are "gravel" samples, that is, samples in which the significant proportion of material is gravel-sized and samples which can be considered to act as gravel during deposition. The straight-line relationship indicated by the correlation coefficient is of course a function of the phi transformation. The true relationship would be logarithmic.

No obvious relationship exists between gravel content and mean long axis length, as can be seen from the fluctuating correlation coefficients (Table 8B.3). None of these coefficients approach statistical significance, in contrast with the extremely significant percentage gravel versus graphic mean correlations. This absence of relationship infers that the method of selection of particles for pebble morphology study succeeded in its objective of providing an unbiased sample of the gravel fraction. The point in favour of using pebble long axis statistics is that a direct comparison of the gravel fraction from sample to sample is facilitated. Each pebble sample is apparently unaffected by the differing proportions of materials in the whole sample, and each set of pebble morphology statistics concentrates only on the behaviour of an unbiased representative sample of the gravel fraction. Cumulative curve statistics, on the other hand, are affected by the entire field sample, even though

gravels form the significant proportion in the samples under consideration in this section.

The implication of the results set down in Table 8B.3 is that the whole sample is not reflected directly by the gravel fraction, even though that gravel fraction is dominant. This is borne out by the non-significant correlations between graphic mean and mean long axis.

COMPARISON OF MEAN VALUES

Direct comparison of mean values appears to be of no value. Correlation coefficients are small. Ignoring the negative sign of the graphic mean, correlation coefficients of mean long axis length versus graphic mean range from -0.05 for the Carstairs samples, through +0.04 for Eddleston samples and +0.29 for Edzell samples, to +0.46 for Bedshiel samples. These are not statistically significant.

COMPARISON OF STANDARD DEVIATION VALUES

As standard deviation values are significantly correlated with mean values for both whole sample and pebble morphology statistics, and as graphic mean and long axis mean values are not significantly correlated, it follows that the two sets of standard deviation values will not be significantly correlated. However, both are recognised as measures of sorting, and it might be expected that a similarity of order of samples within individual suites and a similarity of order between suites would be exhibited.

A simple test of similarity of order is the Spearman rank correlation test. The correlation coefficient is given by the formula

$$R = 1 - \frac{\sum d^2}{n^3 - n},$$

where d represents the numerical difference between individual pairs of variates (these variates being in rank order), and n is the number of pairs. Although this is a non-parametric test, relying on ranked rather than absolute values, it is nevertheless a reliable indicator of the presence or absence of significant correlation.

The rank correlation coefficients found when comparing inclusive graphic standard deviation and long axis standard deviation are all positive, but relatively small. Values range from +0.18 for the Eddleston group of samples, through +0.20 for Bedshiel and +0.36 for Carstairs, to +0.47 for the Edzell outwash samples. None of these correlation coefficients can be regarded as statistically significant. The correlation significance test, when applied to the Edzell sample correlation of +0.47, gives a t value of only 1.59. With 11 samples involved, this t value corresponds to a significance level of about 85 per cent, indicating that there is no marked similarity between ranked inclusive graphic standard deviation values and ranked long axis standard deviation values. This implies that standard deviation within the whole sample and standard deviation within the gravel fraction are not related and should be considered

as being different behavioural parameters. It would follow that inferences regarding the whole sample could not be made from gravel-fraction long axis studies.

It was suggested in Chapter 7, however, that some similarities between degrees of sorting in the two sets of results were apparent. In both cases esker samples seemed to exhibit a lower degree of sorting than outwash or kame samples. Comparing graphic mean with inclusive graphic standard deviation, esker samples seemed to show a generally higher standard deviation than outwash samples (Table 6.4). Kame samples tended to have lower standard deviations than outwash samples, a fact attributed to the slightly higher average gravel content of the kame samples considered. It was noted that better sorting would be expected within outwash samples than within kame samples.

Study of long axis mean versus standard deviation regression lines suggests that esker pebble grades are more poorly sorted for size than either kame or outwash gravels (Figs. 7.2a to 7.2e). Both sets of esker samples show relatively high increases in standard deviation per unit increase in mean long axis length. Eddleston kame samples are intermediate in terms of regression line gradient, while Edzell outwash samples have a relatively low regression line gradient.

While both sets of results are of a tentative nature, a certain amount of parallelism is evident. It seems clear from the considerations outlined above that standard deviation on its own is not a reliable indicator of degree of sorting, but should be combined with

at least one other variable. Inclusion of some measure of central tendency, whether graphic mean or mean long axis length, clarifies the picture to a considerable extent. A further discussion on degree of sorting will follow.

COMPARISON OF INFORMATION LEVEL

From the comparisons outlined thus far in the present section, it seems clear that information from the cumulative curve statistics is not directly comparable to information gleaned from pebble morphology statistics. Both these methods have, however, been used widely in recent years in fluvial and sedimentological investigations, usually with broadly similar aims. The usual aims are the investigation of possible trends and the differentiation of environments of deposition. A comparison of information levels attained by the two different techniques as used in the present study will enable an assessment of the relative usefulness of the techniques to be made. Mean versus standard deviation is the basis for comparison or differentiation most frequently quoted in the literature.

COMPARISON OF MEAN VERSUS STANDARD DEVIATION PLOTS

A simple visual comparison can be made by noting the position of each individual sample relative firstly to the graphic mean versus inclusive graphic standard deviation fitted third degree curve (Fig. 6.1a)

and secondly to the long axis mean versus long axis standard deviation regression line (Fig. 7.1). Both of these trend lines are only partly dependent on the 48 common samples under consideration in the present chapter. In the case of the cumulative curve samples, a number of samples containing low percentages of gravel are included, while the long axis mean versus standard deviation graph includes several duplicate samples as well as several groups of pebbles not related to cumulative curve samples. This does not invalidate the comparison as the two tests are basically different, and as the third degree curve fitted to Figure 6.1a recognises the differential trend gradients caused by the varying percentages of gravel.

When a comparison of positions relative to the mean versus standard deviation trend lines is made and results tabulated, it can be seen that relatively few points show completely different relative positions (Table 8B.4). About two-thirds of all samples have similar positions relative to both trend lines, while three-quarters of the remaining samples vary in degree of deviation from the trend line by a relatively small amount. Only 5 points out of 48, or about 1 point in 10, have widely differing relative positions. This suggests that plots of mean against standard deviation for the two types of data under consideration bring out relatively similar characteristics of the original samples.

Of the five "very dissimilar" samples, one came from each of the Eddleston, Edzell and Bedshiel suites of deposits, while two were taken from the Carstairs esker system. The last-mentioned pair,

TABLE 8B.4

Positions of individual samples relative to mean versus
standard deviation trend lines

Sample suite	Similar	Moderately dissimilar	Very dissimilar	Total
Midlothian	4	0	0	4
Eddleston	6	3	1	10
Edzell	7	3	1	11
Carstairs	7	4	2	13
Bedshiel	6	3	1	10
Total	30	13	5	48

samples E2.2 and E2.10, were both characterised by relatively low gravel percentages, 30.28 per cent and 39.70 per cent respectively. This in itself may not be significant as the lowest percentage gravel sample (E2.4 - 24.05 per cent gravel) was placed in the "moderately dissimilar" category in Table 8B.4. There is, in fact, no consistent trend within the five anomalous samples. One sample (E2.10) has a very high inclusive graphic standard deviation, and one (E1.6) a very low inclusive graphic standard deviation coupled with a relatively high long axis standard deviation. Two samples have relatively high long axis standard deviations (samples 8.1 and 01.5), while the remaining sample (E2.2) has a very low long axis standard deviation relative to mean long axis length. These facts suggest that these five samples are not in fact anomalous within an overall context of

comparison of the two mean versus standard deviation plots, but are simply end members in a continuous distribution of increasing dissimilarity of position relative to the appropriate trend lines.

Reverting to the topic of level of information, it seems that a similar level of information is being conveyed by the two sets of data, as most comparable cumulative curve and long axis samples seem to occupy similar positions relative to the different overall trend lines. The significance of this information again lies in degree of sorting, though it must be assumed, from earlier considerations, that degree of sorting within the whole sample is not directly comparable to degree of sorting within a selection of pebbles from the original sample. This seems relatively obvious from the well-documented fact that differential sorting occurs through different size grades at different current strengths. The winnowing action of relatively quiet flow is an obvious example. The picture is complicated, of course, by the relatively chaotic conditions associated with fluvio-glacial deposition.

The significance of this apparent similarity of position relative to the two main mean versus standard deviation trend lines is not clear. A study of samples classed as being well above or well below both trend lines does not clarify the picture. In the absence of confidence limits to the third degree graphic mean versus inclusive graphic standard deviation curve, a subjective visual basis was used to select samples well above or well below the curve. Samples one standard deviation or more above or below the long axis mean versus standard deviation regression line were also selected.

SAMPLES CLASSED AS EITHER WELL ABOVE OR WELL BELOW BOTH TREND LINES

Of the 6 samples classed as being well above the graphic mean versus inclusive graphic standard deviation curve of Figures 6.1a and 6.1b, only 2 are also 1 standard deviation or more above the long axis mean versus standard deviation line. This is too small a number for analysis. Similarly, only 5 samples can be classed as being well below both trend lines. There are no characteristic skewness or kurtosis groupings among these latter 5 samples. As this is inconclusive a comparison of samples well above or well below either trend line follows.

SAMPLES CLASSED AS EITHER WELL ABOVE OR WELL BELOW THE GRAPHIC MEAN VERSUS INCLUSIVE GRAPHIC STANDARD DEVIATION CURVE

As regards samples classed as either well above or well below the graphic mean versus inclusive graphic standard deviation curve, the tendency is for platykurtic samples to appear in the sections well above the average curve, while leptokurtic samples tend to appear in locations well below the curve. This seems to indicate a degree of association between inclusive graphic standard deviation and graphic kurtosis in gravel samples, a high standard deviation corresponding to low kurtosis and low standard deviation corresponding to high kurtosis. In fact platykurtic samples appear in all positions relative to the curve, reflecting the overall concentration of kurtosis values in the platykurtic and mesokurtic categories.

The leptokurtic samples correspond to low inclusive graphic standard deviations and high gravel percentages. However, equal numbers of samples have relatively high inclusive graphic standard deviations and similar gravel percentages. The inference is that graphic kurtosis is of less value as a measure of environment differentiation than graphic mean or inclusive graphic standard deviation.

No direct inferences can be drawn from the skewness values of samples considered to be either well above or well below the graphic mean versus inclusive graphic standard deviation curve. It is noticeable, however, that samples classed as being well below the average curve tend to have a higher percentage gravel content than samples classed as being well above that curve. Only 2 of the 6 "well above curve" samples contain more than 60 per cent gravel, while only 1 of the 11 "well below curve" samples contains less than 60 per cent gravel. With decreasing gravel content, skewness becomes more negative, reflecting the increasing "tail" in the coarser sediments.

This agrees with theoretical considerations in that a sample which is plotted well below the graphic mean versus inclusive graphic standard deviation curve is assumed to be better sorted for size than average. The relatively low standard deviation should lead to a more leptokurtic sample, and the sample in question should also be less positively skewed. The degree of negativity of skewness is dependent by and large on the percentage of gravel mode in the sample.

The samples classed as being well above the graphic mean versus inclusive graphic standard deviation curve are all from field exposures noted as containing gravels in a sandy matrix, or gravel lenses from generally sandy exposures. This mainly accounts for the high inclusive graphic standard deviation and the generally low kurtosis. It further explains the relatively low percentages of gravel in 4 of the 6 samples. This is not, however, marked by any noticeable grouping of extremely positive skewness. Nor is it marked by any particular sample grouping by suite. The below-curve sample group has no notable field characteristics. Percentage of gravel is on average much higher than the above-curve group, but the range of gravel percentages is from 88.73 per cent (sample 6.4) down to 44.33 per cent (sample 7.7). The higher gravel percentages, as noted earlier, are reflected to some extent by lower inclusive graphic standard deviation and higher graphic kurtosis.

SAMPLES CLASSED AS EITHER WELL ABOVE OR WELL BELOW THE LONG
AXIS MEAN VERSUS STANDARD DEVIATION LINE

Within the 48 samples considered throughout the present section, 11 are 1 standard deviation or more above the long axis mean versus standard deviation regression line as depicted in Figure 7.1, while 10 samples are a corresponding distance below this line.

Samples classed as being well above the line have normal skewness values for these gravels, but are slightly more leptokurtic than

average. If the cumulative curve and pebble morphology statistics were comparable, this would be an apparent logical contradiction. If samples are above the long axis mean versus standard deviation line, then gravel sizes would be assumed to be more widely spread than average. This ought to be analogous with a more platykurtic sample, which is not in fact the case.

Samples classed as being significantly below the average long axis mean versus standard deviation line are slightly more coarse-skewed and slightly more platykurtic than average. This is again a logical contradiction in terms of any attempt to equate the two sets of cumulative curve and pebble morphology data. The below-line position suggests that the gravels are more concentrated than average, having a lower-than-average standard deviation for size. This is not mirrored by the kurtosis statistics.

Average percentage gravel content of the field samples from which the pebble morphology samples were derived further emphasizes the lack of comparability between the two sets of data. Above-line pebble samples are derived from field samples having an average gravel content of 67.75 per cent. The corresponding figure for the below-line samples is 68.71 per cent. In essence, these results emphasize the fact that cumulative curve statistics are not directly comparable with pebble morphology statistics.

SUMMARY

The present chapter essentially compares two sets of results, namely cumulative curve and pebble morphology statistics. The

suggestion can be made that these results are not directly comparable for a number of reasons. Graphic mean, for example, has a strong relationship with the percentage of gravel in the sample, while long axis mean is independent of percentage gravel. Thus long axis mean is not directly related to the whole field sample. Secondly, a direct comparison of mean values, namely graphic mean and long axis mean, gives very small suite correlation coefficients. Thirdly, standard deviations of these mean values are not strongly correlated. Nor is there a strong rank correlation to indicate similarities in order of sorting within samples from individual suites.

It can be said, however, that most samples occupy roughly similar positions relative to the two mean versus standard deviation trend lines. But it seems that position of any individual sample relative to either trend line does not give any information directly relevant to any inferences to be made from the other set of statistics.

CHAPTER 9. RELATION OF CUMULATIVE CURVE AND PEBBLE MORPHOLOGY

STATISTICS TO FIELD MORPHOLOGY

It seems clear from the preceding chapter that a different type of information is being conveyed by the two sets of data, that is by the cumulative curve statistics and the pebble morphology statistics. There seems to be only the weakest association between the two sets of statistics. This association does not seem to be statistically significant on the whole, despite the similarity of positions of individual samples relative to mean versus standard deviation trend lines (Table 8B.4). This latter fact implies some parallelism in degree of sorting between the entire field sample on the one hand and an unbiased selection of 100 pebbles from that sample on the other. Differences in degree of sorting are fundamental to any attempt to differentiate environments of deposition, and a closer examination in terms of individual suites is warranted.

Results set down in Chapters 6 and 7 suggest that the nature of the fluvioglacial depositional environment is such that only the simplest measures of sample profile and pebble morphology are of value. These results were based on general statistical considerations, with little mention of such factors as position of sample within the overall suite of deposits, relationships of sample sedimentation units with contiguous sedimentation units, degree of representativeness of individual samples with respect to overall site conditions, and distance of travel of constituent materials. Closer study of site morphology is required before final conclusions, whether of a positive or a negative nature, can be drawn.

MIDLOTHIAN SUITE OF DEPOSITS (A) FIELD MORPHOLOGY

As outlined in Chapter 1, samples taken from the Midlothian suite of deposits represent some of the dead-ice phenomena of an area where drainage was essentially marginal to, or through, a mass of decaying ice wasting on lower ground to the north and east of the watershed (Kirby, 1968, 1969b). The deposits can be regarded, for the purposes of the present study, as either kame or outwash deposits depending on location. They are all ice-marginal deposits in the sense that they were invariably deposited in contact with, or in close proximity to, the margins of a decaying ice mass. The locations of samples selected are set down in Table 9.1 and shown in Figure 1.2. This figure also shows the positions of sites described in the text from which samples were not taken.

Considering samples site by site, the first site visited was a commercial excavation near Straiton. According to Kirby (1966) this is an area of kame deposition exhibiting characteristic ice-contact slopes. Although digging had presumably commenced from the foot of the ice-contact slope at this site, as evidenced by the level of the floor of the pit, both south- and north-facing ice-contact slopes of between 30° and 35° were visible at the time of sampling (April, 1968). This might suggest extensive crevasse or moulin filling during an advanced stage of glacier decay. The excavation showed the material to be mainly sand, but one prominent gravel lens was present. Samples were taken from this gravel lens, and from adjacent sand beds. The lens itself was about 1 metre thick at most in a 5 metre-deep exposure.

TABLE 9.1

Location of Midlothian Area samples

Site	Approx. Nat. Grid Reference	Sample No	Mechanical Analysis Sample	Pebble Morphology Sample	Common Sample
Straiton Pit	NT 270 666	1.1	x	x	x
		1.2	x		
		1.3	x		
		1.4	x		
Melville Mains Pit	NT 298 666	2.1	x		
		2.2	x	x	x
		2.3		x	
		2.4		x	
		2.5		x	
Burghlee Pit	NT 277 652	3.1	x		
		3.2	x		
Haveral Wood Pit	NT 293 662	4.1	x	x	x
		4.2	x	x	x
		4.3	x		
		4.4		x	
Wadingburn Pit	NT 297 664	5.1		x	
Clippens Pit	NT 267 660	13.1		x	
		13.2		x	
Pentland Mains Pit	NT 258 654	19.1		x	
Niven's Knowe Pit	NT 262 654	20.1		x	
		20.6		x	
			11	14	4

The face ran approximately east-west, and no consistent bedding direction

could be distinguished in this orientation, though slumping of sand beds was apparent. Samples 1.1 and 1.4 contained 59.29 per cent and 72.90 per cent gravel respectively, while only a few isolated pebbles were found in samples 1.2 and 1.3. This in itself indicates quite clearly the immense diversity that can occur within short distances throughout fluvioglacial landforms.

Site 2, Melville Mains pit, is the largest commercial excavation in the area. Massive deposition took place here. Exposures of up to 10 metres are seen, the bedding in these exposures agreeing with the outwash delta origin suggested by Kirby (1966). Material present is mainly sand, the top 1 to 2 metres containing a larger percentage of gravel. Bedding is fairly consistent, mostly gently inclined downwards to north and east, though occasional contortions are noted. Top-set delta bedding can be seen. In some places, however, bedding is sharply truncated by an overburden of about 1 metre of sandy, apparently unstratified material. This itself appears to have been artificially levelled, but may represent the Roslin Till first described in detail by Anderson in 1940. The apparent absence of stratification at these sites suggests that these are not top-set delta beds, though human interference cannot be ruled out. One sand and 1 gravel sample were mechanically sieved, while 4 pebble morphology samples were taken.

Burghlee, Site 3, is now a disused pit. Very little material above sand size is seen. Exposures of up to 5 metres show well-bedded sands with frequent layers of coal fragments. Occasional cobbles are noted. An upper till of thickness between 0.5 and 1.5 metres

lies unconformably above the sand beds. A south-north section shows roughly horizontal bedding. Two sand samples were taken for mechanical analysis, but insufficient numbers of suitably-sized pebbles were found in these deposits for a normal pebble sample to be taken from a single sedimentation unit. Relatively quiet deposition without ice-contact is indicated, similar to conditions of deposition of most of the deposits at Melville Mains, some 2.5 kilometres to the north-east.

Much coarser material was found at Site 4, Haveral Wood, which lies approximately half-way between the Melville Mains and Burghlee sites. At the eastern extremity of the pit, mainly sand, with considerable puckering of bedding, is seen. Ripple marks are also much in evidence. There is, however, an abrupt change to tilted gravel layers westwards, sections of at least 10 metres of well-stratified gravels being seen. Ice-contact deformation is evident. Two gravel and 1 sand sample were mechanically sieved, and an additional sample was taken for pebble morphology analysis to make a total of 3 sets of 100 pebbles.

Approximately half-way between Haveral Wood pit and the Melville Mains site is Wadingburn pit (Site 5). Slumped material has masked the lower parts of faces of this disused pit, but 1 gravel sample was taken for pebble morphology analysis. Gravels are evident in such sections as are available. Kirby (1966) suggests that the Wadingburn and Melville Mains sites are essentially the same fluvioglacial unit, with a direction of meltwater flow from west or south-west being supported by the evidence of larger percentages of finer material

towards the north-east. This appears to be repeated at Haveral Wood, a relatively short distance to the south-west, where coarser material grades into much finer material towards the north-east.

Anderson (1940) describes sections of sand at a pit which, from his description, is almost certainly the presently-named Burghlee site, further still in a south-westerly direction. A series of fluvioglacial units of deposition north-eastwards into ice-dammed or englacial lakes is indicated. Assuming that these are successively younger in a north-easterly direction, a gradation in material sizes might be expected from grain size and pebble morphology statistics.

This succession is complicated somewhat by the fact that sites visited to the south of this area lack visible gravels. Site 15, near the site of Langhill Farm (NT 276641), probably Anderson's "Bilston Pit", shows identical deposits to those found at Burghlee. A relatively flat-topped area falls off gradually to the south-west. Exposures show well-bedded fine sands with occasional coal fragments appearing, concentrated in lenses rather than beds. The sands appear to coarsen upwards, as well as becoming more reddish upwards.

Disused pits between Roslin (NT 270630) and Oatslie (NT 263624) have been largely filled in by coal mining waste, but only sands with occasional thin gravel layers are now visible (Site 24 on Fig. 1.2). Anderson quotes exposures of 10 to 12 metres of sand with occasional lenticular beds of gravel at Oatslie, and notes that "spectacular current bedding" was seen there. Anderson found enough pebbles to make stone counts at his "Roslin pits", but gives no indication of the relative frequency of occurrence of sand and gravel beds at this site.

Sands with only occasional gravel lenses are found in 15 metre sections at Kirkhill (Penicuik), some 3 kilometres further to the south-west of Oatslie (Site 23 at NT 237605). Approximately 3 kilometres east of the Roslin-Oatslie exposures, two further disused pits are found (Site 25 at NT 297630 and Site 26 at NT 299633). The more southerly of these shows up to 8 metres thickness of well-bedded coarse sands and fine gravels. Occasional larger cobbles can be seen. The pit approximately 300 metres to the north-east shows almost entirely fine-bedded sand with conformable veins of coal. Beds dip consistently at angles of about 10° towards the north or north-east. This would appear to mark another minor halt stage in the general retreat of the ice margin northwards.

As well as the Straiton site, 3 other sites nearer the Pentlands were visited and samples taken. The first of these, Site 13 (Clippens) lies approximately 1 kilometre south-west of Straiton pit. Thicknesses of up to 13 metres of well-stratified sand and gravel are seen. Deposits are predominantly of fine sand. Boulders up to 30 centimetres across are encountered. These occasionally form beds in a sandy matrix. The proportions of sand to gravel vary throughout any given vertical face. In lower sections, fine-bedded and contorted sands predominate. These appear to coarsen westwards. In higher sections, gravelly beds are overlain by increasingly more sandy beds. Gravels are more evident in the thicker deposits in the western half of the pit. This suggests material moving from west or south-west, with perhaps a relatively adjacent and oscillating ice front to the west, deposition again presumably being into a large glacier moulin. Two samples were taken

from the middle gravels for pebble morphology study.

Further south-west, approximately 1 kilometre distant from the Clippens site, are the disused pits near Pentland Mains (Site 19) and Niven's Knowe (Site 20). Site 19 appears to be part of a small, isolated, flat-topped kame. One small exposure, from which a pebble morphology sample was taken, shows coarse sands with gravel. Site 20 represents a much larger commercial excavation site. Exposures of up to 7 metres are noted. Contorted sediments with a large range of sizes are present. Many boulders up to 30 centimetres across are seen. Extreme fracturing of sediments is shown in particular by lenses of much-faulted sands. Quartz pebbles are found in some numbers and beds of well-rounded pea-sized gravels are noted. Relatively turbulent conditions of deposition are indicated, and ice-contact deposition is suggested by the extensive faulting of beds. Two pebble morphology samples were taken, one each from the extreme eastern and western ends of the pit. It might be expected that these samples would show a higher percentage of Pentland Hills volcanic pebbles than other samples from pits to north and east if the direction of meltwater were from south or south-west.

These last deposits, being laid down at approximately 170 to 160 metres O.D. may be earlier in time of deposition than the material laid down at about 140 metres O.D. at Clippens and Straiton and also that deposited at Burghlee (about 150 metres O.D.) and Haverall Wood, Wadingburn and Melville Mains (approximately 120 metres O.D.). Deposition would have been controlled to some extent by the englacial water table in the Midlothian basin. The water table would have been progressively

lowered as the ice sheet decayed and the effective margin retreated northwards. A complex succession of deposits has resulted. Kame deposition alternates to some extent with outwash. Evidence of delta deposition, presumably into englacial or ice-ponded lakes, can be seen. The succession is not in any sense continuous, however, and even detailed morphological analysis **does** not reveal the whole picture directly (Kirby, 1969b).

MIDLOTHIAN SUITE OF DEPOSITS (B) SAMPLE STATISTICS

Cumulative curve statistics and pebble morphology analyses do not appear to add much of substance to detailed field mapping in this instance. One point of note is the low kurtosis values found in the Straiton samples. Both gravel samples are platykurtic and both sand samples are mesokurtic. Of the other 7 Midlothian samples, 2 are mesokurtic, 4 leptokurtic and 1 very leptokurtic. Sorting, skewness and kurtosis values are summarized for gravel and sand samples from all suites in Tables 9.2, 9.3 and 9.4 respectively. Verbal classes used are those of Folk and Ward (1957). These tables will be referred to throughout the present chapter.

The concentration of leptokurtic samples in the Midlothian sample group is marked in comparison with the other sample suites. As can be seen from Tables 9.4 and 9.5, there is no obvious correlation between any specific kurtosis grouping and whether the samples are classed as "sand" or "gravel".

TABLE 9.2

Verbal sorting values of cumulative curve samples

	Gravel samples						Sand samples					
	Midlo- thian	Eddle- ston	Car- stairs	Bed- shiel	Edzell	Others	Totals	Midlo- thian	Eddle- ston	Car- stairs	Others	Totals
Very Well Sorted	0	0	0	0	0	0	0	0	0	0	0	0
Well Sorted	0	0	0	0	0	0	0	1	0	1	0	2
Moderately Well Sorted	0	0	0	0	0	0	0	1	0	0	1	2
Moderately Sorted	0	0	0	0	0	0	0	2	2	2	0	6
Poorly Sorted	0	4	0	2	0	1	7	2	2	0	1	5
Very Poorly Sorted	5	14	5	9	8	0	41	0	4	2	0	6
Extremely Poorly Sorted	0	0	0	0	0	0	0	0	0	1	0	1
Totals	5	18	5	11	8	1	48	6	8	6	2	22

TABLE 9.3

Verbal skewness values of cumulative curve samples

	Gravel samples					Sand samples						
	Midlo- thian	Ed- dle- ston	Car- stairs	Bed- shiel	Edzell	Others	Totals	Midlo- thian	Ed- dle- ston	Car- stairs	Others	Totals
Strong Fine	4	4	3	5	3	0	19	0	1	0	0	1
Fine	1	6	2	4	3	1	17	1	1	1	1	4
Near-symmetrical	0	4	0	0	2	0	6	4	2	2	0	8
Coarse	0	4	0	2	0	0	6	0	0	0	1	1
Strong Coarse	0	0	0	0	0	0	0	1	4	3	0	8
Totals	5	18	5	11	8	1	48	6	8	6	2	22

TABLE 9.4

Verbal kurtosis values of cumulative curve samples

	Gravel samples					Sand samples						
	Midlo- thian	Eddle- ston	Car- stairs	Bed- shiel	Edzell	Others	Totals	Midlo- thian	Eddle- ston	Car- stairs	Others	Totals
Very Platykurtic	0	2	1	3	1	0	7	0	1	0	0	1
Platykurtic	2	6	3	1	5	0	17	0	2	2	0	4
Mesokurtic	1	5	0	4	1	1	12	3	4	3	1	11
Leptokurtic	1	5	1	3	1	0	11	3	1	1	1	6
Very Leptokurtic	1	0	0	0	0	0	1	0	0	0	0	0
Totals	5	18	5	11	8	1	48	6	8	6	2	22

TABLE 2.5

Cumulative curve statistics for Midlothian samples

Sample No.	Percentage Gravel	G. Mean (\bar{x})	I. G. S. D. (σ units)	I. G. Skewness	G. Kurtosis
1.1	59.29 G	-2.38	3.40/v. poorly sorted	+0.17/fine	0.69/platykurtic
1.2	0.10 S	+3.23	0.79/moderately sorted	-0.05/near-symmetrical	1.04/mesokurtic
1.3	0.38 S	+2.17	0.76/moderately sorted	+0.13/fine	0.98/mesokurtic
1.4	72.90 G	-3.05	3.17/v. poorly sorted	+0.53/strong fine	0.81/platykurtic
2.1	0.20 S	+3.00	0.55/mod. well sorted	+0.04/near-symmetrical	1.23/leptokurtic
2.2	78.80 G	-2.37	2.31/v. poorly sorted	+0.61/strong fine	1.18/leptokurtic
3.1	1.77 S	+3.01	1.02/poorly sorted	-0.08/near-symmetrical	1.24/leptokurtic
3.2	10.64 S	+2.07	1.75/poorly sorted	-0.46/strong coarse	1.30/leptokurtic
4.1	85.39 G	-2.92	2.04/v. poorly sorted	+0.39/strong fine	1.63/v. leptokurtic
4.2	87.40 G	-3.98	2.48/v. poorly sorted	+0.33/strong fine	1.05/mesokurtic
4.3	0.00 S	+3.10	0.46/well sorted	-0.03/near-symmetrical	0.91/mesokurtic

NOTE: Verbal classes after Folk and Ward (1957)

If the sample is classed as being leptokurtic, then this implies that sorting in the central portion of the cumulative curve is much better than sorting in the tails. A platykurtic value means that the tails of the sample are better sorted than the central portion. This may, in some cases, imply bimodality and the presence of material from two or more distinct sources.

In the present case, as can be seen from Table 9.5, the platykurtic samples from the Straiton site are also the poorest-sorted samples. They are, of course, gravel samples, but none of the other gravel samples in the present group approaches these in terms of pooriness of sorting. All gravel samples have positive skewness, in contrast with 5 of the 6 sand samples. The very leptokurtic sample 4.1 is also a gravel sample. As might be expected, it also exhibits the lowest standard deviation of all gravel samples shown in Table 9.5, but has an intermediate skewness with reference to other gravel samples in this group.

Poorest sorting among the sand samples occurs in the samples from Burghlee. These also contain the highest gravel content of these sand samples. Consequently, it might not be expected that these sand samples from Burghlee are leptokurtic, despite a strong coarse skewness in one case (sample 3.2), while the Straiton sand samples are mesokurtic. This suggests that a wider variety of source currents deposited the Straiton sand samples. A similar conclusion may be drawn with regard to the kurtosis values of the Straiton gravel samples. The positions of all 11 points relative to the graphic mean versus inclusive graphic standard deviation trend line add nothing to these

tentative suggestions, there being no consistent trend among these samples, neither by site nor by percentage gravel. The suggestion remains that the Straiton deposits may have been contributed to by a wider range of sources than Burghlee, Haveral Wood or Melville Mains deposits. The question must now be asked as to whether or not this suggestion is supported by pebble morphology statistics.

The first consideration is long axis mean versus standard deviation. With reference to Figure 7.2a, the largest mean long axis length (33.39 millimetres) is found in the Straiton sample. However, the variation in mean long axis lengths of the 4 Melville Mains samples (32.01, 28.26, 26.93 and 26.64 millimetres) suggest that it would be unwise to treat this as of significance. The relatively high Straiton value may be explained by the relatively high proportion (66 per cent) of Pentland Hills volcanic pebbles, which have a mean long axis length of 33.82 millimetres. The scatter of points on Figure 7.2a shows no significant grouping. Neither shape nor rock type of the samples of 100 pebbles seems to affect position relative to the long axis mean versus standard deviation line for this group of samples.

Some points may be noted in passing with reference to variations in constituent pebble type. Variations in the proportions of individual lithologies are wide (Table 9.6). These variations may be random, as is suggested to some extent by, for example, the variation in numbers of Carboniferous sedimentary pebbles within the 3 Haveral Wood samples, and also the variation in proportions of volcanic pebbles within the 2 Clippens samples (samples 13.1 and 13.2).

TABLE 9.6

Rock type variations in Midlothian pebble samples

Sample no.	Volcanic	O.R.S. Sedimentaries	(Total O.R.S.)	Carboniferous sedimentaries	Highland	Quartzite & quartz	Greywacke	Others/ unidentified
1.1	66	11	(77)	13	3	2	0	5
2.2	39	12	(51)	29	0	5	4	11
2.3	48	19	(67)	25	1	3	0	4
2.4	42	18	(60)	27	0	3	1	8
2.5	54	14	(68)	25	0	3	1	3
4.1	30	18	(48)	41	2	0	0	9
4.2	15	15	(30)	70	0	0	0	0
4.4	25	22	(47)	48	0	0	1	4
5.1	29	17	(46)	35	0	6	4	9
13.1	51	13	(64)	30	0	5	0	1
13.2	19	23	(42)	51	0	2	4	1
19.1	25	22	(47)	42	1	5	3	2
20.1	25	23	(48)	44	0	3	3	2
20.6	36	24	(60)	36	0	1	0	3

The distance of site from the Pentland Hills seems to have had no effect on the proportions of volcanic pebbles present, despite the relative proximity of some sites to volcanic outcrops. In addition, long axis length, roundness and sphericity of volcanic pebbles from these sites show no recognisable trends or obvious groupings.

In summary, it seems from the present results that in the complicated sequence of Midlothian deposits, pebble morphology study does not elucidate the problems of sequence of deposition. Study of cumulative curve statistics does, however, indicate certain areas where further sampling might prove fruitful. The ice-contact deposits of the Straiton site can be distinguished from the kame-outwash sequence of deposits at Burghlee, Haveral Wood and Melville Mains. However, within-site variation remains high with reference to between-site variance. It seems clear that further sampling would be necessary to confirm any possible local differences in depositional environment. The sequence of deposits as a whole shows few trends which can be said to be characteristic. This can be attributed at least partly to the relatively small number of samples and also partly to the changing environment of ice-contact and proglacial deposition as indicated by field examination of the deposits.

EDDLESTON KAME DEPOSITS (A) FIELD MORPHOLOGY

Sissons (1958) suggested that massive kame deposition took place in the Eddleston valley after the development of the watershed to the north, which dammed the previous south-to-north meltwater flow.

Deposition ceased when ice dissolution was so advanced that a southward drainage line to the Tweed valley was established.

In all, 6 sites were visited, 4 of which were active. All 4 active pits were in deposits on the western side of the valley, whereas the other 2 sites were both in deposits on the eastern flank of the valley (Fig. 1.3). From the first 2 of these, Sites 6 and 7, stratified grid samples were taken. Spot samples were taken from the other exposures. Table 9.7 summarizes the location of samples.

Samples from Sites 6 and 7 were discussed, in terms of within-site variation versus between-site variation, in the previous chapter, and only a brief summary of these sites need be given here. Site 6 is at the extreme northern end of the Eddleston valley, where the valley floor rises to the general level of the surrounding terrain. Although thicknesses of fluvioglacial material of as much as 9 metres can be seen at this site, much more extensive deposits are found on lower ground to the north-east, and much greater thicknesses of fluvioglacial material are seen in the deeper parts of the Eddleston valley to the south of this site.

At Site 6, bedding is confused. Faulting and distortion of beds is common. Turbulent water conditions, combined with proximity to disintegrating ice, are indicated. These deposits seem to be part of a continuous sequence of deposition by meltwaters travelling in northward or north-eastward directions, controlled to a great extent by the englacial water table. On higher ground, as at Site 6, deposition was less extensive as erosion would have been more important. Also, this area is not far south of the main watershed as it must have

TABLE 9.7

Location of Eddleston kame samples

Site	Approx. Nat. Grid Reference	Sample No.	Mechanical Analysis Sample	Pebble Morphology Sample	Common Sample	
United Quarries' Eddleston Pit	NT 239 531	6.1	x			
		6.2	x	x	x	
		6.3	x			
		6.4	x	x	x	
		6.5	x			
		6.6	x			
		6.7	x			
		6.8	x			
		6.9	x			
		6.10	x			
		6.11	x			
		6.12	x		x	x
		6.13	x			
Cowies-linn Pit	NT 238 516	7.1	x	x	x	
		7.2	x			
		7.3	x	x	x	
		7.4	x			
		7.5	x	x	x	
		7.6	x			
		7.7	x	x	x	
		7.8	x	x	x	
Nether Falla Pit	NT 239 520	8.1	x	x	x	
		8.2	x			
		8.3	x			
Ship-horns Pit	NT 240 947	9.1	x	x	x	
		9.2	x			
Disused pit	NT 245 491	21.1		x		
Road cutting	NT 245 518	22.1				
		22.2		x		
			26	12	10	

existed in the ice-dissolution period, and would have been meltwater-free and ice-free at relatively early stages in ice retreat.

Just over 1 kilometre to the south lies Nether Falla pit (Site 8). In this relatively small excavation beds of very poorly sorted material, varying in thickness from less than 1 metre to about 3 metres, can be seen. This may well be the remnants of a stony till incorporated into the fluvioglacial material. Ablation till is evident throughout the Eddleston valley, and occasional incorporation would not be unusual. In general, stratification is clear throughout this pit, and a dip of between 20° and 30° eastwards towards the axis of the valley is characteristic.

Approximately 500 metres further south lies the much larger Cowieslinn pit, Site 7. Sections in this pit are characterised by a preponderance of gravels, beds again dipping 20° to 30° towards the axis of the valley a short distance eastwards. Sections of up to 10 metres are seen. Where undisturbed, surface topography to west and south of Sites 7 and 8 is typically kame and kettle, irregular mounds with occasional enclosed depressions.

Two kilometres south of Site 7 lies Site 9, Shiphorns pit. As the Eddleston valley descends towards the Tweed, the summits of deposition here are lower than summits of deposition at Sites 7 and 8. However, considerable thicknesses of fluvioglacial material have been laid down at this site. Faces up to 30 metres high can be seen. Surface terrain is still hummocky, and beds again dip predominantly at 20° to 30° towards the axis of the valley. Slopes from the valley floor, here only about 200 metres across, are steep, reaching 45° in some places.

Occasional quartz pebbles are noted in section, as in the other pits. In common with the other Eddleston valley sites, it can be noted throughout all substantial sections that there is a general lightening in colour upwards. A grey colour at the base of sections lightens upwards to more sandy yellow colours. This need have no explanation other than general weathering and leaching. Material in all exposures in this area is predominantly locally-derived shales and greywackes. The greywacke pebbles tend, if anything, to be slightly more yellow than the blue-grey shales.

Some clear examples of contorted bedding have been noted in Shiphorns deposits. Also present is a concentration of massive boulders in one top section measuring 30 metres by 8 metres. Bedded sands lie below the 2 metre thick layer of very large boulders. Above the boulder layer are some 5 to 7 metres of very heterogeneous stony till-like material lacking stratification. As noted at previous sites, a cover of ablation till would seem to account for this. Nearby conical mounds show confused internal bedding overlain by up to 1 metre of unstratified material. The concentration of large boulders mentioned could have been derived from a flow-till environment where the largest boulders were deposited first. The 15° tilt of these deposits can be attributed to collapse following a melting of adjacent ice blocks.

All exposures described thus far in the present section are located on the western side of the valley. In all sections, except those at Site 6 to the north, beds dip predominantly at moderate angles towards the axis of the valley. Sissons (1958) suggests that

this dip is in fact post-depositional in origin, and was consequent upon the decay of the mass of ice which choked the Eddleston valley before southward drainage was established.

Two small exposures were visited on the east side of the valley. These are both near valley floor level. Site 21, an abandoned pit about 400 metres south of the limit of Shiphorns pit, shows one good section parallel with the axis of the valley. In this section, gravel beds dip at 45° and greater angles to the south. Only post-depositional collapse could account for these high bedding angles.

Several good exposures were made available, and visited in October 1968, by road-straightening works near Nether Falla. Exposures seen were only a few metres lower topographically than the Nether Falla deposits but did not show any obvious preferred direction of dip. Deposits were variable, but well-bedded. Beds were, in all cases, approximately horizontal or gently buckled. Many beds of gravel, loosely held in a clayey matrix and with no interstitial sand-sized particles, were seen. Bands of sand alternated to some extent with bands of gravel, though occasional sand lenses were seen. There was little evidence of ice-contact, in contrast with the deposits to the west of the valley axis, and a deposition in conjunction with a reversal of meltwater flow at a late stage of deglaciation seems feasible.

No sections were found at right angles to the valley axis at either Site 21 or Site 22, but it seems likely from their nearness to the level of the valley floor that both sites represent the last stages of fluvio-glacial deposition in the Eddleston valley. Ice-contact

is especially evident in the case of Site 21, in the narrowest part of the present valley. It might be expected, therefore, that samples from Sites 6, 7, 8 and 9 might show similar characteristics, perhaps grading northwards with the presumed direction of meltwater flow. Samples from Sites 21 and 22, on the other hand, can be presumed to have been deposited by southward-flowing meltwaters, and can be presumed to have been deposited at a later date than material found on the western flank of the valley.

EDDLESTON KAME DEPOSITS (B) SAMPLE STATISTICS

The stratified grid samples from Sites 6 and 7 have been compared in the previous chapter with the specific aim of investigating within-site versus between-site variation. It was concluded that the between-site variation in sample values was not sufficient to overcome the masking effect of within-site variability. Differences between the two sites were noted, but these were not statistically significant.

With reference to cumulative curve statistics and to Tables 9.2, 9.3 and 9.4, Eddleston samples would appear to be slightly more coarse-skewed than average, but would appear to have a fairly average spread of kurtosis values. Cumulative curve statistics for Eddleston gravel samples are shown in Table 9.8, and those for sand samples in Table 9.9.

TABLE 9.8
Cumulative curve statistics for Eddlestone gravel samples

Sample no.	Percentage gravel	G. Mean (β)	I. G. S. D. (β units)	I. G. Skewness	G. Kurtosis
6.2	67.47	-2.25	2.06/v.poorly sorted	-0.16/coarse	0.89/platykurtic
6.4	88.73	-2.88	1.36/v.poorly sorted	+0.27/fine	1.15/leptokurtic
6.5	67.91	-1.55	3.19/v.poorly sorted	+0.41/strong fine	0.90/mesokurtic
6.6	89.37	-3.12	1.48/poorly sorted	+0.34/strong fine	1.24/leptokurtic
6.7	64.99	-2.20	3.43/v.poorly sorted	+0.13/fine	0.88/platykurtic
6.8	67.21	-1.73	1.38/poorly sorted	-0.05/near-symmetrical	0.54/platykurtic
6.9	85.60	-3.68	2.52/v.poorly sorted	+0.18/fine	1.29/leptokurtic
6.12	65.38	-1.77	2.54/v.poorly sorted	+0.31/strong fine	0.85/platykurtic
7.1	77.51	-3.45	2.89/v.poorly sorted	+0.04/near-symmetrical	0.93/mesokurtic
7.3	80.37	-2.65	1.99/poorly sorted	+0.30/fine	0.93/mesokurtic
7.5	80.12	-3.38	2.72/v.poorly sorted	+0.07/near-symmetrical	1.05/mesokurtic
7.6	44.00	-1.08	2.25/v.poorly sorted	-0.25/coarse	0.68/platykurtic
7.7	44.33	-1.08	2.20/v.poorly sorted	-0.22/coarse	0.54/v.platykurtic
7.8	76.31	-3.20	2.88/v.poorly sorted	+0.43/strong fine	0.92/mesokurtic
8.1	86.29	-3.59	2.40/v.poorly sorted	+0.27/fine	1.14/leptokurtic
8.3	53.75	-1.43	2.87/v.poorly sorted	-0.17/coarse	1.12/leptokurtic
9.1	81.25	-3.00	2.17/v.poorly sorted	+0.29/fine	0.77/platykurtic
9.2	51.89	-1.23	2.26/v.poorly sorted	-0.06/near-symmetrical	0.78/platykurtic

NOTE: Verbal classes after Folk and Ward (1957)

TABLE 9.2

Cumulative curve statistics for Eddleston sand samples

Sample no.	Percentage gravel	G. Mean (β)	I. G. S. D. (β units)	I. G. Skewness	G. Kurtosis
6.1	41.40	-0.12	3.65/v. poorly sorted	-0.33/strong coarse	0.65/platykurtic
6.3	46.17	+0.33	2.05/v. poorly sorted	+0.84/strong coarse	0.68/platykurtic
6.10	0.17	+5.57	1.37/poorly sorted	+0.01/near-symmetrical	0.97/mesokurtic
6.11	26.71	+0.85	2.60/v. poorly sorted	-0.45/strong coarse	0.80/platykurtic
6.13	0.38	+4.23	0.93/moderately sorted	-0.00/near-symmetrical	0.98/mesokurtic
7.2	23.16	+0.83	2.76/v. poorly sorted	-0.43/strong coarse	0.97/mesokurtic
7.4	0.39	+2.27	0.78/moderately sorted	+0.23/fine	1.02/mesokurtic
8.2	14.29	+1.17	1.95/poorly sorted	-0.35/strong coarse	1.28/leptokurtic

NOTE: Verbal classes after Folk and Ward (1957)

Immediately noticeable is the generally poor degree of sorting. No samples are classed as better than moderately sorted, and only 2 samples, both sand samples, come into this category. Of the 8 sand samples, 4 are classed as being very poorly sorted, and all but 4 of the 18 gravel samples are very poorly sorted.

The Site 6 gravel samples are, on average, slightly better sorted than the Site 7 gravel samples. Average inclusive graphic standard deviation values are 2.25 ϕ units and 2.49 ϕ units respectively. This is reflected, however, in a slightly higher average percentage gravel content within the Site 6 gravel samples, namely 74.58 per cent, compared with the Site 7 gravel sample average of 67.11 per cent. The slightly higher gravel percentage implies in this case a better-sorted group of samples. Whether this is a reliable indicator of sedimentation direction remains doubtful owing to the relatively wide within-group ranges of values.

It may also be seen from Tables 9.8 and 9.9 that the Site 7 samples appear to be more coarse-skewed than average. This is partly explained by the presence of two samples (7.6 and 7.7) containing relatively low percentages of gravel (44.00 per cent and 44.33 per cent respectively). Classification of these samples as "gravel" follows from considerations in the previous chapter regarding the percentages of gravel corresponding to a graphic mean of -1 ϕ . Samples with graphic mean of -1 ϕ or greater (that is, more negative) were to be classed as gravel samples. This figure corresponds roughly to a gravel content of about 45 per cent (see Table 8B.1).

In general, as has been noted previously, the Eddleston gravels as a group would appear to be more coarsely-skewed than average. This must necessarily lead to a poor degree of sorting as this assumes a minimum percentage of sand of about 10 per cent plus a tail in the larger gravel sizes. The origin of this coarse-skewness and associated poor degree of sorting is not immediately apparent. The answer almost certainly lies with the local bedrock types and relatively short distances of travel of constituent material. Both greywackes and the local shales, which form the bulk of the material, are massive rocks, and greywackes are generally resistant to wear. Larger numbers of cobbles would appear. This, allied to the generally irregular kame depositional environment, would lead to a poor degree of sorting.

The coarse skewness noted within the gravel samples is repeated within the sand samples. As can be seen from Table 9.3, only 8 of the 22 sand samples are classed as strongly coarse-skewed, whereas 4 of the 8 Eddleston samples are in this category. A relatively poor degree of sorting is also indicated within these sand samples. Table 9.2 shows that 4 of the 8 sand samples are classed as being very poorly sorted. None of the samples are better than moderately sorted.

As far as kurtosis is concerned, neither the Eddleston gravel nor the sand sample group is remarkable in its distribution of values. Similarly, the positions of individual site points on the graphic mean versus inclusive graphic standard deviation plot do not show

any significant groupings or trends (Fig. 6.1d and Tables 9.8 and 9.9).

Considering the relevant pebble morphology statistics, most samples lie fairly close to the long axis mean versus standard deviation regression line (Fig. 7.2b). Only one sample, 8.1, lies some way from this line. Some very large cobbles are present in this sample which was taken from a bed of the larger gravels which were common at this site. The largest mean long axis value comes from the Site 9 sample, while the smallest comes from Site 6. There is a crude gradation of values, the average for all Site 7 samples being 28.37 millimetres compared with a Site 6 average of 25.94 millimetres. The Site 21 and Site 22 values are intermediate, however. It might be expected from earlier considerations that these would be composed of further-travelled pebbles, which would have a correspondingly smaller mean long axis value, but this is not brought out by the laboratory results.

Rock type differences are not extensive in the Eddleston case as all samples contain about 80 per cent or more local greywacke and shale pebbles. Small numbers of volcanic rocks and sandstones are found, but these are relatively insignificant except in the case of the Site 6 samples. These 3 samples contain 13 per cent (sample 6.2), 15 per cent (6.4) and 16 per cent (6.12) volcanic pebbles. The next highest percentage of volcanic pebbles is 6 per cent in sample 7.5.

Although only small numbers of sandstone pebbles accompany these volcanic pebbles, a strong lithological contribution from the Pentland Hills area is indicated. Meltwaters depositing material at Site 6 may have come from two sources, the Eddleston valley to the south and

the Auchencorth Moss area to the west. As this site is relatively close to the watershed, a diversion of meltwaters in a west to east direction at the margin of the northward-retreating ice mass may have taken place in an early stage of deglaciation. These meltwaters would have contributed some material to the drift at the head of the Eddleston valley.

It is also possible that Southern Upland ice and Highland ice, the latter moving in an easterly direction over the Pentland Hills, coalesced either at the head of the Eddleston valley or some distance to the west, and that the larger percentage of volcanic pebbles at Site 6 is inherited directly from the till and englacial debris produced by the coalescence of these two ice masses. It has already been noted in the previous section that deposits at Site 6 were considerably more faulted and contorted than deposits seen at other sites in the area. Considerable turbulence of water flow was postulated.

It has also been noted, in Chapter 8A, that samples from Site 6 contain a relatively high percentage of fines. Average figures for Site 6 samples are:- gravel, 59.26 per cent; sand, 27.53 per cent; fines, 13.21 per cent. Site 7 samples, in contrast, have the following average percentages of material:- gravel, 53.27 per cent; sand, 44.53 per cent; fines, 2.20 per cent. This suggests that a much greater amount of washing has taken place at Site 7, although this is not reflected in any increased degree of sorting (Fig. 8A.6). A contribution of material from more than one till might account for the larger percentage fines content.

The volcanic pebbles in these Eddleston gravels have consistently low long axis lengths and relatively high sphericity but have extremely low average roundness values. Average roundness values are as follows:- sample 6.2, 0.24; sample 6.4, 0.31; sample 6.12, 0.26. The 15 volcanic pebbles found in total in the 5 Site 7 samples have an average roundness value of 0.39. These values are consistently lower than average roundness values for the local rocks.

Such extremely low roundness values suggest a very short distance of travel, but this is obviously not the case with the present pebbles.

The consistently low values might suggest frost-action or a high degree of chipping, followed by a relatively short period of fluvial transport. Frost-action seems unlikely unless these pebbles originated in an outwash veneer from the Highland ice and were subsequently incorporated in the Southern Uplands deposits. A high degree of chipping could arise from the coalescence of two active ice masses, these pebbles being the remnants of relatively large cobbles, smaller particles having been reduced to sand size.

Investigation of the surrounding till and stratified drift, of both gravel-sized and sand-sized particles, would indicate which of these possibilities is the more likely. Thin-sectioning would be required to confirm the origin of these volcanic pebbles more precisely. It is of interest that the average roundness value of 11 volcanic pebbles found at Ladyurd to the south-west (NT 149427) is 0.38. This is again lower than the average greywacke roundness for that site and considerably lower than average volcanic pebble roundnesses for sites in the Midlothian area.

In summary, mechanical analysis statistics indicate a relatively poor degree of sorting within these kame deposits. Sand samples are more markedly poorly sorted than gravel samples. This relatively poor degree of sorting may be partly responsible for the coarse skewness which seems to be characteristic of these deposits. Pebble morphology statistics suggest that samples from the area at the extreme northern end of the Eddleston valley contain notably higher percentages of volcanic pebbles which, in the absence of thin-section data, are assumed to have originated in the Pentland Hills to the west. These pebbles exhibit anomalously low values for roundness. However, pebble morphology statistics do not enable differentiation to be made between deposits on the western flank of the valley and those deposits, assumed to be later in time of deposition, on the eastern side.

CARSTAIRS ESKER DEPOSITS (A) FIELD MORPHOLOGY

As detailed in Chapter 1, controversy has surrounded the origin of these features. The consensus of present opinion, for example Sissons (1961c) and McLellan (1967a and 1969), is that these features are of a subglacial esker-type formation. This interpretation is followed in the present work. The locations of samples taken are recorded in Table 9.10 and shown in Figure 1.4. A number of duplicate gravel samples were taken for pebble morphology study in this instance.

TABLE 9.10

Location of Carstairs esker samples

Site	Approx. Nat. Grid Reference	Sample No.	Mechanical Analysis Sample	Pebble Morphology Sample	Common Sample
1. Disused pit near Carnwath Station	NS 968 469	E2.1	x		
		E2.2	x	x	x
2. White Loch pit	NS 958 469	E2.3	x	x	x
		E2.3(2)		x	x
		E2.4	x	x	x
3. Disused pit	NS 954 468	E2.5	x		
		E2.6	x	x	x
		E2.6(2)		x	x
4. Road excavation	NS 940 466	E2.7	x	x	x
		E2.7(2)		x	x
		E2.8	x	x	x
		E2.8(2)		x	x
5. East end pit	NS 929 461	E2.9	x	x	x
		E2.9(2)		x	x
6. East end pit	NS 935 463	E2.10	x	x	x
7. Carstairs quarry	NS 945 459	E2.11	x		
			11	13	13

As may be inferred from Table 9.10, commercial exploitation has revealed internal structure in a number of exposures throughout these deposits. With the exception of the last site, "Carstairs Quarry", all sites are within the main ridge system (Fig. 1.4). No suitable

exposures were found at the north-eastern end of the deposits, where the ridges reduce in number and complexity of branching.

The first pit visited, a disused pit near the site of Carrwath Station, shows sections of predominantly sand-sized material. Sections of up to 10 metres of well-bedded sands can be seen. These sands are yellowish with occasional reddish layers about 2 centimetres thick, in some cases alternating with yellow sand layers about 6 to 8 centimetres thick. Occasional layers contain small stones. These pebbles are small and well-rounded in general. A few pieces of coal and other carbonaceous pebbles are encountered. Sample E2.2 was taken from one such stony layer.

The ridges increase in size and complexity to the west of this site. The second site seen is near White Loch, a shallow kettle lake among the ridges. The loch itself has been much modified in size and shape by adjacent excavations and by use as a settling pool. Many exposures of up to 15 metres are seen at this site. A large range of material sizes is present throughout the deposits here, ranging from clays to boulders as much as a metre across. A predominance of fine sand is common on most faces. Most exposures show contorted bedding of sands and small gravels. A typical west-facing section at the east end of the pit shows a 15 metre section of extensively-faulted sands and fine gravels. The faults dip at about 30° to the north, and confused bedding has resulted. Vertical faults are also seen in a nearby section.

The ridges at this site approach 20 metres in height above the general ground level. At lower levels, beds containing many carbonaceous

fragments are found. In one section, thin beds of coal and shale fragments are overlain by sandy beds containing gravel layers with little interstitial sand. The general dip of beds is towards the south and east. A confused depositional environment with much ice-contact is indicated.

The third site is a disused pit some 400 metres to the west of the extremity of the White Loch pit. The pit is located at the southern border of the ridge belt, and is sited in a small flat between two eskers. There appears to have been a small ridge here, now almost entirely removed by commercial activity. Small sections, a few metres high, remain.

Coarse reddish sands are noted at the foot of the main sections. This sand is darker in colour and considerably coarser-grained than the yellowish sands predominant in exposures to the east and overlying the coarser sands at this site. Coal-rich beds and lenses are seen and the deposits dip generally to the east. Gravel lenses are found within the top yellow sands.

Site 4 commenced as a road excavation early in 1969. Although road work had been completed when the site was revisited in August 1972, excavation was still in progress, this time in conjunction with sand and gravel extraction.

The original road excavation cuts through a large ridge. The outstanding feature of this site is the large number of large boulders present. The majority of these boulders are rounded, but some are extremely angular. Exceptionally, boulders may measure about two metres in all dimensions, but are more typically about one metre long

axis by half a metre intermediate and short axes. Such large boulders tend to confuse bedding, and this is the case at this site. Such bedding as is visible is usually contorted. This is not surprising when the immense strength of meltwater flow required to carry boulders of this size is considered.

Despite the large numbers of these boulders, and the confused and contorted nature of bedding at this site, numerous layers of small gravels are also found. A relatively restricted range of material sizes is found in these small gravel layers as there is little sand or fines fraction in the matrix. One small, almost circular, mound about 50 metres south of the main ridge seems to be composed almost entirely of these small, closely-packed gravels, although this particular feature has been modified to some extent by the surrounding excavations. It may not be in its original form, although internal bedding has not been disturbed by commercial excavation.

Site 5, the so-called East End pit, is the largest commercial extraction site in the area. Excavations run for about 800 to 900 metres through the ridges from the outskirts of Carstairs to near Newhouse (from NS 935463 to NS 928459). This pit contains the largest sections through these fluvioglacial deposits, reaching heights in excess of 25 metres in places.

One sample, E2.10, was taken from a sandy bed containing gravel near the base of exposed sections near the east end of the pit. Another sample, E2.9, was taken from the west end of the pit, in this instance from a horizontally-bedded gravel lens in laminated sands dipping

at about 20° to the east. The sample was taken within 2 metres of the top of the section and the top of the main ridge at that point.

As with the previous site, bedding is confused in many sections by the presence of numbers of large boulders. However, large sand sections are also present within this site, and about 12 metres of well-bedded sands underlie a 2 metre ridge of sand and gravel in one section. Although faulting is not as common as in some other sites in the suite of deposits, ice-contact deformation is evident in many places.

The last site visited, Carstairs Quarry, lies about one kilometre to the south of the main ridge system. The deposits here consist virtually entirely of well-bedded fine sands. Bedding is mainly horizontal or dipping at low angles with no dominant direction of dip. Very little gravel is seen, only occasional small lenses or isolated pebbles. No beds of gravel are noticeable in exposed thicknesses of over 10 metres of yellow sands.

CARSTAIRS ESKER DEPOSITS (B) SAMPLE STATISTICS

The various cumulative curve sample statistics for the Carstairs esker deposits are set out in Table 9.11 and summarized in Tables 9.2, 9.3 and 9.4.

It can be seen that, apart from sample E2.10, most sets of values follow the corresponding total distributions fairly closely. All gravel samples are very poorly sorted, with a high average inclusive graphic standard deviation value of 2.75ϕ units.

TABLE 9.11

Cumulative curve statistics for Carstairs esker samples

Sample No.	Percentage Gravel	G. Mean (β)	I. G. S. D. (β units)	I. G. Skewness	G. Kurtosis
E2.1	0.03 S	+1.97	0.69/moderately sorted	+0.13/fine	1.16/leptokurtic
E2.2	30.28 S	-0.10	2.38/v. poorly sorted	-0.48/strong coarse	0.83/platykurtic
E2.3	70.61 G	-2.47	3.27/v. poorly sorted	+0.28/fine	0.80/platykurtic
E2.4	24.05 S	-0.63	2.62/v. poorly sorted	-0.53/strong coarse	0.98/mesokurtic
E2.5	0.29 S	+1.80	1.00/moderately sorted	+0.08/near-symmetrical	1.06/mesokurtic
E2.6	71.28 G	-2.73	2.88/v. poorly sorted	+0.34/strong fine	0.78/platykurtic
E2.7	56.27 G	-1.72	2.94/v. poorly sorted	+0.16/fine	0.56/v. platykurtic
E2.8	79.78 G	-2.62	2.15/v. poorly sorted	+0.39/strong fine	1.19/leptokurtic
E2.9	71.80 G	-2.52	2.51/v. poorly sorted	+0.37/strong fine	0.82/platykurtic
E2.10	39.70 S	-1.28	4.89/e. poorly sorted	-0.71/strong coarse	0.74/platykurtic
E2.11	0.04 S	+3.18	0.42/well sorted	-0.03/near-symmetrical	1.04/mesokurtic

NOTE: Verbal classes after Folk and Ward (1957)

Sand samples vary in degree of sorting from well sorted to extremely poorly sorted. Sample E2.10 was noted in Chapter 6 as occupying an anomalous position on any of the graphs involving inclusive graphic standard deviation. The sample consisted of sands of various grades plus one large (20 centimetres by 12 centimetres by 8 centimetres) greywacke cobble. This cobble contributed 23.0 per cent by weight of the total sample, while all other gravels totalled only 16.7 per cent by weight. The inclusive graphic standard deviation of 4.89 ϕ units is the highest encountered in all samples taken, and gives the only extremely poorly sorted sample. A very high strong coarse skewness of -0.71 results, but kurtosis, at 0.74, is not extreme.

Skewness and kurtosis distributions are normal, and the only characteristic brought out by the cumulative curve statistics is the generally high lack of sorting.

Pebble morphology statistics again show a high lack of sorting, this time with reference to the long axis mean versus standard deviation plot of Figure 7.2d. These samples exhibit the highest rate of increase of standard deviation with unit long axis mean increase of all sample suites tested. There is, however, no order indicating possible sedimentation characteristics, nor is there any relation with percentage gravel in sample, despite field observation of the presence of much larger boulders at the western end of the deposits, and of the preponderance of sand at the eastern sites. Shape statistics reveal a fairly normal average distribution of 34 spherical particles, 36 discs, 19 rods and 11 blades.

Rock type analysis of the Carstairs esker deposits reveals a fairly consistent picture (Table 9.12). The local material, of

TABLE 9.12

Rock type analysis of Carstairs samples

Sample No.	O.R.S. Volcanics	O.R.S. Sedi- mentaries	(Total O.R.S.)	Carbonif- erous	S. Upland greywackes etc	Highland	Quartz & Quartzite	Others/ unidentified
E2.2	33	13	(46)	18	17	2	15	2
E2.3	30	19	(49)	23	19	1	6	2
E2.3(2)	25	28	(53)	28	13	0	4	2
E2.4	29	16	(45)	20	21	1	8	5
E2.6	30	15	(45)	24	19	0	9	3
E2.6(2)	33	24	(57)	23	12	0	4	4
E2.7	45	17	(62)	15	15	4	2	2
E2.7(2)	24	24	(48)	35	8	0	5	4
E2.8	34	18	(52)	21	14	1	9	3
E2.8(2)	29	20	(49)	32	6	0	7	6
E2.9	42	8	(50)	13	12	3	15	7
E2.9(2)	42	16	(58)	15	12	0	8	7
E2.10	29	11	(40)	13	31	5	10	1

Carboniferous age, forms a relatively low proportion of each sample. An average of 50 per cent of all pebbles are from the Devonian volcanic and sedimentary rocks to west and south, while a small but significant proportion of Southern Upland rocks of Ordovician and Silurian ages is present throughout. Pebbles of Highland origin are found, but are few in number.

A significant proportion of quartz and quartzite pebbles are found throughout these deposits. These are difficult to assign to any one group. There are a number of small quartz-porphyry intrusions in the area. These are of Lower Old Red Sandstone age. The difficulty of identifying pebbles with a relatively low order of magnification, and without recourse to thin sectioning, is apparent here. It is most likely, however, that the majority of these quartz and quartzite pebbles can be associated with the Devonian group in Table 9.12. The possibility of the occurrence of quartz pebbles of Highland origin cannot be ruled out, but this would not affect the overall provenance picture to any marked degree.

The distribution of rock types shown in Table 9.12 indicates clearly and consistently that ice and water movement from south or south-west was responsible for providing the material for the fluvio-glacial suite of deposits. This agrees tolerably well with figures given by McLellan (1969) for White Loch pit and East End pit.

With regard to long axis lengths of individual rock types, sufficient numbers of volcanic, sandstone and greywacke pebbles are present for statistical analyses of pebble morphology data to be meaningful. While all three sets of mean long axis lengths are

highly correlated with the corresponding standard deviations, none of the sets of mean long axis values show any trend over the length of the esker system.

Sphericities and roundnesses of individual lithologies show no consistent or significant trends. Mean versus standard deviation correlations are inconsistent for both sphericity and roundness values. Correlations between the mean values of long axis, roundness and sphericity are also inconsistent, both within the three rock types studied and with theoretical considerations.

In summary, the general conclusion reached earlier in the thesis that only the simplest measures are significant in determining trends within, or fundamental differences between, suites is reinforced by the Carstairs sample statistics. Simple inclusive graphic standard deviation and long axis mean versus standard deviation calculations indicate poor degrees of sorting both within entire sand and gravel samples and within pebble samples. Direct feedback to position of any sample within the overall succession of deposits is impossible to measure owing to the considerable statistical noise caused basically by the confused environment of deposition. While the Carstairs features were undoubtedly englacially or subglacially formed, and undoubtedly are fluvioglacial in origin, the substantial numbers of very large boulders present disrupt normal bedding patterns and make morphological interpretation more difficult.

THE BEDSHIEL ESKER (A) FIELD MORPHOLOGY

The Bedshiel esker situation has already been described comprehensively in Chapters 4 and 5. The fluvioglacial landforms of the area are described in the text of Chapter 5, and Figure 5.5 shows the general field situation. In short, the esker was deposited by eastward-flowing meltwaters. It lies between the National Grid points NT 677504 and NT 711512. Figure 5.7 shows the positions of all sample sites along the length of the esker. Two sets of samples were taken during the course of the study of this feature. The first samples taken were normal field samples, whereas the second group involved the selection of material for pebble morphology study only.

Internal bedding is not visible as there are no commercial excavations at the site. Pebble orientation study reveals a strong dip imbrication in a westerly direction, indicating the direction of origin of meltwaters. Sand beds dipping roughly horizontally were seen in some very small sections near the base of smaller parts of the esker. Stevenson noted that stratification was "... very irregular and frequently inclined at various angles" (Stevenson, 1864, p.124), though he does not give an exact location for any sections.

The first run of samples, E1.1 to E1.11, were taken from small exposures on the sides of the esker where slumping had provided natural cuttings. Samples were taken only after digging into the esker for about one metre in order to avoid sampling ablation moraine. Samples E1.1 and E1.2 were combined, and both cumulative curve and

pebble morphology statistics were calculated for the resulting 10 samples.

Samples E1.12 to E1.21 were taken at intervals along the crest of the ridge at a depth of about one metre. Full samples were not taken as material was sieved at site to provide pebbles for pebble morphology study. Again, internal bedding was not revealed although the presence of large numbers of cobbles in the topmost half metre of deposits was noted.

THE BEDSHIEL ESKER (B) SAMPLE STATISTICS

Full analysis of the cumulative curve statistics is obviously impossible in this case as bedding conditions throughout the esker remain largely unknown. However, conclusions of a general nature may be inferred from the sample statistics tabulated hereafter (Table 9.13). Reference may again be made to Tables 9.2, 9.3 and 9.4.

All samples taken were classed as gravel samples and the distributions of sorting and skewness values follow the overall distributions. A high average inclusive graphic standard deviation of 2.94 ϕ units is obtained. Two samples with low percentages of gravel, E1.2 and E1.4, are coarse-skewed. The remaining samples, all but one of which contain over 75 per cent gravel, are either strongly fine-skewed or fine-skewed.

TABLE 2.13

Cumulative curve statistics for Bedshiel esker samples

Sample No.	Percentage Gravel	G _c Mean (β)	I. G. S. D. (β units)	I. G. Skewness	G. Kurtosis
E1.1	60.07 G	-2.12	3.18/v. poorly sorted	+0.26/fine	0.61/v. platykurtic
E1.2	45.62 G	-0.88	3.30/v. poorly sorted	-0.22/coarse	0.70/platykurtic
E1.5	78.21 G	-2.33	3.19/v. poorly sorted	+0.55/strong fine	0.61/v. platykurtic
E1.6	87.25 G	-3.65	1.49/poorly sorted	+0.11/fine	1.46/leptokurtic
E1.7	77.05 G	-3.17	3.54/v. poorly sorted	+0.46/strong fine	1.06/mesokurtic
E1.8	81.72 G	-3.97	1.41/poorly sorted	+0.52/strong fine	1.24/leptokurtic
E1.9	77.95 G	-3.43	3.01/v. poorly sorted	+0.13/fine	0.93/mesokurtic
E1.10	79.91 G	-3.85	3.34/v. poorly sorted	+0.34/strong fine	1.04/mesokurtic
E1.11	78.30 G	-3.10	2.96/v. poorly sorted	+0.23/fine	1.10/mesokurtic
E1.4	47.60 G	-0.85	3.71/v. poorly sorted	-0.11/coarse	0.59/v. platykurtic
E1.3	75.50 G	-1.73	3.15/v. poorly sorted	+0.36/strong fine	1.11/leptokurtic

NOTE: Verbal classes after Folk and Ward (1957)

The distribution of Bedshiel kurtosis values is slightly irregular compared with the overall distribution (Table 9.4). Although there are three very platykurtic samples, there is only one platykurtic sample. Only one of the very platykurtic samples, E1.4, is associated with a very high sorting value (3.71 ϕ units). No obvious relationship with percentage gravel exists.

Although this is a linear feature and is therefore associated with one constant direction of meltwater flow, no appropriate trends are visible from the cumulative curve sample statistics. This may be due in some part to the method of sampling, as has been suggested in Chapter 5 in connection with trends in pebble morphology statistics.

Both sets of pebble morphology statistics have been analysed in depth in Chapter 5, and a summary of the main conclusions follows. The second set of samples yielded 50 sandstone and 50 greywacke pebbles at each site. As this is a non-representative sample as far as average pebble numbers are concerned, statistics were calculated for the two lithologies separately and not for combined samples of 100 pebbles as in the first group of samples.

The long axis mean versus standard deviation plot of the first set of samples shows a fairly rapid rise in standard deviation per unit increase in long axis mean (Fig. 7.2c). The gradient is second only to the corresponding Carstairs esker plot. There is, however, no order of either mean or standard deviation relative to position along the esker.

With regard to individual rock types, Table 5.3 and Figure 5.4 indicate that the percentage of greywacke pebbles in the represent-

ative pebble samples rises more or less continuously from west to east along the esker. The percentage of sandstones drops in the same direction. This implies a west-to-east formation for the esker as the softer sandstones would be more quickly worn by transport to below the minimum size for selection.

Graphs of sphericity and roundness against distance were drawn (Figs. 5.2 and 5.3). No consistent pattern emerged and it was assumed that this was due in large part to the method of sampling. A more rigorous sampling scheme, whereby only the last depositional phases at each point along the esker were sampled, was adopted and a clearer picture emerged (Figs. 5.10 and 5.11).

As recorded in Chapter 7, comparisons of mean versus standard deviation of roundness and sphericity for the two groups of greywacke and sandstone samples yielded very inconsistent correlation coefficients (see Tables 7.4 and 7.5). These correlation coefficients were not only inconsistent between the two groups of samples but were inconsistent with theoretical considerations.

In summary, it can be seen that, as with the Carstairs esker samples, a high lack of sorting is indicated both within the entire field samples and within the selected pebble samples. As before, only relatively simple cumulative curve or pebble morphology statistics seem to be significant.

EDZELL OUTWASH DEPOSITS (A) FIELD MORPHOLOGY

Samples were taken from the upper part of the North Esk-West Water outwash sheet. A number of suitable exposures were found in

the first few kilometres of deposits beyond the gorge of the River North Esk. The location of these are set down in Table 9.14 and are shown in Figure 1.5.

TABLE 9.14

Location of Edzell outwash samples

Site	Approx. Nat. Grid Reference	Sample No.	Mechanical Analysis Sample	Pebble Morphology Sample	Common Sample
Disused pit in gorge of R. North Esk	NO 589 731 "	01.1 01.2		} ^x	
Disused pit	NO 603 713 "	01.3 01.4	x	x	x
Disused pit	NO 609 704 "	01.7 01.7(2)	x	x x	x x
Terrace edge	NO 608 696 "	01.8 01.8(2)	x	x x	x x
Terrace edge	NO 617 686	01.9	x	x	x
Terrace edge	NO 624 679	01.10	x	x	x
Capo pit	NO 628 672 " "	01.5 01.5(2) 01.6	x x	x x x	x x x
	NO 629 667	01.11	x	x	x
			8	11	11

As can be seen from Table 9.14, a number of the samples were taken from the scarp faces of terrace edges. The outwash has in fact

been extensively terraced by meltwater rivers. All samples were, as far as could be judged, taken a short distance down from the main present-day terrace surface in order to ensure some degree of comparability. The lower parts of the outwash sheet, extending past the site of Marykirk, were not sampled in order to concentrate on the, theoretically, more rapid changes in pebble morphology and sample profile near the apex of the outwash fan.

Samples O1.1 and O1.2 were taken from a disused pit in the gorge of the North Esk. No attempt was made at obtaining a representative sample of material at this site as coarse gravels predominate. Many cobbles up to 40 centimetres across are present at this site. A sample was taken from the smaller gravels present. Pebble morphology statistics calculated for this site were not included in any calculations as the material is not strictly part of the outwash deposits. It was found, however, that sample values from this site fitted closely such trends as were recognised within the main outwash deposit values.

The second site is also a disused gravel pit, this time a relatively short distance beyond the mouth of the North Esk gorge. O1.3 was a sample of scree gravels, and was not analysed. O1.4 was taken from material in situ; smaller gravels in a matrix of fine reddish-yellow sand. The matrix resembled clay but was too well-drained to be other than fine sand. Boulders up to one metre across are common.

Samples O1.7, O1.8, O1.9 and O1.10 were all taken from terrace edges at between one and two metres below the upper terrace surface.

01.7 was in a small excavation. The site of sample 01.8 shows no stratification, and may well be slumped material. The pebbles of sample 01.9 were set in a noticeably sandy matrix. The pebbles at this site are mostly schists and gneisses, but one large Old Red sandstone boulder measuring approximately 1 metre by 30 centimetres by 30 centimetres was seen nearby.

The remaining samples were taken from Capo gravel pit, the only active commercial excavation in the area. The pit is relatively shallow, no faces being more than 5 metres deep. Cobbles up to 30 centimetres long axis length can be seen, but there are noticeably few large stones compared with exposures nearer the apex of the outwash. Stratification of the gravels is pronounced. Dips are very small and horizontal overall, there being no preferred direction of dip. Samples 01.5 and 01.6 were taken from the northern end of the pit, at about 2 metres below the main terrace surface. Sample 01.11, at the southern end of the pit, was taken at approximately 4 metres below this surface.

At least some of these samples must contain material derived from the West Water glen as well as that derived from the North Esk glen. It is assumed that this will not distort any trends within measured values as the two sources must have supplied material of similar lithology and degree of wear. Also, sample sites likely to have received material from both sources, from about the site of 01.8 southwards, are roughly equidistant from the mouths of both glens. Distances of travel of material within the two separate outwash fans can therefore be assumed to be equal. No obvious demarcation line between the two separate fans can be seen, and

disturbed bedding conditions indicating a turbulent meeting of meltwaters were not seen in any field sections.

EDZELL OUTWASH DEPOSITS (B) SAMPLE STATISTICS

Table 9.15 shows the cumulative curve statistics for these outwash samples. These are summarized in Tables 9.2, 9.3 and 9.4.

As with the Bedshiel samples, all Edzell samples are classed as gravels. All are very poorly sorted on the Folk and Ward (1957) scale. The skewness and kurtosis distributions are normal in terms of the overall totals of gravel samples. Degree of sorting is remarkably constant at around an average inclusive graphic standard deviation value of 2.67 ϕ units. Trends are not distinguishable over any of these statistics, including percentage gravel and graphic mean.

However, pebble morphology statistics do show trends which would be expected from field observation. In this instance, a marked decrease in mean long axis length takes place away from the apex of the outwash near the mouth of the North Esk gorge (Fig. 9.1). This decrease in mean long axis length continues, but at a lower rate, in the lower parts of the outwash deposits (J. Maizels, personal communication).

The long axis mean versus standard deviation plot shows a relatively low gradient (Fig. 7.2e). This indicates a more constant degree of sorting than was found in, for example, the esker sample suites. There is a relationship between mean long axis length and position on the feature, as shown by Figure 9.1, but this is not as

TABLE 9.15

Cumulative curve statistics for Edzell outwash samples

Sample No.	Percentage Gravel	G. Mean (ϕ)	I. G. S. D. (ϕ units)	I. G. Skewness	G. Kurtosis
01.4	70.84 G	-2.50	2.36/v. poorly sorted	-0.06/near-symmetrical	0.86/platykurtic
01.7	80.07 G	-3.84	2.63/v. poorly sorted	+0.42/strong fine	0.99/mesokurtic
01.8	79.48 G	-3.10	2.76/v. poorly sorted	+0.62/strong fine	1.30/leptokurtic
01.9	57.29 G	-1.71	3.51/v. poorly sorted	+0.24/fine	0.78/platykurtic
01.10	74.51 G	-3.09	2.60/v. poorly sorted	+0.38/strong fine	0.79/platykurtic
01.5	63.55 G	-2.29	2.46/v. poorly sorted	+0.16/fine	0.75/platykurtic
01.6	62.11 G	-2.46	2.62/v. poorly sorted	+0.20/fine	0.70/platykurtic
01.11	52.89 G	-1.32	2.45/v. poorly sorted	-0.03/near-symmetrical	0.64/v. platykurtic

NOTE: Verbal classes after Folk and Ward (1957)

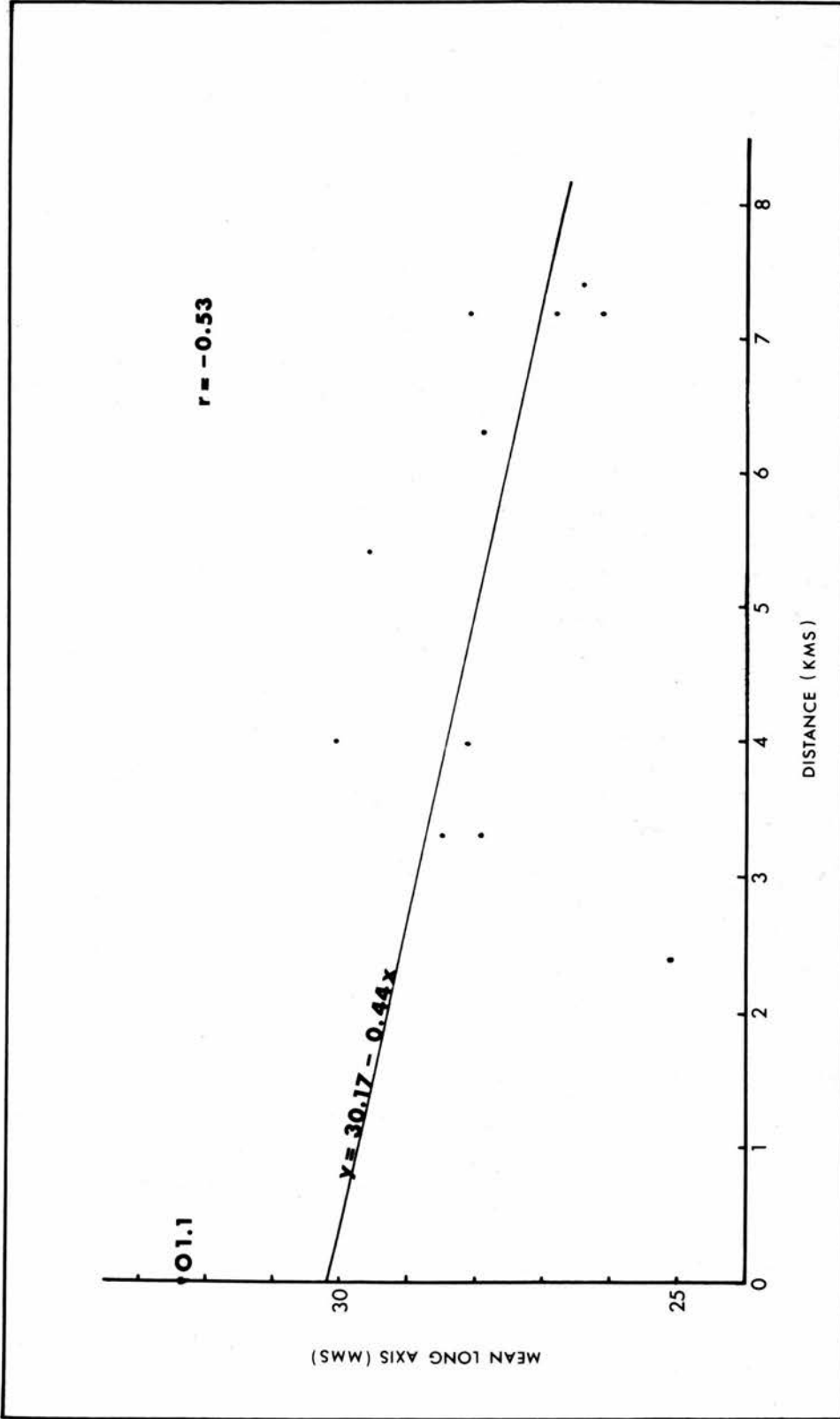


FIGURE 9.1. Mean long axis length of pebble samples versus distance from Site One, North Esk outwash

clear on the long axis mean versus standard deviation regression line. All points lie relatively close to this line (Fig. 7.2e). The reason for this lies with the type of feature.

A constant direction of meltwater flow coupled with a constant source area of constituent materials means that natural fluvial sorting processes can act more normally than in the ice-contact situation. A smaller mean long axis length will invariably be accompanied by a smaller standard deviation in the fluvial situation, but the ~~within~~-sample variations in size will not be as great as in the more confused depositional environment of the esker or the kame. A lower long axis mean versus standard deviation gradient must result in the truly fluvial environment. The Edzell outwash sample gradient is less than all other suite gradients except that of the Midlothian samples. However, the Midlothian samples were mainly classed as outwash, if of a less "classical" type than the Edzell deposits. Lower standard deviations would be expected in the Midlothian situation owing to greater distances of travel of constituent material and the presence of less resistant material.

Despite the obvious sensitivity of long axis length to distance of transport, and despite the progressively better degree of sorting downstream, shape statistics show no trends. Percentages in fact remain remarkably consistent around average values of 27 spheres, 40 discs, 19 rods and 14 blades.

Sphericity and roundness values for entire samples also show no trends. Whole samples were used in this instance as almost all pebbles were either schist or gneiss. Small numbers of Old Red

sandstone pebbles were found. These were not present in significant numbers at any site, averaging about 4 per cent. The variety of metamorphic pebbles present was large, but these were difficult to class satisfactorily in hand specimen.

In summary, the pebble morphology statistics indicate, by the notable reduction of long axis length downstream, the nearness to source of these deposits and the relatively rapid size changes that take place near the apex of an outwash fan. Changes in shape proportions are not found in the pebble grades and, contrary to expectation, initially rapid sphericity and roundness changes are not found. It seems clear that the initial rapid sphericity and roundness change phase will not be measurable in the fluvio-glacial environment owing to the modifying action of englacial transport.

A relatively constant degree of sorting is shown by cumulative curve statistics, reflected to some extent in the pebble long axis mean versus standard deviation plot.

CHAPTER 10. CONCLUSION

The objective of the thesis, as stated in Chapter 1, is to attempt to differentiate between environments of deposition within different types of fluvioglacial deposits. Secondary to this main theme is the evaluation of the quantitative techniques used, evaluation in terms of the usefulness of the information yielded concerning variations in the fluvioglacial depositional environment. The conclusion reached throughout most of the work is that only relatively simple measures show any significance. It is suggested that this is due to the nature of the depositional environment rather than being due to shortcomings in the techniques themselves.

It seems unlikely that the answer lies with incorrect techniques. The techniques used, as described in Chapters 3 and 4, have been well-tested in fluvial, marine and aeolian situations. As far as cumulative curve statistics are concerned, most published work has been concerned with sizes of material below gravel size. In the present study, the gravel-sized fractions have been concentrated upon, with rather less attention being given to the sand and fines fractions. Table 9.2 shows that of the 48 gravel samples, 7 are classed as being poorly sorted and 41 very poorly sorted according to Folk and Ward's verbal sorting scale (Folk and Ward, 1957). On the other hand, the spread of the 22 inclusive graphic standard deviation values of sand samples covers the range of verbal sorting classes from well sorted to extremely poorly sorted. These facts suggest that the sorting scale is satisfactory for sand samples, but relatively unsatisfactory for

gravel samples. Thus, as far as sorting is concerned, the technique and accepted verbal scale used do not differentiate between gravel samples to any great extent. Some division of the poorly and very poorly sorted classes might aid further study of relative degrees of sorting within fluvioglacial gravels.

Sorting depends on a number of factors. It is strongly dependent on mean size, as is shown by Figures 6.1a and 6.1b. Therefore the sizes of materials supplied to the environment are of prime importance in determining sorting conditions within that environment. In the case of fluvioglacial deposition, material supplied is usually only a relatively short distance from source. It has usually been transported englacially. Tills are notable for their extreme lack of sorting. It can therefore be assumed that material present at the commencement of the fluvioglacial deposition phase of deglaciation is generally in a relatively unsorted state.

Sorting is also dependent on the state of the current transporting the material. Currents of relatively constant strength will eventually lead to a high degree of sorting. This is true of both relatively low and relatively high current strengths, though not of very weak or very strong currents. Currents which fluctuate rapidly do not give rise to high degrees of sorting. Rapidly fluctuating currents are typical of most types of fluvioglacial conditions. Seasonality is a very relevant factor, but even within seasons a wide range of current strengths may be experienced in a relatively short time due to changing conditions within the decaying ice mass. The sudden collapse of ice tunnel walls or the release of ice-dammed

waters are two common examples. Sudden fluctuations of current strength are relevant even in the proglacial fluvial environment, though the effects are progressively damped with increasing distance from the apex of the outwash fan.

The type of deposition is also relevant with reference to sorting. The so-called "bean-spreading" type of deposition, in which currents work over thin sheets of grains continuously will lead to a relatively high degree of sorting, as in longshore drift for example. More typical of the fluvioglacial environment is the "city-dump" type of deposition in which sediments are dumped and then rapidly buried by more sediments.

From consideration of factors such as these, it can be seen that in general a relatively low degree of sorting will prevail in the fluvioglacial environment. This is borne out by the distribution of verbal sorting values of the gravel samples already mentioned.

However, it has been stated in the present work that differences in degree of sorting exist between the various sample suites. The proportion of these apparent differences due to fundamental differences in depositional environment, and the proportion due to local factors such as lithology, distance of travel of constituent particles and local ice conditions, must be considered. These differences in degree of sorting suggested by present results cannot be proved to be statistically significant according to the usual levels of significance, partly due to the relatively restricted numbers of samples.

The question of operator variance has been resolved as far as possible, and sample values can be considered to be relatively error-

free. A much more significant factor, related fundamentally to the environment of deposition, is the relatively large within-site variability encountered. It has been demonstrated, in Chapter 8A, that within-site variability effectively masks between-site variance over short distances within fluvioglacial deposits. This suggests that random variations could in fact give rise to the between-site differences in degree of sorting tentatively observed in Chapters 6 and 7.

The main conclusion reached in Chapter 6 was that esker samples show a relatively poor degree of sorting compared with kame and outwash samples. Table 6.4 shows that both Bedshiel and Carstairs samples exhibit relatively high average inclusive graphic standard deviations despite having intermediate average gravel percentages and intermediate average mean values. The Eddleston kame gravel samples are, on average, better sorted than gravel samples from the other suites, yet Table 9.2 shows that Eddleston sand samples are on the whole more poorly sorted than the Midlothian or Carstairs sand samples. This suggests that sand samples and gravel samples from the same suite of deposits, or even from the same site, are in no sense comparable. The Eddleston sand samples are in fact more coarse-skewed on average than either of the other groups of sand samples. That is, percentages of gravel in the Eddleston sand samples are higher than in the Midlothian or Carstairs sand samples. This indicates a more uniform deposit, with less variance compared with other suites.

It is perhaps surprising to find that, with the present samples, kame gravels are better sorted than outwash gravels according to

cumulative curve statistics. As can be seen from Table 6.4, however, the differences in average inclusive graphic standard deviation values are not great. It is possible that differences of this order are caused either by random fluctuations or by differences in the sizes of material supplied to the fluvioglacial process. Rock type must therefore be a factor as different rock types will reduce at different rates during transport. However, both the Eddleston and Bedshiel gravels are largely composed of very local rocks, and the Bedshiel gravel samples have the poorest average sorting value. The relatively far-travelled Carstairs material shows an intermediate average sorting value. Numbers of samples are not large enough to eliminate lithology as a factor in sorting, nor would it be correct to do so. But Midlothian and Carstairs samples are roughly similar in lithologic proportions, as suggested by pebble morphology statistics, yet average cumulative curve statistics suggest that these are not similar in gravel sample profile (Table 6.4).

Table 6.4 suggests that percentage gravel may have a strong effect on cumulative curve statistics. Percentage gravel is a major factor in determining graphic mean, and graphic mean is closely related to all three other cumulative curve statistics (see Figs. 6.1b, 6.2b and 6.3b). This is partly brought out by the average figures shown in Table 6.4. It seems clear, as far as cumulative curve statistics of gravel samples are concerned, that differences between these different fluvioglacial environments are relatively small and may be inherited directly from the source material. Differences in average sorting values are noted and are explicable in terms of modes of deposition.

Differences in degrees of sorting, this time within the selected pebble samples, are also brought out in Chapter 7. Figures 7.2a to 7.2e, showing long axis mean versus standard deviation of the various suite samples, suggest a better sorting for these particular gravel grades within the Midlothian and Edzell samples. The Eddleston kame samples are intermediate in this instance, while the Bedshiel and Carstairs esker samples again show the worst degrees of sorting. Although considerations in Chapter 8 suggest that pebble morphology statistics do not on the whole reflect cumulative curve statistics, the generally poor degrees of sorting within esker samples are notable.

The Carstairs deposits in particular contain large numbers of boulders at their western end. Both sands and gravels at the eastern end of the suite also show notably poor sorting, despite the marked preponderance of bedded sands. A layer of large stones just below the crest of the Bedshiel esker was ascribed to an ablation moraine, but in the absence of sections revealing internal bedding conditions it can not be assumed that these boulders do not reflect poor degrees of sorting within the esker.

No very large boulders were seen in the Midlothian deposits, nor in general in the Eddleston deposits. Small boulders were common in the Edzell outwash deposits near the apex of the outwash, but were not seen in any great numbers at Capo pit some 7 kilometres from the gorge of the North Esk river.

Volume of meltwater is of course a limiting factor in determining the maximum size of particle that can be carried by a glacial stream. Force, or volume per unit area, would reflect the maximum particle

size to a great extent. In the present case, large amounts of material have been deposited in all suites. The total amount of material is almost impossible to estimate owing to insufficient numbers of sections to base of deposits, but the Bedshiel esker probably contains less material than other deposits owing to its isolated occurrence. The larger proportion of boulders found in the Bedshiel and Carstairs deposits can therefore be related to strength of meltwater flow. It is not unreasonable to assume that waters flowing in englacial or subglacial tunnels will generally be under considerable hydrostatic pressure and will thus have greater strength of flow than waters of similar volume in an ice-marginal or proglacial situation. Under these conditions of stronger, and invariably more turbulent, flow, deposition is almost certain to be more chaotic. A poorer degree of sorting is bound to result, and this is supported, though tentatively, by the present results.

Long axis mean versus standard deviation plots of individual rock types repeat the whole-sample conclusions to a great extent (see Figs. 7.3, 7.4 and 7.5). Although all sandstone regression lines have similar gradients (Fig. 7.3), greywacke and volcanic pebble regression lines show higher gradients for esker samples (Figs. 7.4 and 7.5). The even sandstone pebble regression lines merely reflect the lower resistance to wear of sandstone pebbles compared with greywacke and volcanic pebbles. The steep gradients of these sandstone lines emphasize this.

Studies of shape, roundness and sphericity reveal little in terms of either short-range changes or differences between suites.

This is amply illustrated by Tables 7.4 and 7.5, which show correlations between mean and standard deviation of single rock type roundnesses and sphericities. The correlation coefficients are remarkable only for their extreme inconsistency.

The unreliability of sphericity and roundness values in recording short-range change has also been demonstrated in Chapter 5, with reference to the Bedshiel esker. Trends over the length of the esker are weak and for the most part inconsistent. Much longer features, or suites of features, would be more likely to produce reliable trends. Rapid changes, such as might be expected in the Edzell outwash deposits, are not found. This implies that even relatively short distances of glacial and fluvio-glacial transport modify constituent pebbles to shapes beyond the initial, theoretical, rapid modification phase.

Both the Edzell outwash and Bedshiel esker features are single-direction, isolated features and both contain a majority of material which has travelled short distances before incorporation in the fluvio-glacial landform. The Edzell outwash pebble samples show a relatively strong decrease in mean long axis length away from the apex of the outwash fan (Fig. 9.1), whereas no such trend is noticeable within the Bedshiel esker pebble samples. Even the individual rock type samples show no trend. Proximity to source is probably not a factor in this, as material has been derived in both cases from short distances upstream. Distance of transport within the feature itself is also not of importance. The Bedshiel esker is approximately 4 kilometres long compared with the 5 kilometre distance between Samples

01.4 and 01.11 on the Edzell outwash. The answer obviously lies with the different environment, subglacial esker compared with proglacial outwash.

Regarding the low significance of pebble morphology results in general, the fault does not lie with the method of selection of pebbles, as this was extremely rigorous. It is more likely that the fault lies with the selection of samples, for a number of reasons.

In the first instance, there may not be enough samples, due in part to a lack of good exposures throughout most of the deposits considered. Secondly, samples taken at any one site are difficult to interpret in respect of either distance of travel or time. They are difficult to interpret in respect of distance as samples taken from any one face are in vertical, rather than horizontal, sequence. They are also difficult to interpret in respect of time owing to the uncertainty of sequence of deposition within a vertical face. The beds, or sedimentation units, are often contorted, and are rarely horizontal in any case, so the vertical sequence may not be relevant. Successively higher beds are usually, but not necessarily, sequential. For example, bed 1 may be laid in one depositing season, then bed 2 may be laid elsewhere in the deposit during the next depositing phase. Bed 3 may subsequently be deposited on top of bed 1 during the next season. The time relation between successive beds is controlled by conditions both within the ice at site and upstream in relation to channels opening and closing within rotting ice. While it would not be correct to imply randomness, the complex of within-ice conditions is such as to effectively prevent simple time-successive assumptions

being made regarding deposits at any individual exposure. However, there is a certain amount of deposition in time sequence within outwash deposits, and to a lesser extent within esker deposits owing to the persistence of deposition along one particular drainage line.

There is also the difficulty of interpreting time-distance relations between samples from different exposures. Although similar sedimentation units are used as far as possible, there is no guarantee that these represent related deposits. To attempt to relate these would imply either similarity of deposition or contemporaneity of deposition. Outwardly similar gravel deposits could well be near the top of sequence at pit A, hence representing later phases of deposition, and be near the bottom of sequence at nearby pit B. This deposit would then represent an early phase of deposition at site B, but could still be contemporaneous with the similar deposit at A. It could be topographically higher or lower than the deposit at A; it could have been deposited via a completely unrelated ice stream; or even in extreme circumstances could belong to a different depositional environment. It could, for example, be part of a buried esker, as against kame deposition at A, or even buried outwash as against kame deposition. This latter point implies that the two deposits could feasibly belong to different phases of one deglaciation.

Such deposits are not likely to be products of phases of different deglaciations in the areas under consideration, at least within suites of deposits, though possibly between suites, as, for example, the Midlothian and Edzell suites of deposits.

It can be seen from preceding discussion that only relatively simple cumulative curve and pebble morphology measures are necessary to investigate short-range differences in environment of deposition within the fluvioglacial context. The more complex measures such as sphericity, roundness and skewness and kurtosis of the cumulative curve add little to an understanding of differences in environment of fluvioglacial deposition. These measures would undoubtedly be more important where much larger features, or more intensive sampling schemes, were being considered.

Chapter 8 demonstrates clearly that short-range variation, at least within the Eddleston kame deposits, is difficult to determine. Within-site variability clearly masks any significant between-site variation.

It has also been demonstrated in Chapter 8 that direct comparison between the cumulative curve statistics of a sample and its pebble morphology statistics is of limited value. The 100 selected pebbles are as representative as possible of the selected gravel grades, but do not in general reflect cumulative curve statistics, even where samples contain a high percentage of gravel.

The only relationship that seems to offer reasonable ground for direct comparison is mean versus standard deviation. A simple visual comparison of the positions of common samples relative to the mean versus standard deviation trend lines of Figures 6.1a and 7.1 reveals that most points occupy roughly similar positions relative to both these trend lines. The significance of this is not clear, other than as a simple statement that degrees of sorting for size are

roughly similar within both the whole field sample and the laboratory-selected gravel sample. In general, however, the position of individual samples relative to either trend line does not seem to give any information likely to be of use in differentiating fluvio-glacial environments.

Direct application of sample statistics to field morphology underlines the fact that only the simplest statistics enable more definite short-range trends to be recognised than are evident from a visual study and description of site conditions throughout any individual suite. Feedback from laboratory results to position of sample within suite, to variation within sites and to variation between suites is small. On the whole, a section through any of the landforms considered does not appear to vary greatly from the confused bedding situation typical of fluvioglacial deposits. Faulting is common. Beds dip at apparently random angles in all cases except proglacial deposition. Even in the proglacial environment rafted blocks of ice frequently give rise to post-depositional slump. Differences between the various suites of features studied are difficult to discern. Topographic differences obviously exist, but the comparisons of field morphology with sample statistics set out in Chapter 9 are largely negative in the nature of their conclusion.

In summary, it seems that, apart from measures of sorting, differences in environments of fluvioglacial deposition are difficult to measure quantitatively. Only relatively simple measures are of use in investigation of either differences between types of deposition or short-range trends within suites of deposits. Field samples taken

from "average" sedimentation units may be analysed to give inclusive graphic standard deviation values as an indicator of degree of sorting. Though most fluvioglacial gravel samples give values of the same order, esker deposits are more poorly sorted than either kame or outwash material. The addition of skewness and kurtosis measures add little to the sorting values within relatively restricted depositional suites, but may be of more value in continuous suites of deposits of larger dimensions than those considered in the present study.

Simple measures of long axis length mean and standard deviation of pebbles selected from a restricted size range also indicate differences in sorting, though the relationship between the abstracted pebble sample and the entire field sample is not clear. Sphericity and roundness measures are, on the basis of the present statistics, unreliable as indicators of short-range trends in the confused depositional environment of glacial meltwaters.

It must be concluded from the results presented in this thesis that the nature of fluvioglacial deposition is such that short-range variations in deposits of the order of up to several kilometres in length are not measurable with acceptable degrees of certainty. However, the techniques used in this study are generally reliable indicators of both environment of deposition and direction of sedimentation, when applied to other water-laid sediments. Future work on fluvioglacial deposits could use these techniques to advantage, if applied to much larger suites of deposits than have been studied in this thesis. An intensification of sampling at individual sites

would merely underline the large within-site variation which exists throughout fluvioglacial deposits, and would involve uneconomical expenditure of labour. The present results are sufficiently significant to suggest that a similar study of the deglaciation sequence deposits over a comparatively large area of relatively uniform bedrock would add substantially to an understanding of both the varying environmental conditions of fluvioglacial deposition and the deglaciation sequence itself.

LIST OF REFERENCES CITED

- ANDERSON, J.G.C. 1940. Glacial drifts near Roslin, Midlothian. *Geol. Mag.*, 77, 470-3.
- APPEL, E.T. 1938. Phase sampling of sediments. *J. sedim. Petrol.*, 8, 67-8.
- ASCHENBRENNER, B.C. 1956. A new method of expressing particle sphericity. *J. sedim. Petrol.*, 26, 15-31.
- BAILEY, E.B. and R.J.A. ECKFORD 1956. Eddleston gravel-moraine. *Trans. R. Soc. Edinb.*, 16, 254-61.
- BERTHOIS, L. 1952. Abaques pour le calcul des indice des galets. *Revue Géomorph. dyn.*, 3, 199-205.
- BLENK, M. 1960. Ein Beitrag zur morphometrischen Schotteranalyse. *Z. geomorph.*, 4, 202-42.
- BOULTON, G.S. 1972. Modern Arctic glaciers as depositional models for former ice sheets. *J. geol. Soc. Lond.*, 128, 361-93.
- BRITISH STANDARDS INSTITUTE 1960. Methods for sampling and testing of mineral aggregates, sands and fillers. B.S.812. London, British Standards Institute.
- BROOKS, C.E.P. and N.CARRUTHERS 1953. Handbook of statistical methods in meteorology. London, H.M.S.O.
- BUCKMAN, H.O. and N.C. BRADY 1960. The nature and properties of soils. 6th ed. New York, Macmillan.
- CAILLEUX, A. 1947. L'indice d'émoussé: définition et première application. *C. r. somm. Séanc. Soc. géol. Fr.*, 13, 250-2.
- CARR, R. 1937. Glacial terraces. *Hist. Berwicksh. Nat. Club*, 29, 284-8.
- CARRUTHERS, R.G. 1939. On northern glacial drifts: some peculiarities and their significance. *Q. Jl geol. Soc. Lond.*, 95, 299-330.

- CHARLESWORTH, J.K. 1926. The readvance, marginal kame-moraine of the south of Scotland, and some later stages of retreat. *Trans. R. Soc. Edinb.*, 55, 25-50.
- CHORLEY, R.J. 1966. The application of statistical methods to geomorphology. *in* DURY, G.H. (ed.) *Essays in geomorphology*. London, Heinemann. pp.275-387.
- CLOSE, M.H. 1867. Notes on the general glaciation of Ireland. *R. geol. Soc. Ire. J.*, 1, 207-42.
- CROXTON, F.E. and D.J. COWDEN 1968. *Applied general statistics*. 3rd ed. London, Pitman.
- CURRAY, J.R. 1960. Tracing sediment masses by grain-size modes. *in* Report of the 21st International Geological Congress, Copenhagen. pp.119-30.
- DAVIS, S.N. 1958. Size distribution of rock types in stream gravel and glacial till. *J. sedim. Petrol.*, 28, 87-94.
- DEPARTMENT OF AGRICULTURE AND FISHERIES, SCOTLAND 1961. Dogden Moss, Berwickshire. Moss survey reports, 50.
- EMRICH, G.H. and F.J. WOBBER 1963. A rapid visual method for estimating sedimentary parameters. *J. sedim. Petrol.*, 33, 831-43.
- FLINT, R.F. 1928. Eskers and crevasse fillings. *Am. J. Sci.*, 5th ser., 15, 410-6.
- 1957. *Glacial and Pleistocene geology*. New York, Wiley.
- FOLK, R. L. 1965. *Petrology of sedimentary rocks*. Austin, Hemphill.
- 1966. A review of grain-size parameters. *Sedimentology*, 6, 73-93.
- FOLK, R.L. and W.C. WARD 1957. Brazos River bar; a study in the significance of grain size parameters. *J. sedim. Petrol.*, 27, 3-26.

- FRIEDMAN, G.M. 1961. Distinction between dune, beach and river sands from their textural characteristics. *J. sedim. Petrol.*, 31, 514-29.
- GILL, M.A. 1969. Flatness index of non-spherical sedimentary particles. *J. Geol.*, 77, 120-4.
- GLEN, J.W.,
J.J. DONNER and
R.G. WEST 1957. On the mechanism by which stones in till become oriented. *Am. J. Sci.*, 255, 194-205.
- GOODCHILD, J.G. 1898. The Bedshiel kaims. *Hist. Berwicksh. Nat. Club*, 16, 295-312.
- GOODLET, G.A. 1964. The kamiform deposits near Carstairs, Lanarkshire. *Bull. Geol. Surv. Gt Br.*, 21, 175-96.
- GRIFFITHS, J.C. 1953. Estimation of error in grain size analysis. *J. sedim. Petrol.*, 23, 75-84.
- 1957. Size-frequency distribution of detrital sediments based on sieving and pipette sedimentation. *Bull. geol. Soc. Am.*, 68, 1739.
- 1967. Scientific methods in analysis of sediments. New York, McGraw-Hill.
- GRIFFITHS, J.C. and
M.A. ROSENFELD 1954. Operator variation in experimental research. *J. Geol.*, 62, 74-91.
- GRIFFITHS, J.C. and
C.M. SMITH 1964. Relationship between volume and axes of some quartzite pebbles from the Clean Conglomerate, Rock City, N.Y. *Am. J. Sci.*, 262, 497-512.
- HARRISON, P.W. 1957. New technique for three-dimensional fabric analysis of till and englacial debris containing particles from 3 to 40 mm. in size. *J. Geol.*, 65, 98-105.
- HATCH, T. and
S.P. CHOATE 1929. Statistical description of the size properties of non-uniform particulate substances. *J. Franklin Inst.*, 207, 369-87.

- HELLAAKOSKI, A. 1931. On the transportation of materials in the esker of Laitila. *Fennia*, 52 (7), 41 pp.
- HOLMES, C.D. 1941. Till fabric. *Bull. geol. Soc. Am.*, 52, 1299-1354.
- HOUGH, J.L. 1942. Sediments of Cape Cod Bay, Massachusetts. *J. sedim. Petrol.*, 12, 10-30.
- INMAN, D.L. 1952. Measures for describing the size distribution of sediments. *J. sedim. Petrol.*, 22, 125-45.
- JAMESON, T.F. 1860. On the drift and rolled gravel of the north of Scotland. *Q. Jl geol. Soc. Lond.*, 16, 347-71.
- KENDALL, P.F. 1902. A system of glacial lakes in the Cleveland Hills. *Q. Jl geol. Soc. Lond.*, 58, 471-571.
- KING, C.A.M. 1966. *Techniques in geomorphology*, London, Arnold.
- KING, C.A.M. and J.T. BUCKLEY 1968. The analysis of stone size and shape in Arctic environments. *J. sedim. Petrol.*, 38, 200-14.
- KIRBY, R.P. 1966. The glacial geomorphology of the Esk Basin, Midlothian. Unpublished Ph.D. thesis, Univ. of Edinburgh (2 vols).
- 1968. The ground moraines of Midlothian and East Lothian. *Scott. J. Geol.*, 4, 209-20.
- 1969a. Till fabric analyses from the Lothians, Central Scotland. *Geogr. Annlr.*, 51A, 48-60.
- 1969b. Morphometric analysis of glaciofluvial terraces in the Esk Basin, Midlothian. *Trans. Inst. Br. Geogr.*, 48, 1-18.
- 1969c. Variation in glacial deposition in sub-glacial environment: an example from Midlothian. *Scott. J. Geol.*, 5, 49-53.

- KRUMBEIN, W.C. 1934. The probable error of sampling sediments for mechanical analysis. *Am. J. Sci.*, 27, 204-14.
- 1936. The use of quartile measures in describing and comparing sediments. *Am. J. Sci.*, 32, 98-111.
- 1941. Measurement and geological significance of shape and roundness of sedimentary particles. *J. sedim. Petrol.*, 11, 64-72.
- 1942. Settling-velocity and flume-behaviour of non-spherical particles. *Trans. Am. geophys. Un.*, 23, 621-33.
- KRUMBEIN, W.C. and R.L. MILLER 1953. Design of experiments for statistical analysis of geologic data. *J. Geol.*, 61, 510-32.
- KRUMBEIN, W.C. and F.J. PETTIJOHN 1938. *Manual of sedimentary petrography*. New York, Appleton-Century.
- McCALL, J. and G.A. GOODLET 1952. Indicator stones from the drift of south Midlothian and Peebles. *Trans. Edinb. geol. Soc.*, 14, 401-9.
- McCAMMON, R.B. 1962a. Moment measures and the shape of size frequency distributions. *J. Geol.*, 70, 89-92.
- 1962b. Efficiencies of percentile measures for describing the mean size and sorting of sedimentary particles. *J. Geol.*, 70, 453-65.
- MACGREGOR, M. 1927. The Carstairs district. *Proc. Geol. Ass.*, 38, 495-9.
- McLELLAN, A.G. 1967a. The distribution, origin and use of sand and gravel deposits in central Lanarkshire. Unpublished Ph.D. thesis, Univ. of Glasgow (No. 2904 - 2 vols).
- 1967b. The distribution of sand and gravel deposits in west central Scotland and some problems concerning their utilization. Glasgow, University of Glasgow.
- 1969. The last glaciation and deglaciation of central Lanarkshire. *Scott. J. Geol.*, 5, 248-68.

- MANNERFELT, C.M. 1945. Some glaciomorphological forms and their evidence as to the downwasting of the inland ice in Swedish and Norwegian mountain terrain. *Geogr. Annlr.*, 27, 1-235 (English summary 223-8).
- MANSIKKANIEMI, H. 1970. Deposits of sorted material in the Inarijoki-Tana river valley in Lapland. *Annls. Univ. Turku.*, 43, 1-63.
- MASON, C.C. and R.L. FOIK 1958. Differentiation of beach, dune, and aeolian flat environments by size analysis, Mustang Islands, Texas. *J. sedim. Petrol.*, 28, 211-26.
- NOSSIN, J.J. 1959. Geomorphological aspects of the Pisuergra drainage area in the Cantabrian Mountains. *Leid. geol. Meded.*, 24, 283-406.
- OTTO, G.H. 1938. The sedimentation unit and its use in field sampling. *J. Geol.*, 46, 569-82.
- 1939. A modified logarithmic probability graph for the interpretation of mechanical analyses of sediments. *J. sedim. Petrol.*, 2, 62-76.
- PAGE, H.G. 1955. Phi-millimetre conversion table. *J. sedim. Petrol.*, 25, 285-292.
- PETTIJOHN, F.J. 1949. *Sedimentary rocks*. New York, Harper.
- PLUMLEY, W.J. 1948. Black Hills terrace gravels; a study in sediment transport. *J. Geol.*, 56, 526-78.
- POWERS, M. 1953. A new roundness scale for sedimentary particles. *J. sedim. Petrol.*, 23, 117-9.
- RAGG, J.M. 1960. The soils of the country round Kelso and Lauder. *Mem. Soil Surv. Gt Br. (Scotland)*, Sheets 25 and 26, 201 pp. Edinburgh, H.M.S.O.
- ROSENFELD, M.A. and J.C. GRIFFITHS 1953. An experimental test of visual comparison technique in estimating 2-dimensional sphericity and roundness of quartz grains. *Am. J. Sci.*, 251, 553-85.

- ROYAL SOCIETY, THE 1965. General notes on the preparation of scientific papers. London, The Royal Society.
- SISSONS, J.B. 1958. Supposed ice-dammed lakes in Britain with particular reference to the Eddleston valley, southern Scotland. *Geogr. Annlr.*, 40, 159-87.
- 1960. Some aspects of glacial drainage channels in Britain (Part I). *Scott. geogr. Mag.*, 76, 131-46.
- 1961a. Some aspects of glacial drainage channels in Britain (Part II). *Scott. geogr. Mag.*, 77, 15-36.
- 1961b. A subglacial drainage system by the Tinto Hills, Lanarkshire. *Trans. Edinb. geol. Soc.*, 18, 175-93.
- 1961c. The central and eastern parts of the Lammermuir-Stranraer moraine. *Geol. Mag.*, 98, 380-92.
- 1967. The evolution of Scotland's scenery. Edinburgh, Oliver and Boyd.
- SNEED, E.D. and 1958. Pebbles in the Lower Colorado River, R.L. FOLK Texas; a study in particle morphogenesis. *J. Geol.*, 66, 114-50.
- SORBY, H.C. 1880. On the structure and origin of non-calcareous stratified rocks. *Q. Jl geol. Soc. Lond.*, 36, 46-92.
- STEINMETZ, R. 1962. Sampling and size distribution of quartzose pebbles from three New Jersey gravels. *J. Geol.*, 70, 56-73.
- STEVENSON, W. 1864. On Bedshiel 'kaims' and their relations to similar deposits to eastward and westward. *Hist. Berwicksh. Nat. Club*, 5, 124-8.
- STRÖM, K.M. 1945. Geomorphology of the Rondane area. *Norsk geogr. Tidsskr.*, 25, 360-78.
- TRASK, P.D. 1930. Mechanical analysis of sediments by centrifuge. *Econ. Geol.*, 25, 581-99.
- 1932. Origin and environment of source sediments of petroleum. Houston, Gulf Publishing Company.

- TURABIAN, K.I. 1959. A manual for writers of term papers, theses, and dissertations. Revised ed. Chicago, Univ. of Chicago Press.
- UDDEN, J.A. 1914. Mechanical composition of clastic sediments. Bull. geol. Soc. Am., 25, 655-744.
- VAN ORSTRAND, C.E. 1925. Note on the representation of the distribution of grains in sand. Research in Sedimentation in 1924. Comm. on Sedimentation, Natl. Res. Council (Ottawa), pp. 63-7.
- WADELL, H. 1932. Volume, shape and roundness of rock particles. J. Geol., 40, 443-51.
- 1933. Sphericity and roundness of rock particles. J. Geol., 41, 310-31.
- 1935. Volume, shape and roundness of quartz particles. J. Geol., 43, 250-80.
- WENTWORTH, C.K. 1922a. A scale of grade and class terms for clastic sediments. J. Geol., 30, 377-92.
- 1922b. The shapes of beach pebbles. Prof. Pap. U.S. geol. Surv., 131-C, 75-83.
- 1933. Fundamental limits to the size of clastic grains. Science, N.Y., 77, 633-4.
- WOLMAN, M.G. 1954. A method of sampling coarse river-bed material. Trans. Am. geophys. Un., 35, 951-6.
- YOUNG, J.A.T. 1966. Analysis of glacial deposits near Fala, Midlothian. Unpublished Ph.D. thesis, Univ. of Edinburgh.
- ZINGG, T. 1935. Beitrag zur Schotteranalyse. Schweiz. miner. petrogr. Mitt., 15, 39-140.