A study of the superficial deposits in upper Weardale

Falconer, Allan

A Study of the Superficial Deposits in Upper Weardale

by

Allan Falconer B.Sc. (Dunelm)

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ABSTRACT

The geomorphology of the upper reaches of the River Wear Valley has been based on individual assessments of the complex topography of the area. Evaluation of the superficial deposits as a method of understanding the area, has so far been limited to subjective assessment.

In this study a technique recently developed in sedimentary petrology is applied to samples of the suite of deposits existing in Upper Weardale. Two samples are considered, one, a purposive sample chosen to "represent" the deposits of the region for an initial evaluation of the technique, the other sample, a random sample, to permit general conclusions about the nature of the deposits existing in that area.

Analysis of the particle-size distribution of the sediments obtained in each sample gives a basis for conclusions about the representative nature of both purposive and random samples. Factor Analysis of the particle-size data gives similar results for each body of data and the Factor analyses of all data as a single unit demonstrates an equal consistency.

Consideration of the nature of the four factors produced in this way leads to their tentative identification as the products of glacial action, water-washing processes, rock decomposition and gelifluction. This tentative identification is reinforced by the statistically significant trend surface patterns which emerge from further data analysis.

In the final section all other evidence is considered together with the results obtained from data analysis. The conclusions about the geomorphological history are compatible with the evidence considered by previous workers, although the conclusion that the whole area was over-ridden by ice is a departure from the commonly-held view.

Conclusions of a methodological nature concerning the wider application of these techniques to complex suites of deposits are also formulated.

ACKNOWLEDGEMENTS

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My wife's contribution has been too great to evaluate adequately. To her and my family, I offer apologies for long periods of preoccupation with matters geomorphological and sincere thanks to my wife for her patience and devotion.

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Preface

The majority of recently published studies of Pleistocene geomorphology are essentially descriptive. In many cases there is an appreciation of the need for quantitative description and as a result many tables of data exist detailing the length, width, height, chemical composition or weight of an assortment of variables. Geomorphologists are still not aware of the full significance of many of these variables and seem to be failing in their attempt to move forward from the compilation of descriptive studies of the 1940s and 1950s with their valuable analyses of topographic data. The next step appears to be the diagnosis of sediment types and their relationships to topography, climate and geomorphological processes.

Previous generations of geomorphologists have demonstrated the value of interpreting the general physiography of a region. The increasingly specialist nature of geomorphology is leading towards its recognition as a true science and this fact requires not only that measurements be taken and recorded but also that they be analysed. In the words of Russell (president of the Association of American Geographers 1948) in his preface to Yatsu's (1966) book: "Geomorphologists too long have shied away from investigating basic processes associated with landform origin and development." He further develops this theme by posing the question "How many engineers, geologists, mineralogists, pedologists, ecologists, foresters, chemists, physicists or agriculturalists turn to geomorphological literature for information that might aid them in solving problems related to the earth's land surface?" He answers this question by saying "It is a sad commentary, but in all probability their harvest would reveal few grains of corn embedded in huge volumes of chaff."

This comment written so recently by an eminent geographer has been responsible for the tone of the present text. Yatsu (1966) emphasises the scientific nature of geomorphology. In a small aside at the end of the first chapter he notes "Geomorphologists have been trying to answer the what, where and when, of things, but they have seldom tried to ask how. And they have never asked why. It is a great mystery why they have never asked why."

The present study does attempt to answer the what and where of glacial processes in Upper Weardale. "When" is difficult to investigate but the available evidence is considered. How these things may be established is developed from the use of a combination of sedimentary analyses, data processing and trend-surface mapping. The implications of this continue to be a major field of interest for the author in further research.

Yatsu in a more recent address (1969) stated "... some aspects of landform materials have been studied for many years. For example the mechanical, chemical and mineralogical composition of sediments and soils have long aided the identification of the origin and nature of landforms. Sediments and soils result from the action of processes, therefore they are very helpful keys to the understanding of processes which have taken place."

In this present study the question "why" has formed a background to much of the initial work. "Why" measure particle size distribution in sediments? "Why" not use the particle size data as an aid to the identification and origin of landforms (as suggested by Yatsu)? The answers to these and many similar questions ultimately answer the question: "How do we derive an understanding of glacial processes in upland areas?" In so doing, these answers provide the more basic "what, when and where" information usually produced in similar studies. Furthermore we are left with the ultimate questions of why such results emerge and how they relate to the actual mechanisms of glaciation. These latter questions are fundamental, and can only be answered by continued research. The present work reveals only that certain types of sedimentological data are sufficiently important to yield basic information if they are suitably analysed (rather than summarised as is commonly the case in geomorphological studies). The implications of these results can only be fully realised by continued investigation of geomorphological processes.

This study is presented in the hope that it will illuminate the general need for data processing in geomorphology and provide a basis for a more detailed understanding of the type of data frequently accumulated. The demonstrated relationships between different types of deposits and the apparently polygenetic nature of several of the samples seem to indicate a need for more sensitive studies of superficial materials. Consideration of such materials as a part of the total system of deposits in a region seems to offer a sounder basis for continued investigation. In this study the system in question is the whole suite of superficial deposits in Upper Weardale. Taking heed of the quotation "Unless one is a genius it is best to aim at being intelligible" (attributed to G.K. Chesterton) the present study attempts to explain, intelligibly, the use of a particular combination of techniques applied for the first time to obtain an understanding of Pleistocene and Recent deposits. The author hopes that, in Russell's terminology, the reader may find a few grains of corn in what otherwise must be a volume of chaff.

Allan Falconer

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Chapter 1

Introduction

Smailes (1960) in his book "North England" provides a descriptive summary of the geography of that area which includes references to the valley of the River Wear. He states:

> "The (River) Wear is especially interesting as exemplifying contrasts in valley types. Its composite valley includes the dale section, where the river is flowing south-east in the drift covered floor of a broad, open, pre-glacial valley ..." (Smailes, 1960, p. 44).

It is the dale section of the River Wear which forms the focus of this study. For ease of reference the term Upper Weardale is used and defined as that part of the Wear valley bounded to the east by easting 410,000 of the National Grid (1° 50' 50" W.) and to the north, west and south by the watershed of the Wear (see Figs. 1.1, 1.2, 1.3). The area thus defined is the one studied by Atkinson (1968) in his work entitled "An investigation of the pedology of Upper Weardale, Co. Durham." Figure 1.4 shows the numbers and incidence of Ordnance Survey sheets in this area.

Upper Weardale has received very little attention from geomorphologists. Documented work on the area is restricted to Dwerryhouse (1902), Maling (1955) and Atkinson (1968) with mention of the area included in the more general works of Raistrick (1931), Trotter and Hollingworth (1932), and Trotter (1929) all of whom accept Dwerryhouse's opinion that Upper Weardale has evidence only of local glaciation. This particular opinion is further reinforced by Maling who states

> "The present writer agrees with Dwerryhouse (1902) and Trotter (1929) that foreign erratics are com-

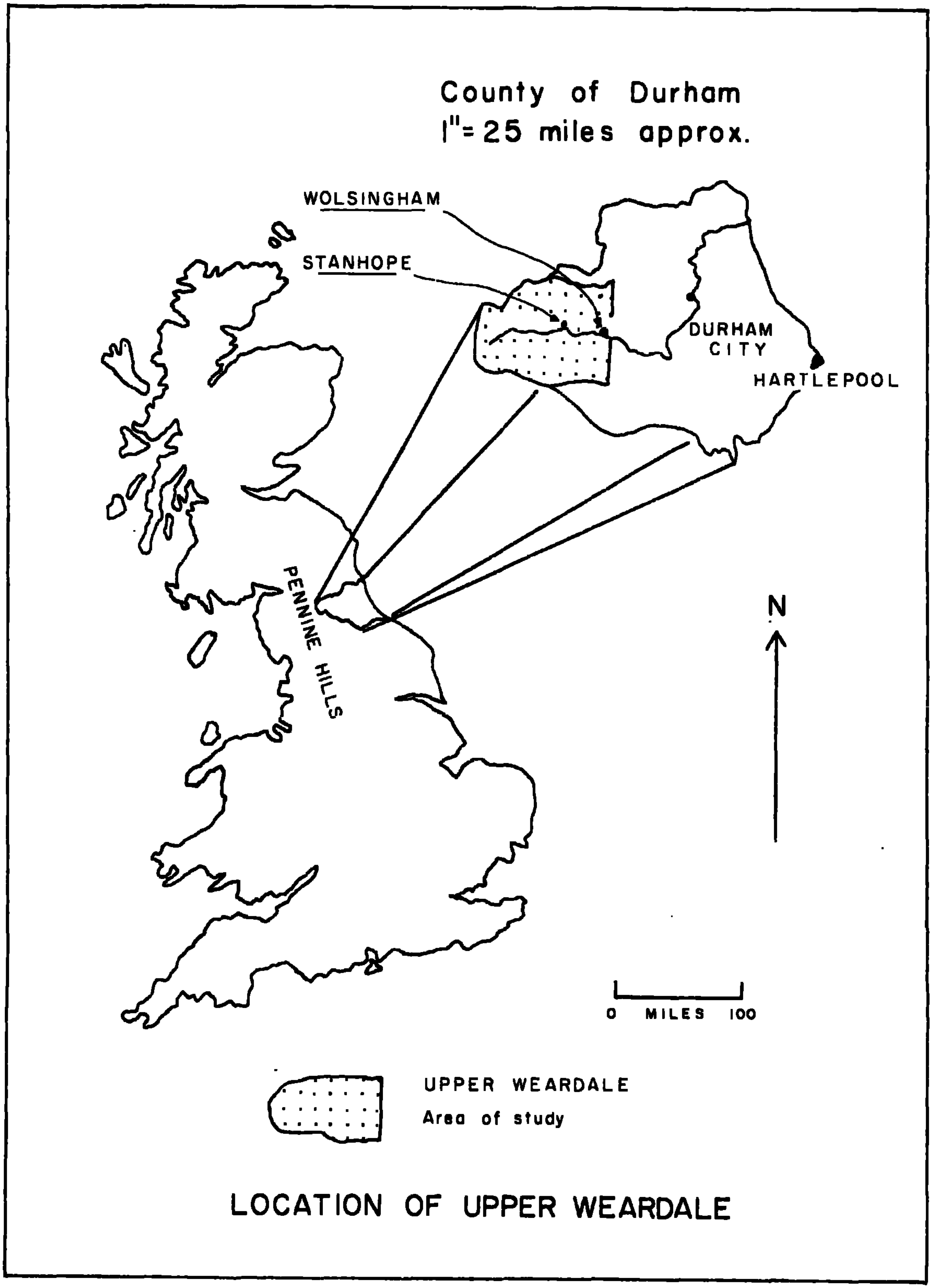

County of Durham
1" = 25 miles approx.
WOLSINGHAM
STANHOPE
DURHAM CITY
HARTLEPOOL
PENNINE HILLS
N
0 MILES 100
UPPER WEARDALE
Area of study
LOCATION OF UPPER WEARDALE

Figure 1.1

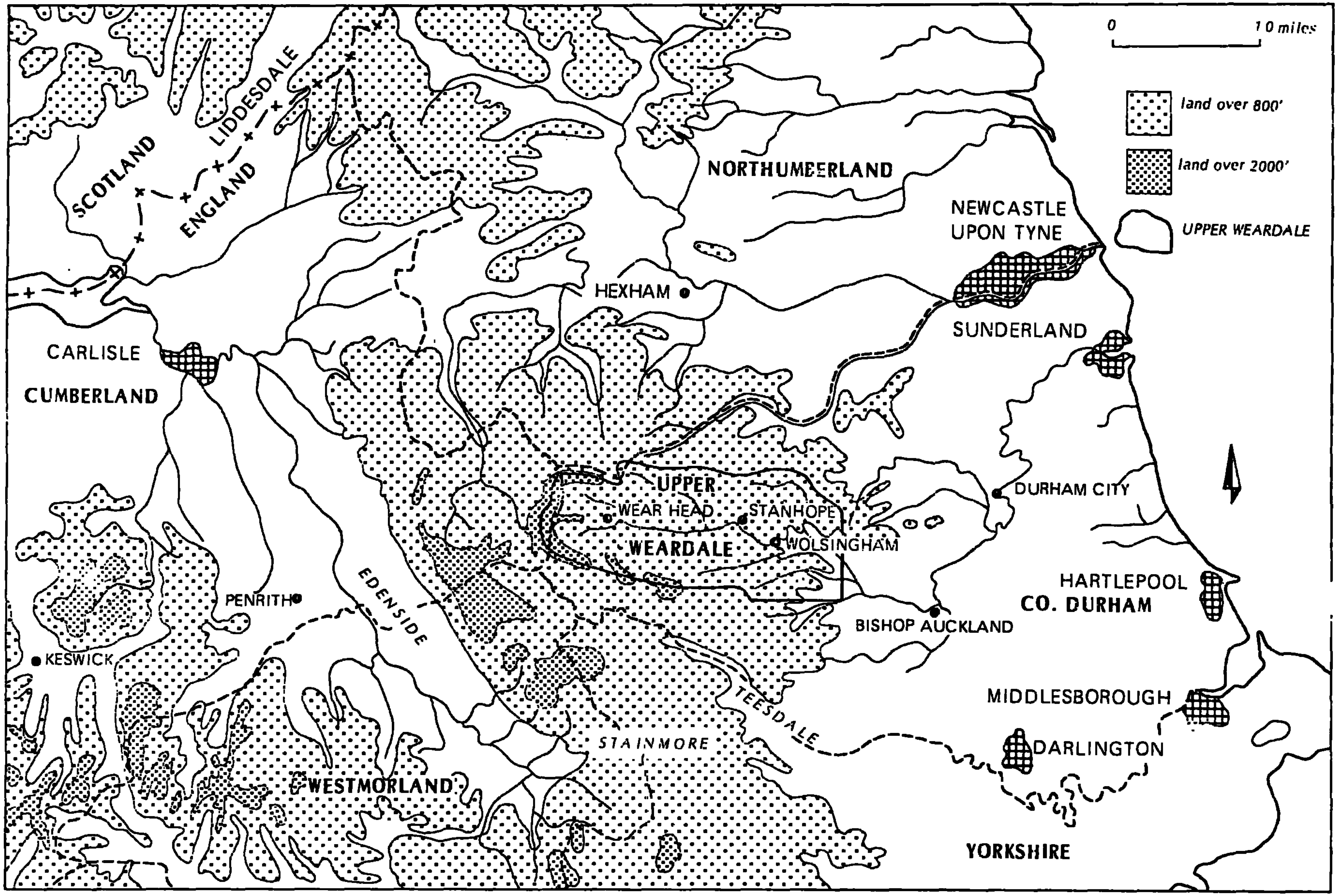
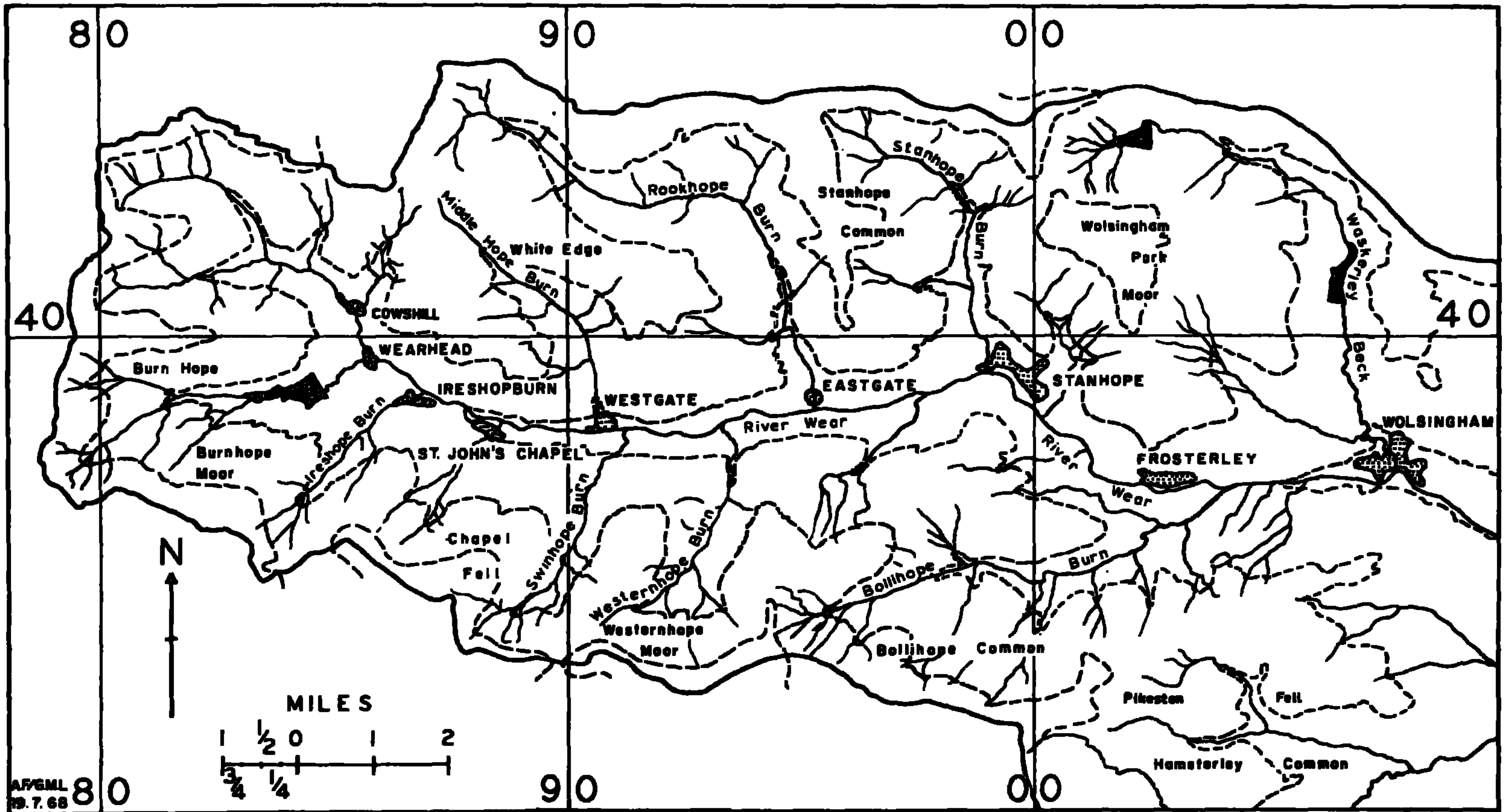


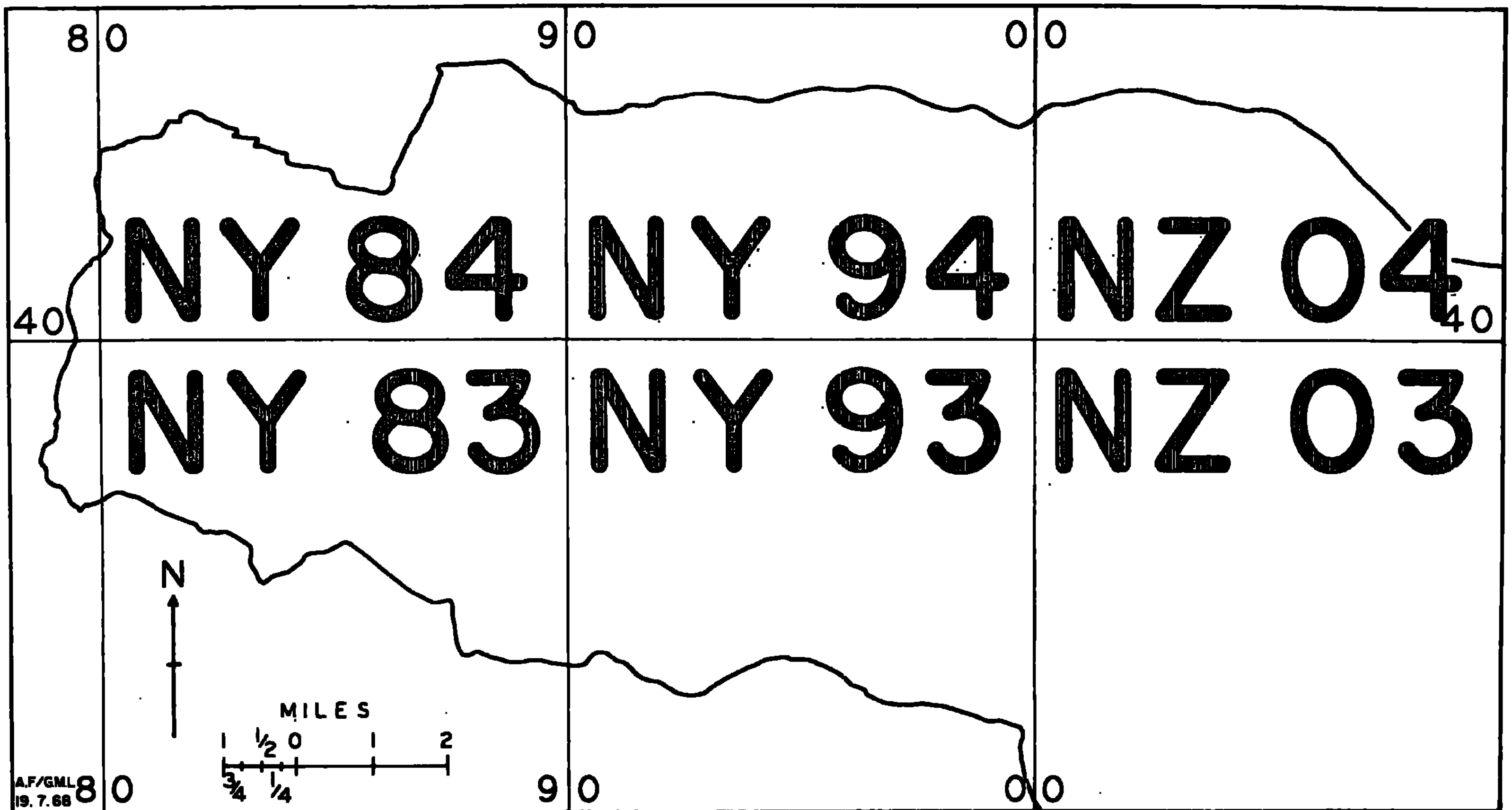
Figure 1.2 Upper Weardale Regional Setting



UPPER WEARDALE

EXTRACT FROM 1" O.S. MAP SHOWING MAJOR STREAMS AND LOCAL NAMES

Figure 1.3



UPPER WEARDALE

INCIDENCE OF O.S. SHEET NUMBERS

FOR O.S. 1:25,000 PROVISIONAL EDITION

Figure 1.4

pletely absent from Weardale and that the glaciers of the dale were isolated from other ice-sheets throughout the Pleistocene."
(Maling, 1955, p. 89).

Beaumont's excellent summary of the history of glacial research in Northern England (Beaumont 1968) indicates that the lack of detailed work in Weardale is a reflection of a general lack of sustained interest in the physical landscape of N.E. England. In a general comment on studies in Co. Durham he states

"... Durham has lacked a continuity of study of the Pleistocene deposits, and has been characterised by a few important works separated by long periods of relative inactivity."
(Beaumont, 1967, p. 26)

When Weardale alone is considered, only Dwerryhouse (1902) and Maling (1955) have been directly concerned with its geomorphology, the former providing a summary of known striae and erratics, the latter with erosion platforms associated with Tertiary landscape development.

During the past decade geomorphologists have begun to focus more of their attention on process. Increasingly information about process is being derived from detailed studies of sediments a point reinforced by Yatsu who states that

"sediments and soils result from the action of processes, therefore they (the sediments) are very helpful keys to the understanding of processes which have taken place." (Yatsu in press).

If a more detailed understanding of the morphology of Upper Weardale is to be obtained then it is necessary to view the present landscape as the only record of its geomorphological history which is available for study. The present landscape owes its morphology, in part, to the geological structure of the area and, more significantly, to the action of a variety of erosional and depositional process acting on the constituent rocks. Evidence of the action of these processes must be found in the superficial materials of the area. This is especially true if we accept Smailes statement that

> "The glaciation interrupted an incompleted cycle of subaerial erosion and the ice-sheets generally smoothed and softened the contours of the pre-glacial surface. By blanketing them for a long period and coating them with drift, glaciation undoubtedly exercised a largely protective role." (Smailes, 1960, p. 39).

In Upper Weardale such a sequence of events must be further complicated by subsequent periglacial action and the re-establishment of sub-aerial processes following the retreat of the ice. There is a further complication in that "glaciation" is not a simple process and Smailes' statements imply the possibility that glaciation involves several phases of glacierization and deglacierization of the area.

Nineteenth century studies which launched the glacial theory were concerned with the nature of the deposit left by a retreating glacier. Similarities between the terrain immediately adjacent to glacier snouts in the Alps and terrain in Southern Scotland were the basis for many of Agassiz's remarks when he first propounded his glacial theory in Britain. (Agassiz, 1840, pp. 328-330). Similarity in terrain type also included similarities in the nature of the deposits themselves and these two classes of evidence, morphology and sediment characteristics, have formed the basis for all subsequent work in glacial geomorphology. Regrettably morphology has, in some works (especially Davis, 1902, Penck, 1953 and Scheidegger, 1961) been over emphasised and too great a reliance has been placed on intuitive deduction from a subjective classification of a landform without a full consideration of the sedimentary record. In some cases (e.g. Straw, 1968, Harris, 1967) controversies arise over the interpretation of individual landscape features. Explanations of glacial action exist with no supporting evidence from laboratory experiments or observations of ice mass disintegration.

It is a feature of recent theses in geomorphology that increasing attention is being paid to laboratory analysis of sediments and statistical processing of the resulting data (e.g. John, 1963, Young, 1966, Beaumont, 1967, Vincent, 1969). Whilst this trend emerges in geomorphology, studies by geologists and sedimentologists are increasingly devoted to detailed analysis of sediments and an overall application of statistical methods (e.g. Imbrie, 1963, Imbrie and Van Andel, 1964, Klovan, 1966, Krumbein and Graybill, 1965, Miller and Kahn, 1962). Distinguishing between differing sedimentary environments has been the concern of several geologists (Folk and Ward, 1957, Mason and Folk, 1958, Inman, 1952, Krumbein and Pettijohn, 1938, Klovan, 1966) and limited success was enjoyed by several of these workers. They found the use of certain statistical parameters a considerable aid in the interpretation of the genesis of deposits and the results of this work pertinent to geomorphology are summarised by King (1966) in her book "Techniques in Geomorphology".

In the context of this trend in both geomorphology and geology it was the author's opinion that Upper Weardale, an area with no published evidence of external influence during the Pleistocene (Dwerryhouse, 1902, Maling, 1955) would provide a suite of deposits well suited to sediment analysis. This suite of deposits, observed and written about by Maling and Dwerryhouse should provide the record of the sequence of events described by Smailes (see above). The present work was undertaken to elucidate the nature of the deposits now existing in Upper Weardale and thereby to comment on their geomorphological significance.

By analysing deposits it is proposed that an understanding of the processes producing them will result. Certain characteristics of glacial deposits permit their identification as a general group. It is proposed that detailed investigation will permit closer identification of their genetic history in the same manner that environments of sedimentation are being identified for marine and aeolian deposits (see Krumbein and Pettijohn, 1938, Twenhofel, 1932, Klovan, 1966, Imbrie and Van Andel, 1964, Harbaugh and Merriam, 1968).

The first portion of this study presents a brief summary of pertinent information about the geology and the geomorphology of the area. Immediately following this is a reassessment of the Weardale landscape in the light of Atkinson's recent study of pedology in Upper Weardale. This part of the study includes comment based on the information gathered in the field survey of the region undertaken by the present author. Comments on the sequence of events which established the present geomorphology of Weardale are developed into a framework for a more detailed investigation of the present-day geomorphology.

Consideration is given to the structure of a geomorphological investigation and the sampling procedures for the present survey are established. In the light of recent comment about the increasing need for detailed sediment analysis in geomorphological studies, the study is designed to examine the particle-size distribution for each major sediment-type. The major sediment-types are considered to be distinguishable on the basis of their particle-size distribution and a recent study applying data processing techniques to such data (Klovan, 1966) suggests that the distinction may be made with the aid of these numerical techniques. The particle-size data from a purposive sample are used to test the factor analysis model developed by Klovan (1966). The apparent success of this initial test is further investigated by the use of a random sample from which grain-size data were obtained. Both the purposive and random sample data are compared and the results of factor analysis of these data are compared also. The results demonstrate a surprising consistency and the results of a factor analysis of all available data are presented as the basis for evaluation of the technique.

An examination of the factors identified by the data analysis techniques (Q-mode factor analysis and correlation) leads to the definition of the nature of these factors as glacial influence, hillslope processes, bedrock disintegration and gelifluction processes. By characterising each deposit by the dominant factor loading it is possible to consider each sample as the product of several influences one of which is dominant. This information is then subjected to trend surface analysis to determine the type of regional trends which exist. The assessment of the validity of these trends reveals certain areal influences which are in agreement with the conclusions reached by Vincent in his study of an adjacent area (Vincent, 1969). Trend surface analysis is extended to examine the distribution of factor influences in the vertical plane and the significant trends revealed are discussed in conjunction with the results of trend-surface analysis of the area.

The information thus processed is then considered in a subjective evaluation of the layering of the deposits as revealed at each site. Layering in the deposits is considered as both the sequential action of the dominant factor-processes and as the product of interaction of these processes in each case. All the conclusions based on the evidence of the data processing and trend-surface analysis results are then considered with the results of the evaluation of the layering of the deposits. Ultimately this produces a more detailed evaluation of the evidence which was recorded by previous workers but not analysed in such detail. Of particular importance are conclusions about regional ice movement based on trend-surface analysis. The measures of the relative influence of each process on the genesis of each sediment provide, for the first time, a factual basis for theorising about the sequence of events in post-glacial times and the final conclusions endorse much of the existing work in the Upper Weardale area.

Chapter 2

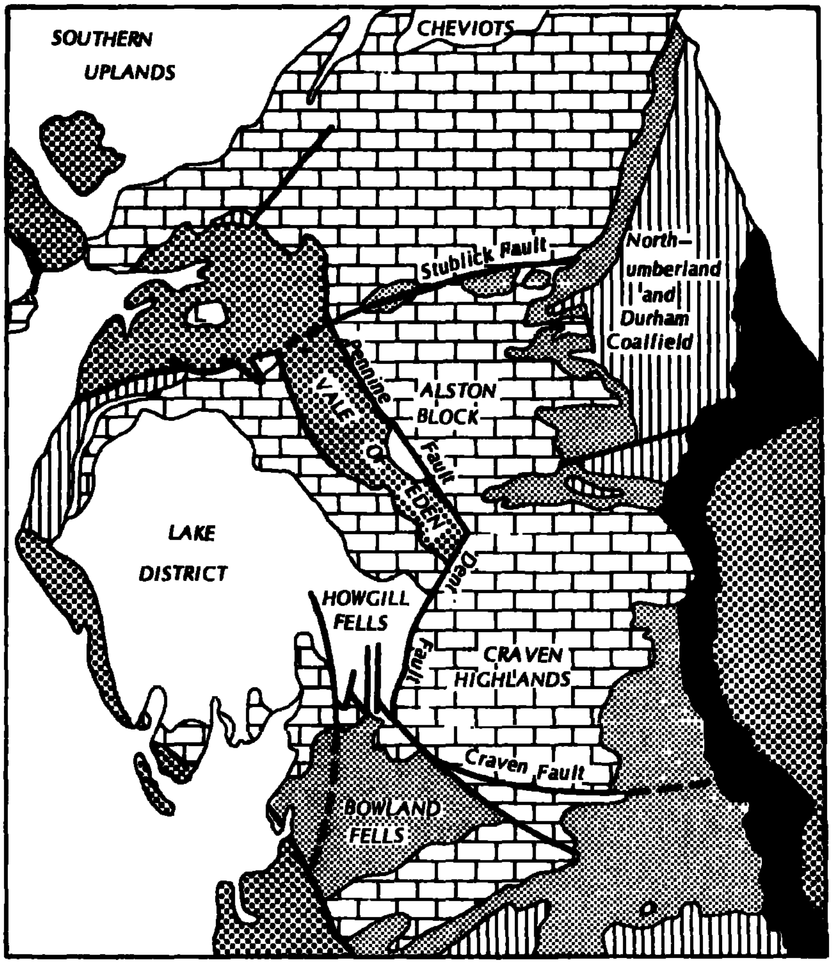
Upper Weardale: A North Pennine Valley

The River Wear flows eastwards to the sea from a drainage basin opening from the centre of the Alston Block. To the north is the Tyne drainage system and to the south is the drainage basin of the River Tees (see Fig. 1.2). In order to present the reader with a description of the regional setting of this area it is necessary to include some comment on the general physiography of the area and a brief synopsis of the underlying geological structure. The geology of this region has been investigated in detail by Dunham (see detailed references below) and excellent summaries of the available work are contained in the studies of Maling (1955), Atkinson (1968) and Vincent(1969). It is, however, considered necessary to include a review of this information in the present work.

2.1 Geology: Structure

Figure 2.1 shows the generalised geology structure of Northern England. This figure based on a diagram published by Wells and Kirkaldy, shows in a simplified way the main geological regions. The name "Craven Highlands" applied to the area north of the Craven Fault and east of the Dent Fault is often replaced by the name "Askrigg Block" in geological literature (e.g. King, 1969). Between the Alston and Askrigg Blocks is a depression along the line of the Stainmoor Syncline which represents the southern limit of the Alston Block.

The composition of the Alston Block is best presented in



GENERALIZED GEOLOGY STRUCTURE OF NORTHERN ENGLAND
(after Wells and Kirkaldy)

Pre-Carboniferous
Coal Measures
Lower Carboniferous
Magnesium Limestone
Millstone Grit
Permo-Trias

Scale 0 20 40 60 Miles

Figure 2.1

schematic cross section (see Fig. 2.2) as in the work of Bott and Johnson (1967) which clearly reveals the basic structure of the region. The underlying rigid block is a granitic mass proven to exist in 1960 by a deep borehole sunk at Rookhope (Grid ref. 937420) in Weardale following the extensive work by Dunham which indicated the existence of a large intrusive mass at depth within the region. This is overlain by the Mountain Limestone Facies, the Yoredale Series, the Upper Limestone Group Facies and the Coal Measure Facies. Within the area of Upper Weardale only a limited portion of this sequence is exposed. This sequence is shown in Figure 2.3 and is based on the Geology Survey terminology hence showing the Yoredale Series as the Middle Limestone Group. The apparently simple structure of the region has, in fact, been the basis for a great deal of research (see Dunham, 1948a, 1948b).

Upper Weardale lies within an area recognised as being developed on one of the ancient land masses existing in the Lower Palaeozoic Era and ultimately becoming submerged in the Carboniferous period when the present rocks were laid down. The ancient landmass of the Northern Pennines is that which Smailes (1960, p. 14) chooses to call the North Pennine Massif rather than use the term "Alston Block" as Trotter and Hollingworth did in their earlier work.

The whole of the Alston Block was investigated by Dunham whose work on the North Pennine Orefield (1948) led to the theory that the area was underlain by a granite boss. Geophysical evidence supporting this contention was subsequently provided by the work of Bott and the existence of the granite was proven by a borehole sunk in 1960. The granite discovered was encountered at a depth of 2,000' immediately

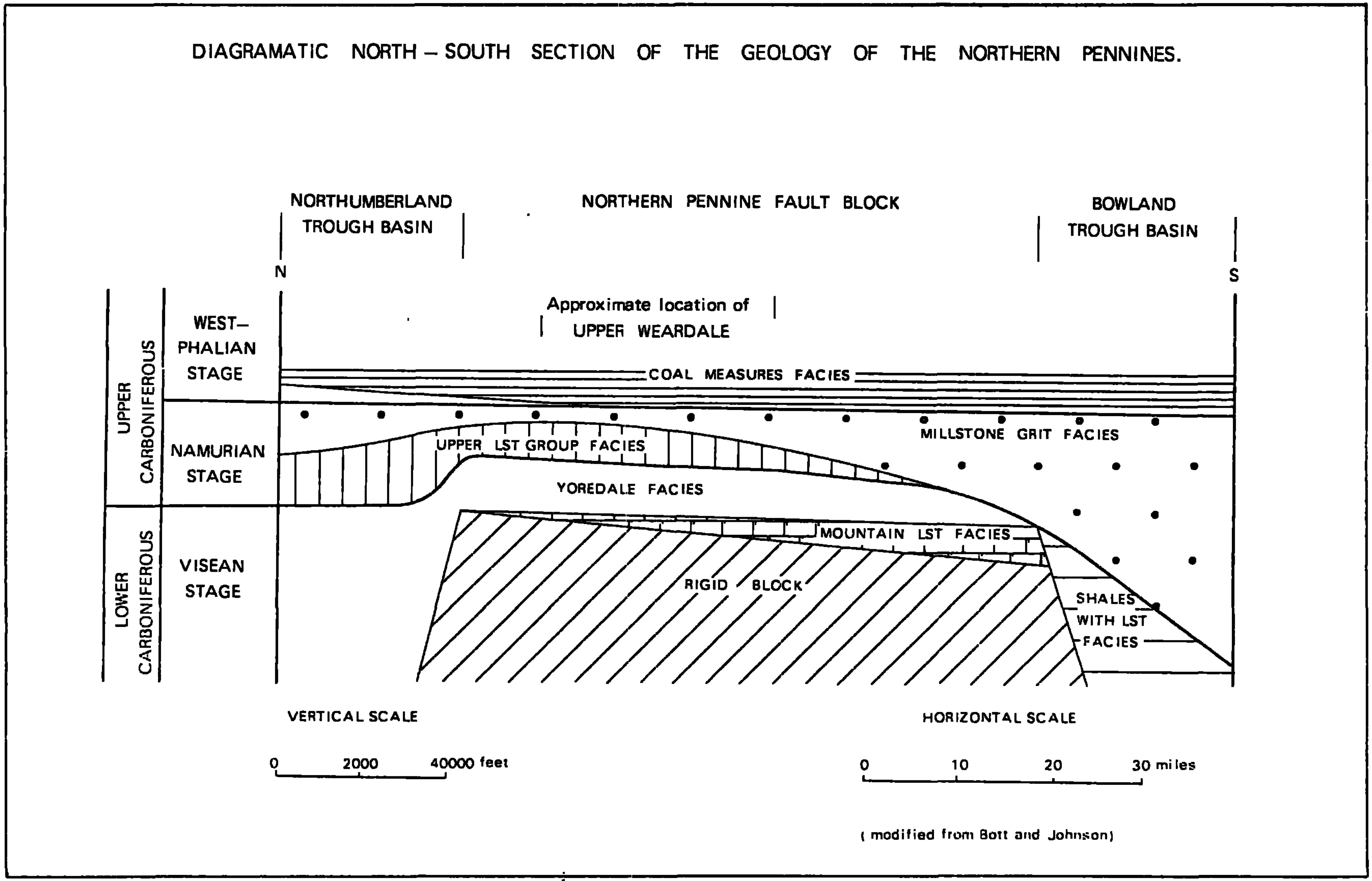

DIAGRAMATIC NORTH – SOUTH SECTION OF THE GEOLOGY OF THE NORTHERN PENNINES.
NORTHUMBERLAND TROUGH BASIN
NORTHERN PENNINE FAULT BLOCK
BOWLAND TROUGH BASIN
N
S
Approximate location of UPPER WEARDALE
UPPER CARBONIFEROUS
WEST– PHALIAN STAGE
NAMURIAN STAGE
LOWER CARBONIFEROUS
VISEAN STAGE
COAL MEASURES FACIES
MILLSTONE GRIT FACIES
UPPER LST GROUP FACIES
YOREDALE FACIES
MOUNTAIN LST FACIES
RIGID BLOCK
SHALES WITH LST FACIES
VERTICAL SCALE
0
2000
40000 feet
HORIZONTAL SCALE
0
10
20
30 miles
(modified from Bott and Johnson)

Fig. 2.2.

Fig. 2.3. Stratigraphic column for Upper Weardale (based on Dunham 1965)

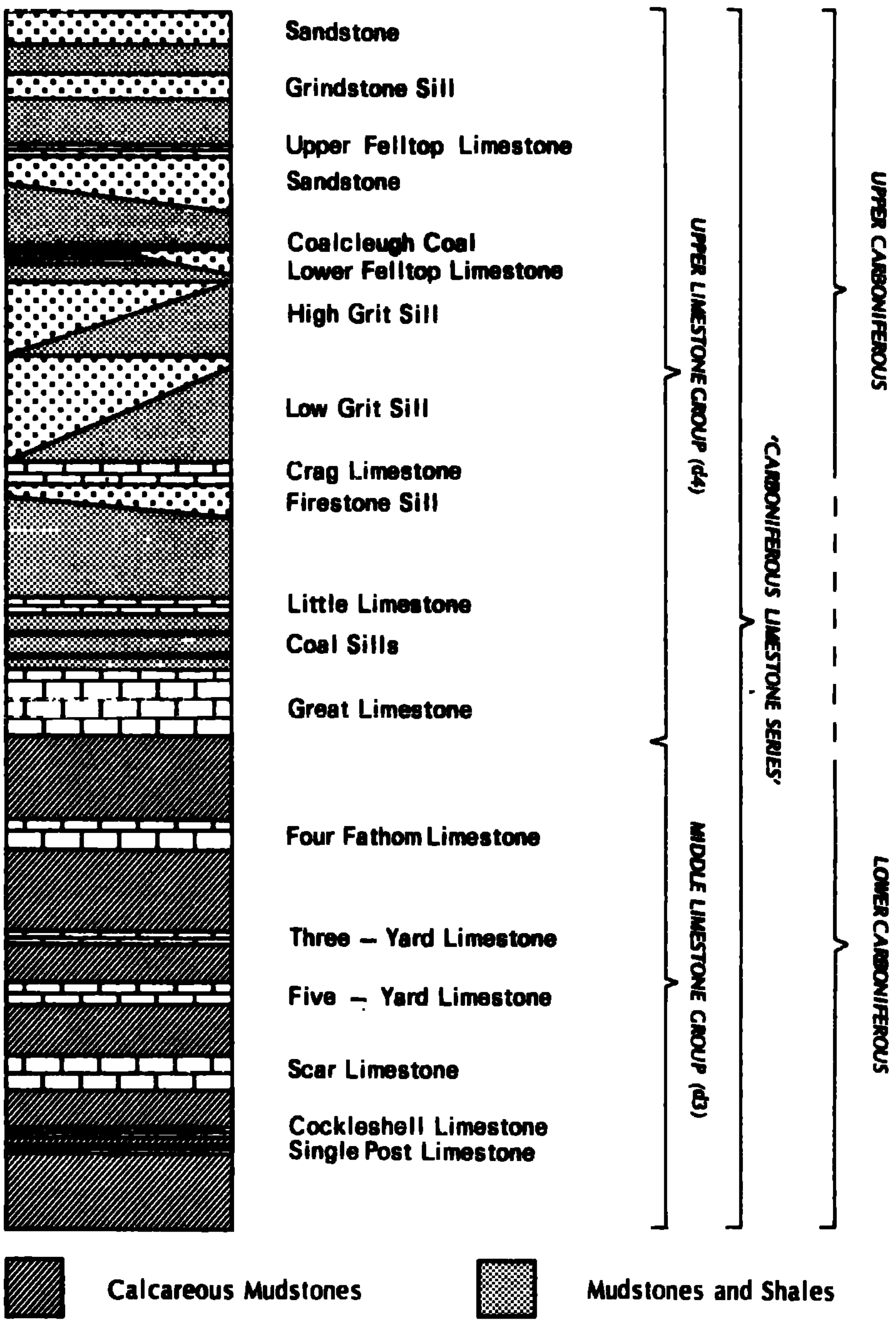


Figure 2.3

below the Carboniferous strata. The granite was dated at 363,000,000 years (Caledonian) and evidently was the crustal block Smailes referred to as the North Pennine Massif, which is the underlying structure of the Alston Block. This dating showed that contrary to expectations, the granite mass was not directly related to the mineral veins found extensively in the overlying Carboniferous strata

Further geophysical investigation showed indications that a second body of granite exists at a depth of 0.8 miles below the surface and in partial confirmation of this, mineral veins were found within the Caledonian granite. Bott's work on the existence of this granite mass led to his theory that the intrusion of a second granite mass at depth resulted in the mineralization of the Caledonian granite and the overlying Carboniferous strata. The Caledonian granite itself, (named Weardale granite) has a mass deficiency which would have permitted the elevation of the area to take place (Bott, 1967). Structurally this area seems to have remained undisturbed since the Tertiary or Hercynian diagenesis.

Within the area of study the rocks have a gentle dip to the east (130' per mile) and the whole area is bounded by a fault system (see Fig. 2.1). King describes this well in her introduction where she defines the Alston and Askrigg Block area as being

> "... bounded on three sides by the great capital sigma - shaped fault system, which bounds this part of the Pennines." (King, 1969).

The dating of the fault systems bounding the Alston Block is somewhat problematical as cited by Atkinson (1968) and discussed in detail by Maling (1955). Trotter views the dating of these faults as Tertiary

(Trotter, 1953, 1954) whereas Wells and Kirkaldy (1948, 1957) and Dunham (1952) regard them as more probably Hercynian in age.

The Alston Block is therefore the northern portion of the Pennine escarpment with the scarp face in the west overlooking the Vale of Eden and the dip slope (dipping at 130' per mile) falling away to the east. Underlying this is a granitic mass (Weardale Granite) overlain by 2,000' or more of Carboniferous strata. Both the granitic mass and the Carboniferous strata have been metamorphosed along the lines of mineral veins which are extensive in the Alston Block. These mineral veins, containing primarily lead, silverand fluorspar are considered to be associated with a further granitic mass intruded below the Weardale granite at some time since the Carboniferous deposits were laid down. Much of the evidence for this dating comes from the study of these Carboniferous strata which are discussed below.

2.2 Geology: Rock Type

The simple statement that the area is an upland valley developed in relatively undeformed strata of the Upper and Middle Limestone Groups of the Carboniferous, belies the variability of these groups. It is clear that these relatively undeformed strata are part of an area of mineralisation associated with a Hercynian intrusion of granite at depth and minor faulting resulting from this. This latter statement fails to convey the effects of local metamorphism on an already variable rock sequence. The variations of metamorphic action within each aureole and the large number of individual intrusions of mineral veins further add to the variability of the lithology. In total this area provides a suite of sediment types varying from the coarse millstone grits of deltaic deposition to the fine calcareous shales and limestones developed from marine sedimentation. Intrusions provide a dimension of variability in the resistances of all these sediment types (depending on the local effects of mineralisation) and also introduce quartz-dolerite into the area.

The map of Upper Weardale showing a simplified Geology (Fig. 2.4) demonstrates clearly that the watersheds bounding the study area are developed in Upper Carboniferous strata. In Upper Weardale these are sandstone beds shown in the stratigraphic column (Fig. 2.3) and in the section shown in Figure 2.5. Sandstone beds in this context refer to inter-bedded sandstones, mudstones and shales with occasional thin limestones e.g. Upper Felltop Limestone (see Fig. 2.3) and one extremely thin coal seam (Coalcleugh Coal, see Fig. 2.3). These strata are shown both in the stratigraphic column (Fig. 2.3) and in the section (Fig. 2.5) the latter indicating their relationship to the topography.

Figure 2.4 shows that the Lower Carboniferous strata outcrop mainly in the valley sides and it is within these areas that most of the deposits of boulder-clay have been mapped. The broad watershed areas developed on sandstones and shales are areas where superficial deposits have not been recorded on maps.

It is generally agreed (Wells and Kirkaldy, 1959, Smailes, 1960) that the earliest Carboniferous strata were laid down in the areas immediately north and south of the Alston Block and the stratagraphic record here begins in the later stages of the Lower Carboniferous with the cyclic deposition of the Yoredale series (see Figure 2.6). However, during this depositional phase the rocks laid down do not reach the

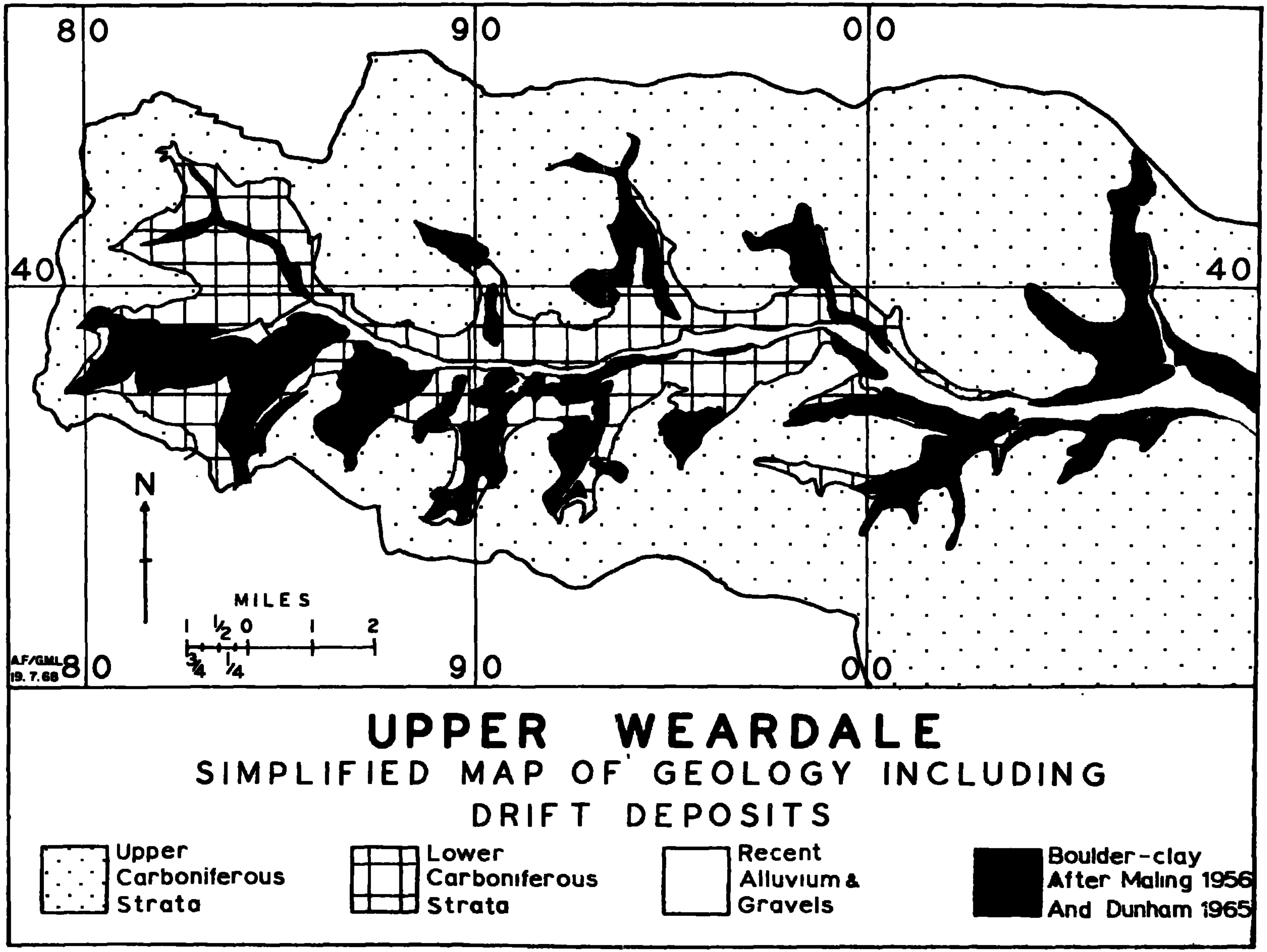

80
90
00
40
40
N
MILES
1 ½ 0 1 2
¾ ¼
A.F/GML
19.7.68
80
90
00
UPPER WEARDALE
SIMPLIFIED MAP OF GEOLOGY INCLUDING
DRIFT DEPOSITS
Upper Carboniferous Strata
Lower Carboniferous Strata
Recent Alluvium & Gravels
Boulder-clay After Maling 1956 And Dunham 1965

Figure 2.4

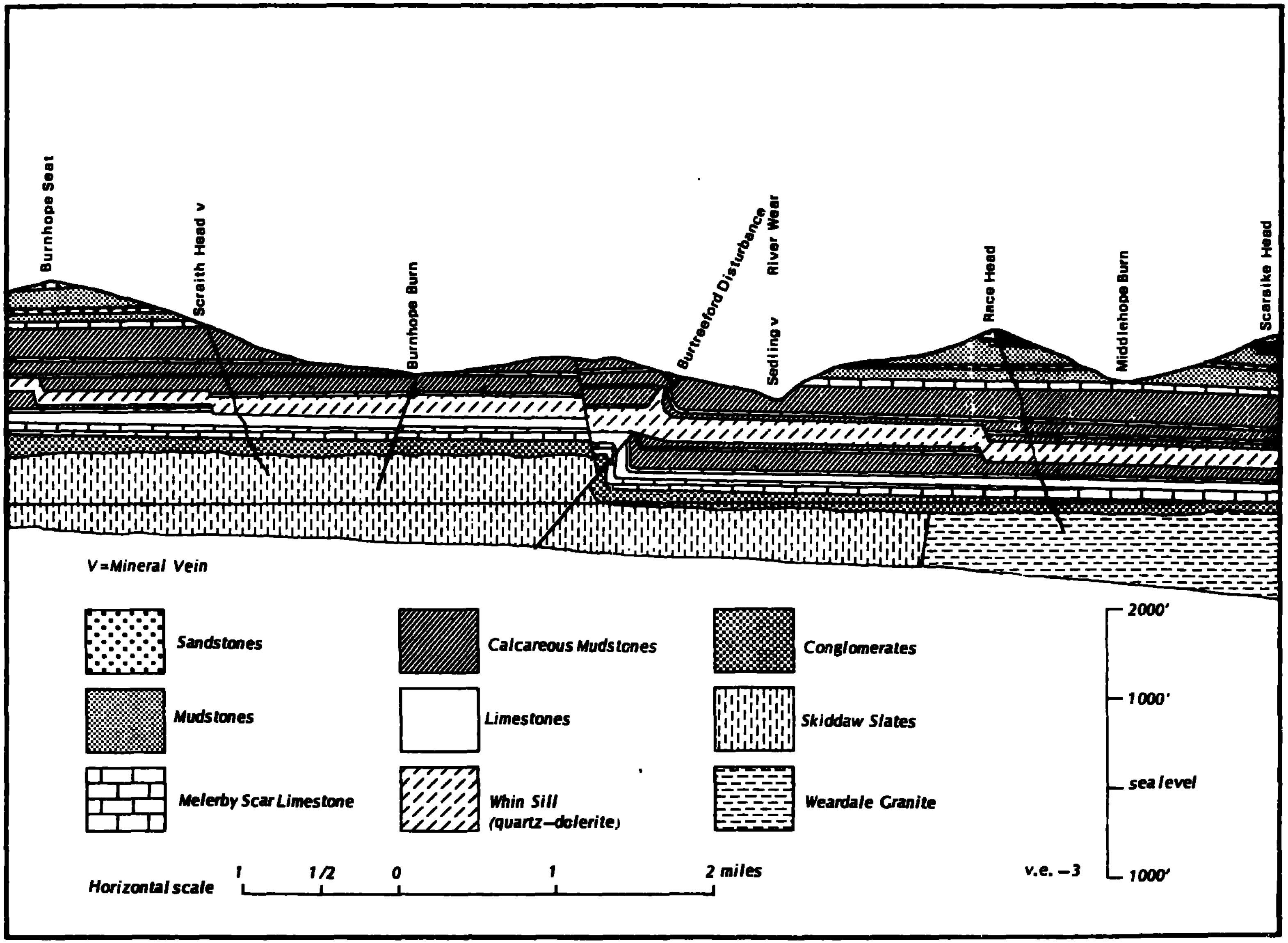


Figure 2.5 (part 1) Geological Section Burnhope Seat to Scarsike Head (based on G.S. sheet 25)

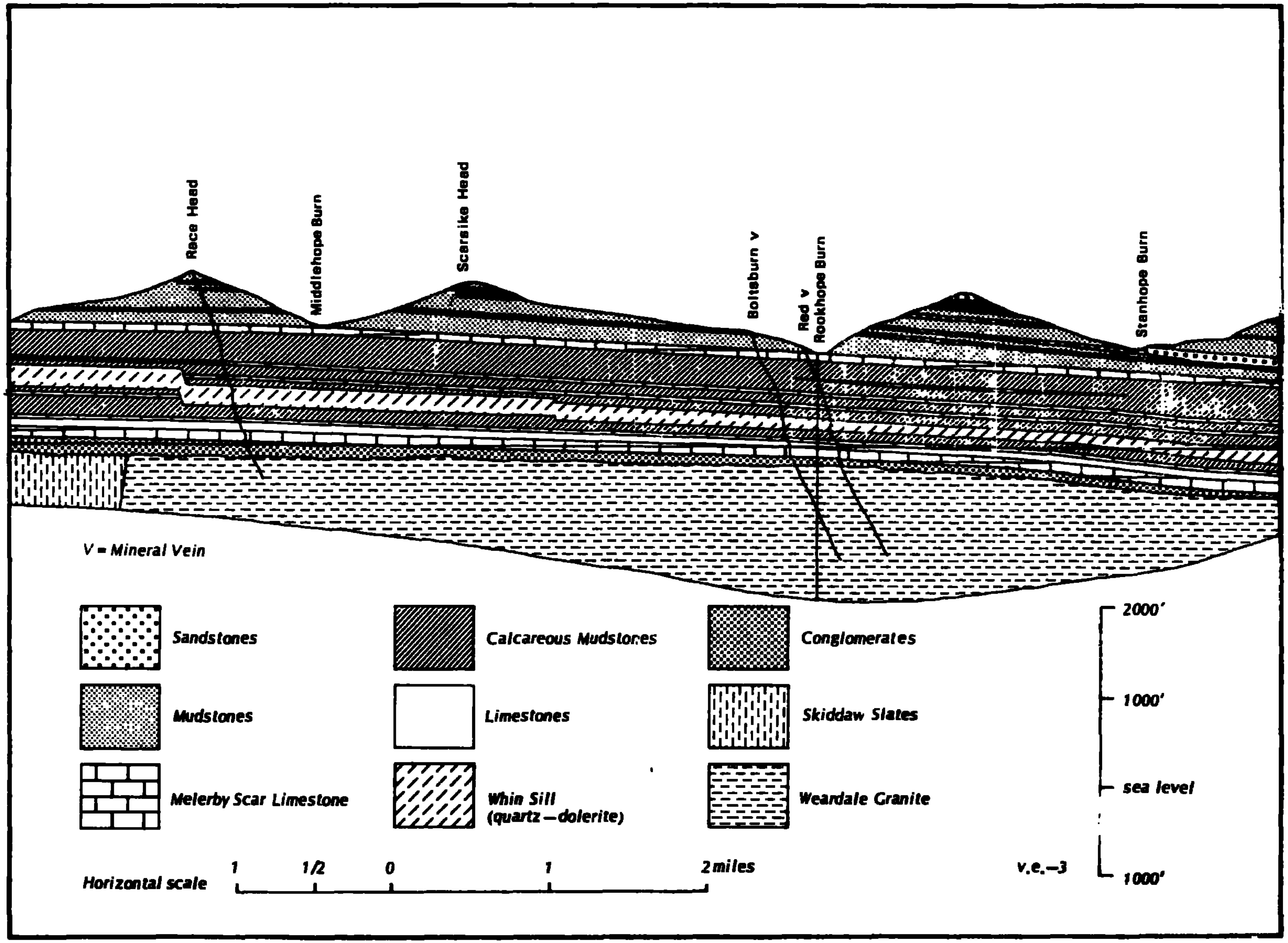


Figure 2.5 (part 2) Geological Section Scarsike Head to Stanhope Burn
(Based on G.S. sheet 25)

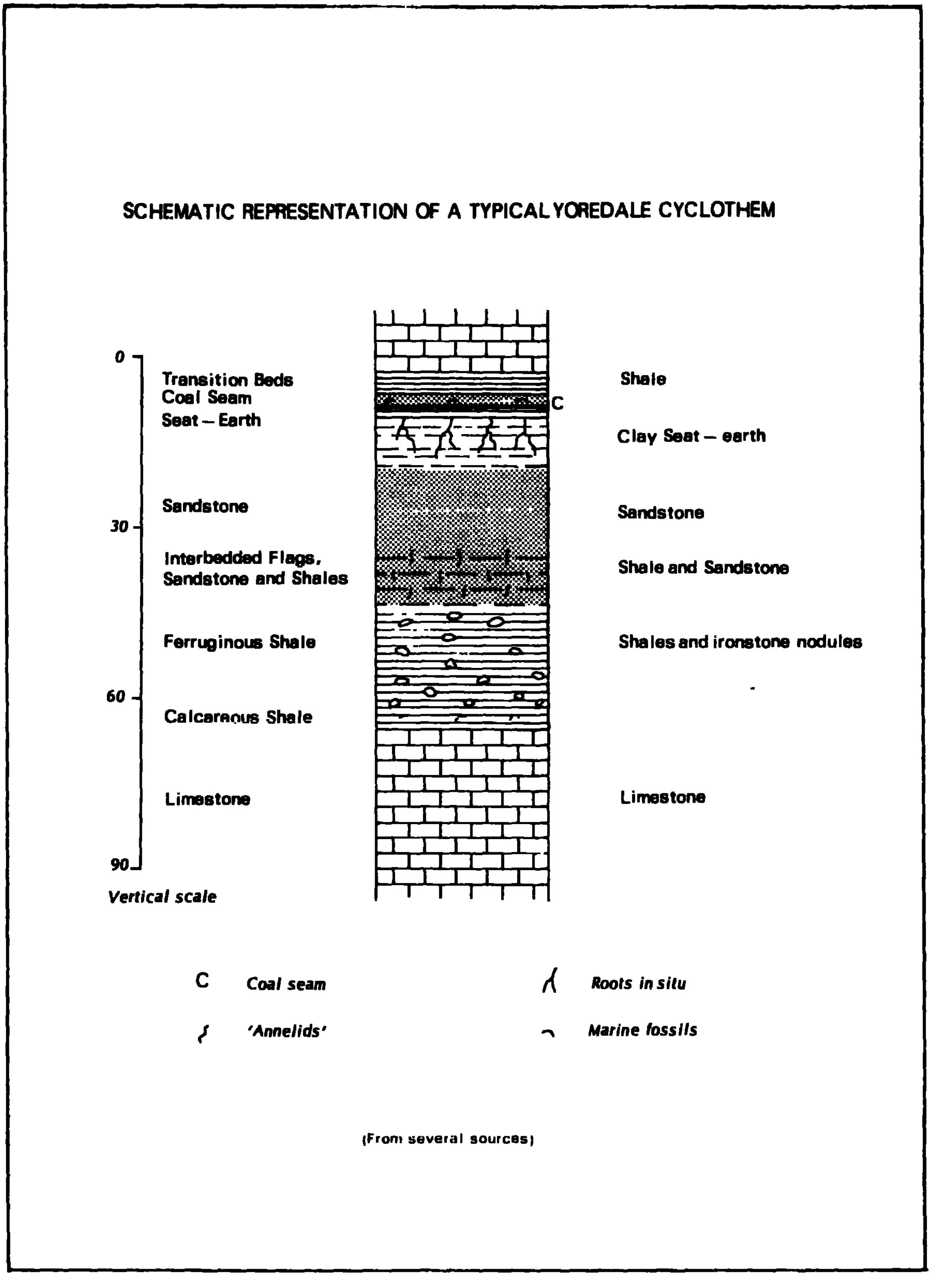

SCHEMATIC REPRESENTATION OF A TYPICAL YOREDALE CYCLOTHEM
0
Transition Beds
Coal Seam
Seat – Earth
Sandstone
30
Interbedded Flags,
Sandstone and Shales
Ferruginous Shale
60
Calcareous Shale
Limestone
90
Vertical scale
C
Shale
Clay Seat – earth
Sandstone
Shale and Sandstone
Shales and ironstone nodules
Limestone
C Coal seam
'Annelids'
Roots in situ
Marine fossils
(From several sources)

Figure 2.6

thickness found in the areas to the north and the south.

The nature of the rocks of the Yoredale series require little comment. Figure 2.6 indicates the typical succession of the rock type and in detail the limestones are dark-blue in colour, finely grained and thinly bedded. Johnson (1963) describes them in greater detail and states that they are formed of a calcite mudstone in which organic matter occurs as a dark pigment. The shales occurring within the Yoredale Series are usually dark-grey hard, well-bedded and highly fossiliferous. Overlying these (see Fig. 2.6) are ferruginous shales (shales with ironstone nodules) grading upwards into sandstones. Sandstones in Weardale in both the Upper and Lower Carboniferous strata are either white or brown rocks, with sub-angular quartz grains 0.3-0.1 mm. in diameter. Butterfield (1940) published a study in which he described their composition as quartz, feldspar, mica and with occasional calcareous or ferruginous inclusions.

Whilst the Alston Block is a relatively stable massif it is, nevertheless fractured and faulted. Within the area of study only the Burtreeford Fault causes any significant disruption of the strata and associated with this is the quartz-dolerite intrusion at Copt Hill (Grid ref. 853408). Quartz-dolerite is again exposed in the vicinity of Eastgate (953384) here underlying the Three-Yard limestone. These outcrops are more extensive than the exposure at Copt Hill and are quarried for road metal. At this point in the valley the more resistant nature of the quartz-dolerite sill ("Little Whin Sill") and its associated metamorphic aureole, result in a steepening of the valley bluffs giving the river a more clearly defined flood plain.

2.3 Conclusion

Such a geological composition forms a complex source area for a glacially produced till because of the varied lithology. In Upper Weardale we have a sequence of limestones, sandstones and shales complicated by the presence of an igneous intrusion and extensive mineralisation. The metamorphism associated with each mineral vein and the variations thus introduced into the composition of the shales and sandstones make the situation more complex.

The absence of a coherent theory of glacial deposit genesis from which to construct the characteristics of a "till" derived from bedrock of this type means that there is no simple way to define the characteristics of a till produced in this area. This lack of a rigorous model from which to predict the results of the processes acting is commonly encountered in scientific investigation and leads to the types of geomorphological argument discussed by King (1966); argument developed by the inductive method and argument developed by the deductive method. In this case deduction is difficult as the framework required - a detailed knowledge of till genesis - does not exist. Induction is the major approach remaining and is adopted in the succeeding chapters.

Chapter 3

Upper Weardale: Development and Morphology

The eastward flowing drainage in this region has been ascribed to a relief developed on a cover of chalk, removed without trace leaving Linton's (1964) sub-Cennomanian surface on which the eastward flowing drainage was superimposed. A more recent study by Sissons (1960) suggests the area is primarily the product of Tertiary earth-movements and Pliocene marine platforms. Work based on a system of formline mapping, led Sissons (1960) to conclude that there was considerable evidence for post-Tertiary submergence of the area and its emergence from the Pliocene sea, giving a series of marine erosion surfaces and elongated rivers. King (1963) has demonstrated that several of these surfaces do not meet the criteria, established elsewhere, for marine erosion surfaces and doubts that this explanation is now completely satisfactory.

In more recent work making use of trend-surface mapping, King's (1969) analysis of summit surfaces in this area shows a close correspondence between the contours of the Great Limestone and the existing surface. The pattern of drainage developed on the surface perpendicular to the trend lines together with apparent warping of the present surface and the underlying Limestone suggest that a single erosion surface has been warped rather than a series of gradients established with differing base levels. King therefore concludes that Trotter's (1929) suggestion that the area is an uplifted and warped erosion surface is supported by her work because she finds no evidence to support the concept of cyclical erosion with differing base levels. It seems therefore, that the pre-glacial development of this area was the sub-aerial erosion of a surface inclined towards the east. This surface, increasing its elevation as the granite mass intruded at depth became stable (Bott, 1967), would become warped and uplifted as suggested by Trotter (1929) and King (1969). Dating of these events must remain in doubt but certainly is pre-Pleistocene and post-Tertiary (Trotter, 1953, 1954) or post-Hercynian (Dunham, 1952).

It was onto this surface that the glaciers of the Pleistocene advanced. The glacial history for Britain indicates that Upper Weardale fell within the limits of the Saale and Weichselian glaciation of the British Isles (West, 1968). Evidence from the adjacent areas (Dwerryhouse, 1902, Trotter, 1929, Raistrick, 1931, Peel, 1949, Maling, 1955, Wright, 1955, Beaumont, 1967, Vincent, 1969) indicates that ice has indeed been present probably on at least two separate occasions. The absence of any section in the superficial materials of Upper Weardale demonstrating two or more ~~till~~ different tills means that at present there is no conclusive evidence for multiple glaciation of the valley. This must therefore, remain a speculation. Francis working in the Middle Wear lowlands finds no evidence of multiple glaciation (cited in Beaumont, 1968) and indeed, all previous workers have been equally unable to confirm the hypothesis of multiple glaciation of Weardale.

3.1 Glacial action in Upper Weardale

Early work on the glaciation of the Alston Block was concerned especially with the distribution of erratics. Eastwood's summary map of erratic distribution provides an excellent synthesis of these data. This map is reproduced as Figure 3.1. Dwerryhouse's early summary of erratic distribution (1902) appears to be the ultimate source for much of the information. Beaumont's redrawing of Raistrick's map of ice movement during the glaciation of Northumberland and Durham provides a concise summary of supposed ice movements in Northumberland and Durham (see Fig. 3.2).

Dwerryhouse's conclusions about the distribution of ice and the postulated directions of movement provide a basis for a more detailed examination of the glacial geomorphology of Weardale. His map and conclusions are redrawn onto the Upper Weardale base map and presented as Figure 3.3. Obviously his conclusions were influenced by the present topography. However, his important conclusions appear to be that the watershed areas remained ice-free and that ice action produced the blue boulder-clay of Weardale. The latter contention is supported by observed striae (see Figs. 3.3 and 3.4) as recorded by Dwerryhouse and stone orientation data assembled by the present author and by Atkinson(1968). Figure 3.4, a composite map of striae, stone orientations and the trend of interfluves within the valley indicates the generally preferred trend of both topography and evidence of glacial action. On this basis alone it would seem reasonable to contend that an easterly flowing ice mass had occupied the Wear valley.

Dwerryhouse described the glacial deposit of Weardale as a stiff blue boulder clay and Atkinson further amplified this description in his work stating

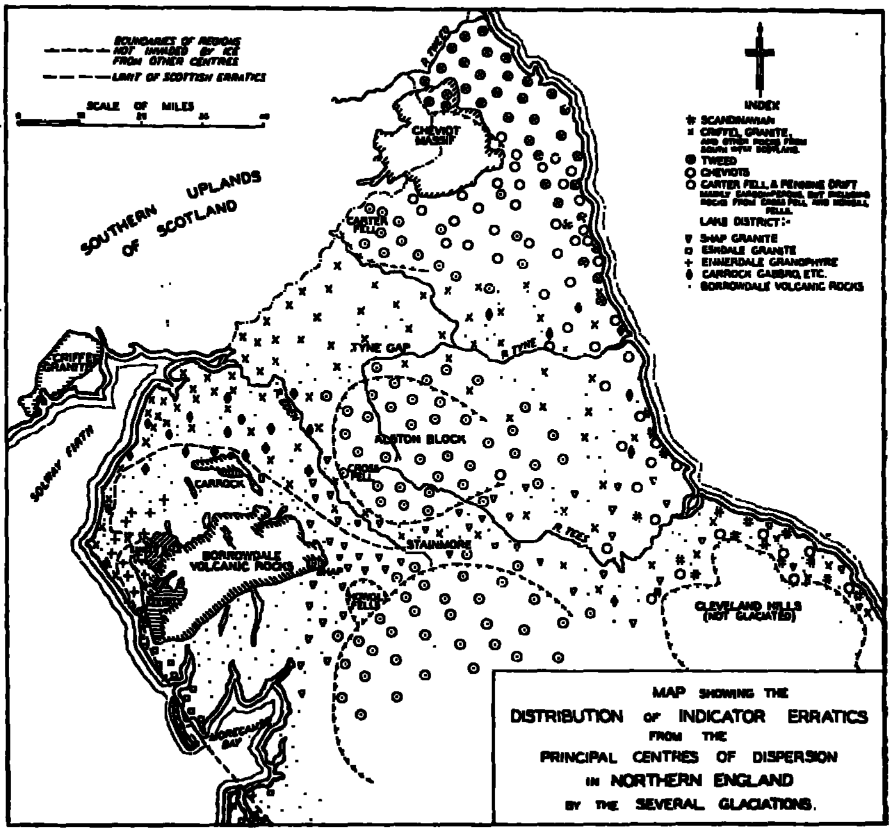


Figure 3.1 (after Eastwood 1953; British Regional Geology)

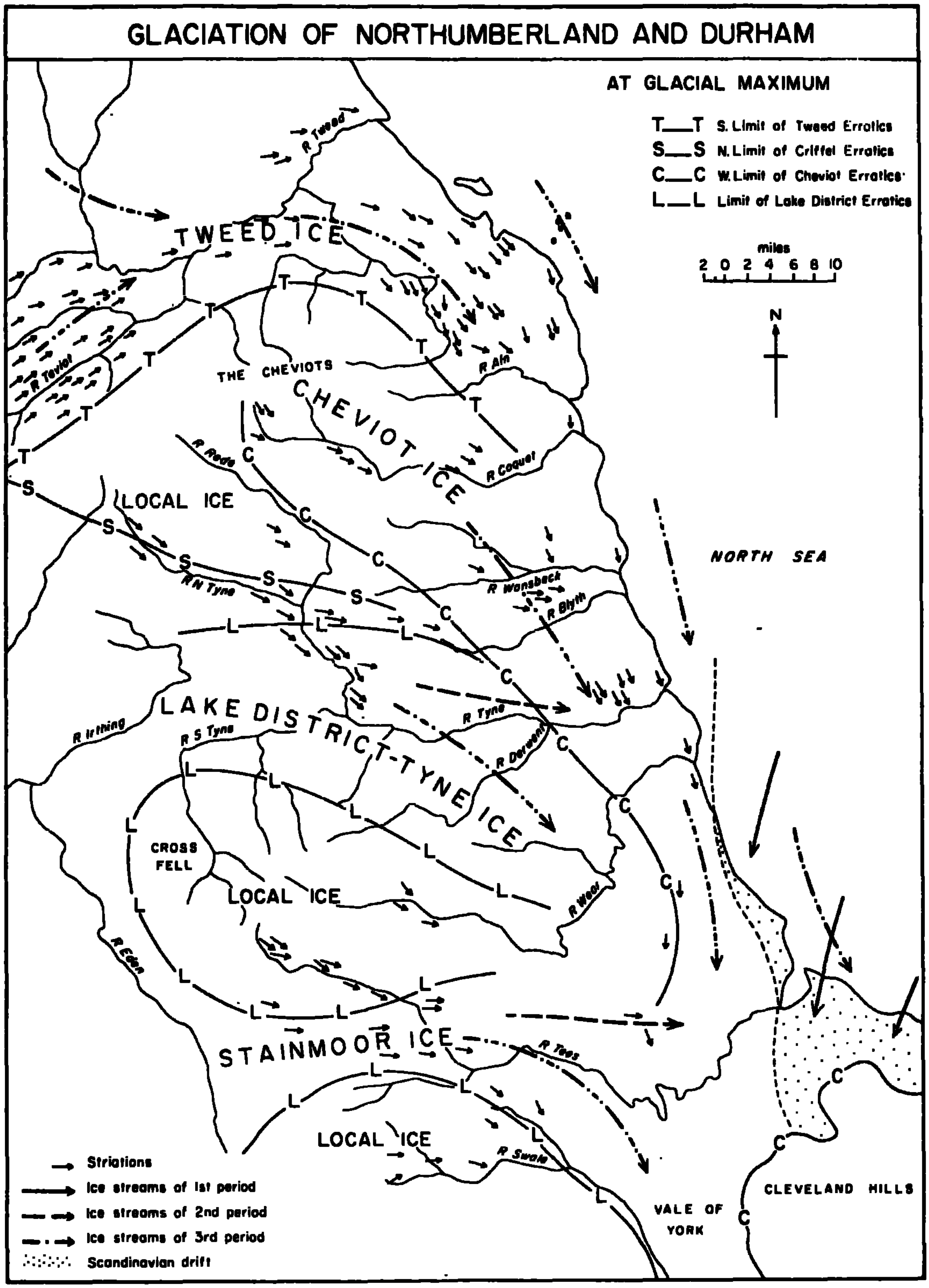
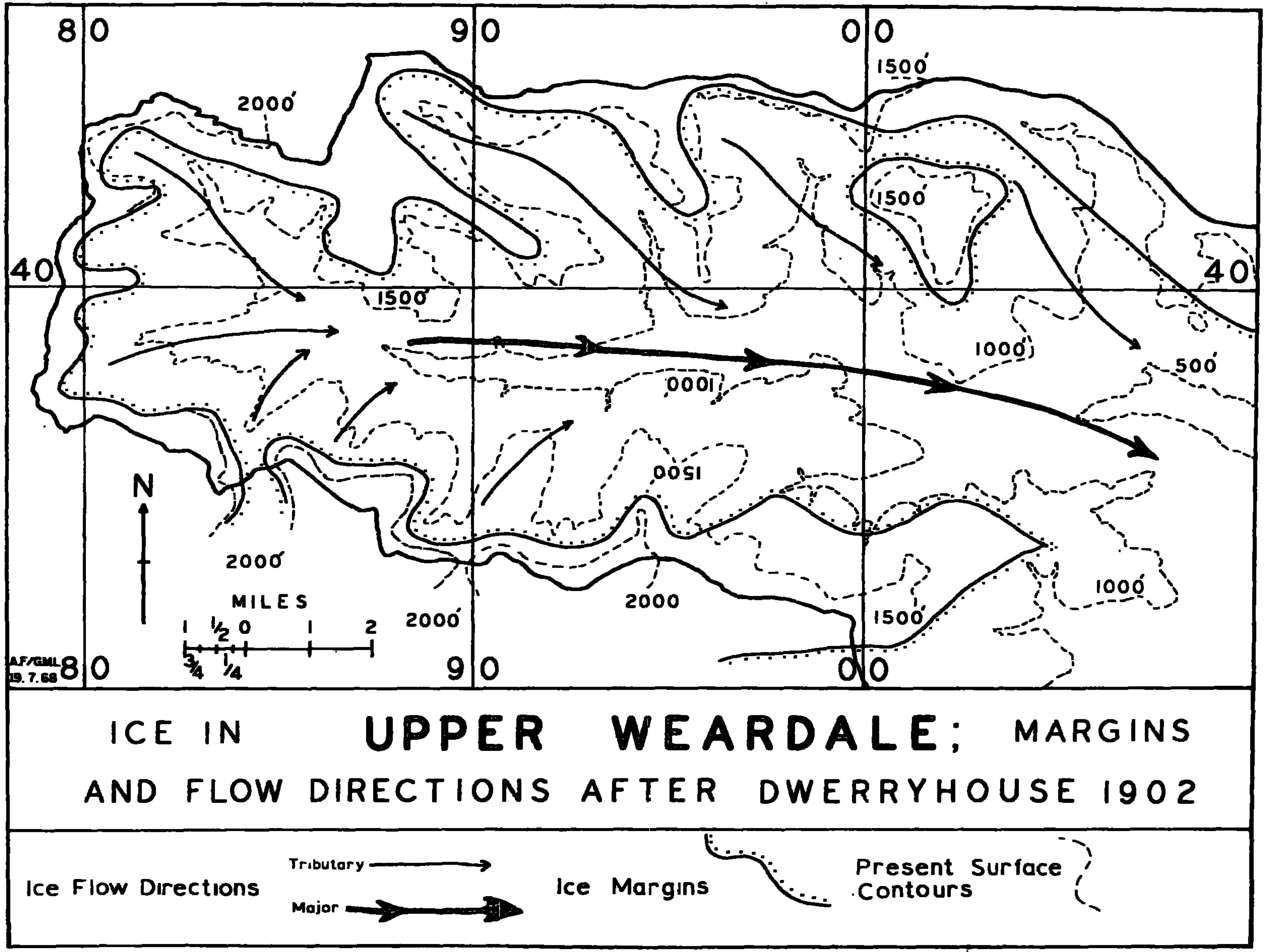
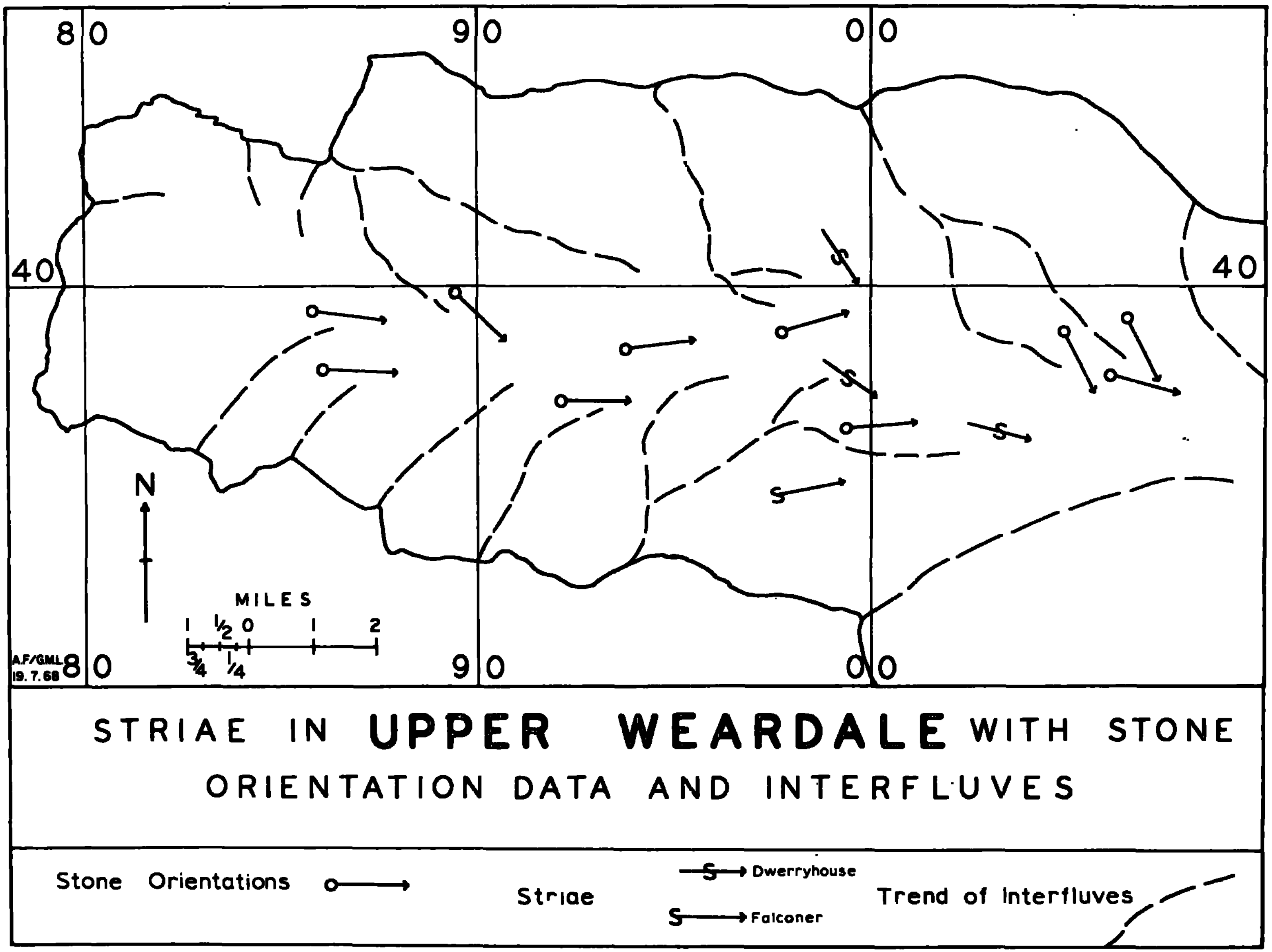

GLACIATION OF NORTHUMBERLAND AND DURHAM
AT GLACIAL MAXIMUM
T—T S. Limit of Tweed Erratics
S—S N. Limit of Criffel Erratics
C—C W. Limit of Cheviot Erratics
L—L Limit of Lake District Erratics
miles
2 0 2 4 6 8 10
N
R Tweed
TWEED ICE
R Teviot
THE CHEVIOTS
R Aln
CHEVIOT ICE
R Rede
R Coquet
LOCAL ICE
NORTH SEA
R N Tyne
R Wansbeck
R Blyth
LAKE DISTRICT-TYNE ICE
R Irthing
R S Tyne
R Tyne
R Derwent
CROSS FELL
LOCAL ICE
R Wear
R Eden
STAINMOOR ICE
R Tees
LOCAL ICE
R Swale
CLEVELAND HILLS
VALE OF YORK
Striations
Ice streams of 1st period
Ice streams of 2nd period
Ice streams of 3rd period
Scandinavian drift

Figure 3.2



80
90
00
40
2000'
1500'
1000'
500'
1000
1500
2000
N
MILES
1 ½ 0 1 2
¾ ¼
AF/GML 19.7.68
ICE IN UPPER WEARDALE; MARGINS AND FLOW DIRECTIONS AFTER DWERRYHOUSE 1902
Ice Flow Directions
Tributary
Major
Ice Margins
Present Surface Contours

Figure 3.3



STRIAE IN **UPPER WEARDALE** WITH STONE ORIENTATION DATA AND INTERFLUVES

Figure 3.4

> "It (the till) is a bluish grey in colour (5b5/1) with reddish blotching around included stones and root channels. It has the evocative description 'Blue Joss' from the local dalesfolk. Its structure is generally massive, becoming prismatic on dehydration." (Atkinson, 1968).

Maps of the distribution of this material in Weardale are limited to the map folio of Maling's thesis (1955) and the section of the area within the 1965 redrawing of the Alston sheet of the Geological Survey map (Dunham, 1965). Combining this information with the boundaries of the ice free zones postulated by Dwerryhouse (1902) gives an indication of the irregular deposition of till by the ice sheet which created the striae. Smailes' comment on the protective role of glaciation in this area would seem to be especially pertinent as the valley slopes show little sign of the distinctive features of erosion by ~~Alpine~~ valley glaciers.

The elevation of this area (2,452' in the west and 441' in the east) would seem to be the major reason for the absence of the craggy features found in the Lake District in areas of elevation of 3,000' +. This can be attributed to the differences in precipitation resulting from the differences in elevation, which during the Pleistocene would be reflected in the ability of the Lake District to nourish more vigorous valley glaciers. Manley (1955) considers the climate and snow accumulation in greater detail and his conclusions are the basis for this comment. Upper Weardale certainly offers no evidence of forms associated with vigorous glacial erosion although the valley sides have a pronounced series of benches. Atkinson comments on these (1968) stating that

> "Long and continuous slope facets are rare, the dominant topographic pattern being one of rock controlled benches and scarps producing a stepped effect in cross valley profiles."

The association of these benches and scarps with certain of the rock types, neatly tabulated by Atkinson, is striking. It is tempting to give these benches greater significance as lateral drainage channels but no sedimentological data support this and morphological data in this region are reduced in value because of the comparatively low resistance to erosion of some of the rock types. If such channels were indeed cut by meltwater their characteristics have been long changed by the down-slope migration of disintegrating rock debris.

The benches themselves must have been modified by the existence of ice in Weardale but evidence of this is submerged in the mantle of hillslope and glacial debris found within the area. Morphology is of only limited value in interpreting the sequence of deposits as is clearly illustrated in the case of Parson Byers quarry. Figure 3.5 shows the detail of three sections in the quarry on opposite sides of a valley and a ridge crest. This sequence of sections was particularly disturbing in that there was no topographic evidence of the dramatic change from the surface developed on disintegrating bedrock (section 1) to that developed over a clay with stones which has the attributes of the till described by other workers. The third section (section 3), a thin layer (5') of material overlying limestone (similar to the slope deposit described by Atkinson) was again undifferentiated from the former two by topographic features.

Glacial action in Upper Weardale is therefore, only evidenced

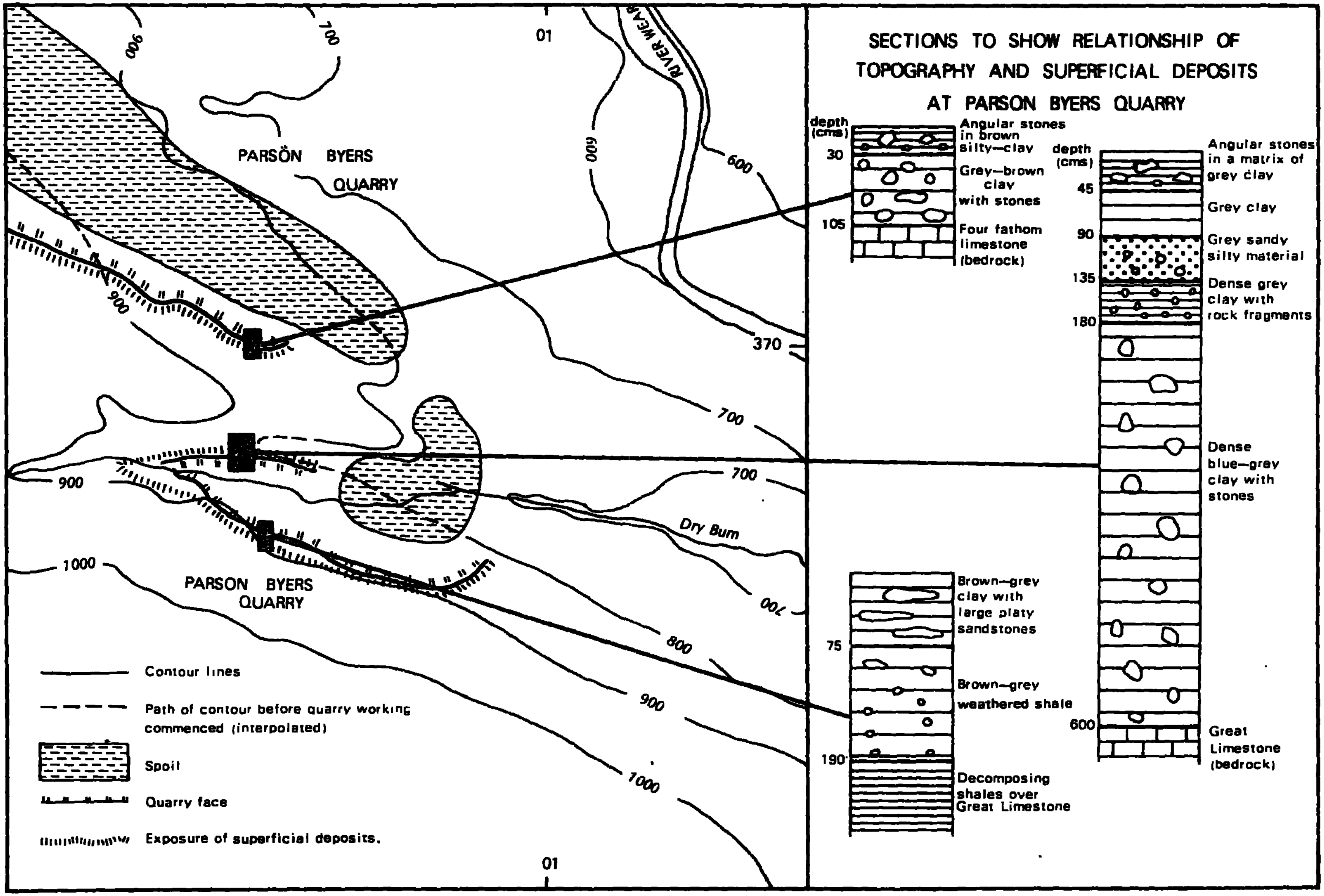

SECTIONS TO SHOW RELATIONSHIP OF TOPOGRAPHY AND SUPERFICIAL DEPOSITS AT PARSON BYERS QUARRY
PARSÖN BYERS QUARRY
PARSON BYERS QUARRY
RIVER WEAR
Dry Burn
01
900
700
600
370
800
1000
depth (cms)
30
105
Angular stones in brown silty—clay
Grey—brown clay with stones
Four fathom limestone (bedrock)
45
90
135
180
600
Angular stones in a matrix of grey clay
Grey clay
Grey sandy silty material
Dense grey clay with rock fragments
Dense blue—grey clay with stones
Great Limestone (bedrock)
75
190
Brown—grey clay with large platy sandstones
Brown—grey weathered shale
Decomposing shales over Great Limestone
Contour lines
Path of contour before quarry working commenced (interpolated)
Spoil
Quarry face
Exposure of superficial deposits.

Figure 3.5

by the deposits of till and the existence of striations. Characteristic landform associations of glaciated areas are not evident and within the main valley there are no terminal moraines or similar major features.

3.2 Late-Glacial and Post-Glacial Action in Upper Weardale

The characteristics of the surface layers of material in many parts of Weardale attest the action of frost in their development. Atkinson cites examples of cryoturbation, solifluxion and seasonal pipkrakes in his description of the superficial deposits and frost-wedges can frequently be found together with stones having the characteristic cutanic sheathing of rocks in areas of intense frost action.

In total the Late- and Post-Glacial era in Weardale must have been one of intense periglacial climate with permafrost having a con- (no evidence for this) siderable effect on the character of the clay rich rock strata. Mass wasting and hill wash must at this stage have been active in the production of the typically stratified hillslope material with a layer of large stones found about 1' below the surface.

Nivation processes may have been particularly active and they too would contribute significantly to the deterioration of any bedrock appearing at the surface. In total it would be surprising if a mantle of any debris could exist unaltered through this time. Even the deposits of till themselves may have undergone considerable modification except in the areas of deepest deposition. Superficial features have necessarily been modified to some degree by subsequent processes, leaving the present landscape with a generally rounded topography. It may be best summarized as a landscape moulded by processes acting in unison. The gentle eastward dip of the rock strata together with the eastward movement of the ice mass in a previous era produced no landform which impeded the drainage from the ice mass during deglacierization. The periglacial processes of solifluction and subsequent mass wasting and colluviation would act ultimately to move detritus eastward under the influence of gravity, in harmony with the more rapidly acting processes of sheet wash and stream transport.

Changes in the intensity of these process with the change in prevailing climate since the retreat of the ice have been suggested by Atkinson in a table of "Glacial and Post-Glacial Chronology" (Atkinson, 1968, Table 4). This table suggests a period of cryoturbation followed by a period of intense nivation activity. These phases are dated as Zones I and II of Godwin's Post-Glacial history for the first major period of cryoturbation, Zone III for the nivation activity and Zone IV for a second period of cryoturbation.

The formation of birch forest in Zones V and VI followed by peat formation in Zone VII suggest a period during which fluvial erosion must have been considerably enhanced. Any glacial deposit within this region accordingly has a complex history. It would be surprising indeed if Atkinson were to assert other than that, "It is extremely difficult to map the boundaries of regolith, solifluction deposits and till ..." (Atkinson, 1968, p. 59).

3.3 Morphology and Morphometry

Standard techniques of morphometry have been applied to this area by Atkinson (1968) and although such measures are useful in a general description of the area their use as a tool for landscape evaluation is limited. Maling's work offers an interesting use of morphometric data particularly in the production of the graph showing mean dissection per square kilometer for the Alston Block. This illustrates clearly the greater dissection of the land of 2,000'+. It is perhaps easier to consider this as the height difference between the monadnocks and the 2,100'-2,400' erosion level recognised by Maling (1955). King also supports this view with her trend surface analysis of the Alston Block clearly showing a surface at 2,000'+ in the western area with positive residuals from the surface confirming Trotter's contention that there are monadnock areas rising above the summit surface.

Streamlined forms exist as hogs back ridges or rounded drainage divides throughout the valley. These are the features shown in Figure 3.4 as the trend of interfluves and with the associated orientation and striae data they provide an indication of landforming processes. However, further evidence of the micro morphology of ice dispersion or accumulation or even glacio-fluvial deposition is lacking. In a valley of this nature valley trains of erratics, moraines or outwash might reasonably be expected. Early field observation of morphology and attempts to map the features within Upper Weardale were abandoned. Atkinson neatly summarises the difficulties encountered by citing spoil as one of the classes of soil parent material. Extensive quarrying, lead mining and re-working of spoil heaps for fluorspar has given human activity a greater than usual role in the creation of the present landscape. When such areas are abandoned for periods of a half century or more it is difficult to determine the precise limits of the disturbance.

Reference to Atkinson's map of the slope facets in Upper Weardale shows that the steeper slopes are associated with the actual bluffs of the Wear floodplain in the area around Ireshopeburn. On the southern side of the valley there are steeper slopes in the tributary valleys of Swinehope and Westernhope Burns. The morphometric analysis of this area both by Atkinson (1968, Fig. 10) and Maling (1955, Table 6) indicates only the existence of "levels" at 2,000'-2,400', 1,700'-1,800', 1,250'-1,320'. The latter level is apparent only in Atkinson's area-height graph.

Morphology and morphometry, therefore, appear to be of only limited value in the detailed investigation of the area. It is considered that Atkinson's comment on the possibility of spoil providing misleading landforms is particularly important as a background to any evaluation of morphology in Weardale.

> "Human activity in the form of mining and quarrying has a long history in the Upper dale (Dunham, 1948; Raistrick, 1932). An important pedogenic result is the production of completely man-made topographic forms (tips, fans, embankments etc.) which since the cessation of mining have become the site of renewed pedogenesis. The extent of such relics in the area is truly remarkable ... and without a completely documented record for economic activity, the chances of gross geomorphic misinterpretation would be high and not a little amusing."
>
> (Atkinson, 1968, p. 64)

The present author is in complete agreement with this point and considers the complexity of the Upper Weardale landscape to be too great for evaluation by the more traditional techniques. Sediment analyses seem to offer the only valid way to reach a detailed understanding of the area and the next chapter considers these points in more detail.

Chapter 4

Field Investigation

4.1 Field Mapping

During the initial work in this area attempts to classify landform regions and map glacial features were entirely unsatisfactory for reasons given above (see Chapter 3.3). Examination of deposits exposed in quarry sections, stream banks and newly made road excavations produced the increasing suspicion that earlier maps of glacial till were based primarily on formline mapping. The dangers inherent in this procedure were demonstrated in Figure 3.5.

Maling's map of boulder-clay was of considerable use in indicating areas for investigation and, although the boundaries given are not in any way the defined boundaries between distinct classes of superficial material they provide an essential basis for the work undertaken. The inspection of deposits at this stage provided an impression of the material within the region although considerable difficulty was experienced in attempting to attach definitive names to the deposits in the field. This was the first encounter with the problem commented on by Atkinson in his statement of the problems of mapping regolith, solifluction deposits, and till.

Criticism of the Geological Survey maps by Maling (1955) would seem for the most part to be valid. Over much of the area solid rock is near the surface but the drift varies considerably in depth over very short distances. An example of this variation in drift thickness was demonstrated in the case of Parson Byers Quarry (see above, Fig. 3.5).

In this quarry the south side of the excavation shows virtually no superficial material. The shales overlying the limestone in this case have decomposed to give a clay deposit which appears to be the parent material from which the soil developed. The north side of the quarry has a thickness of glacial till in excess of 30' in certain places. A second quarry immediately north of this - some 200 yards away exposes in its south face a thickness of superficial deposit which is not in excess of 5'. The material here is brown in colour and similar to the rotted shale found on the southern face of Parson Byers quarry.

Parson Byers quarry is oriented E-W and has exploited the valley of an Eastward flowing stream. At the western end of this quarry the superficial deposits consist of large angular stones overlain by the grey-silty deposit typically found on the higher slopes of the valley side. An important point here is that, although the quarry cuts into the solid rock, the topography of the area does not appear to change from topography which has developed in areas overlain by drift.

The view to the west of the quarry, which is presumably an undisturbed area, reveals no topographic criteria for distinguishing landform zones. The quarry cutting into this reveals that the topography north of the stream is a moulded drift or boulder clay and to the south of the stream the landforms are developed over solid rock. In every case the topography is moulded and rounded appearing as a series of gentle swellings in the valley side separated by shallow valleys. Davis would undoubtedly have classified this landscape as "mature". There is little doubt that this topography is similar to that described by Ragg and Bibby (1966) and Tivy (1962) in their work which is centred on the study of slope deposits in upland areas.

4.2 Upland Deposits

Ragg and Bibby (1966) in the introduction to their paper indicate how poorly documented are the deposits of upland regions. The important point in the introduction to their paper is the statement,

> "The main subject of this paper is the nature and distribution of the deposits above 600m which are vertically sorted and provide the raw material of the solifluction deposits below. (i.e. at lower elevations). Between 450 and 600m there are materials of indeterminate nature."

They also state,

> "Deposits of this type at lower altitudes (450) in Southern Scotland correlate with 'head', the term used in England for crudely stratified unsorted solifluction debris (Dines et al 1940)."

The deposits referred to are of deep stony "regolith".

Ragg and Bibby have certainly highlighted one of the major fields requiring detailed investigation. It is no longer sufficient to dismiss the superficial deposits of a large area as "regolith". Physical geography has long paid lip-service to the existence of hill-creep and solifluction as major types of erosion and transportation process but the detailed consideration of the effects of the processes in Post-Glacial times has been neglected. There are too few investigations which consider the possibility that such deposits have characteristic sediment parameters. It is important to consider that upland hill-slope deposits may have a polygenetic character, having in some part characteristics of the parent rock, and characteristics attributed to the processes of cryoturbation. Glacial processing of rock may also produce a veneer of debris on the hillslope which subsequently becomes incorporated into the hillslope material thus complicating the understanding of the genesis of these materials.

Upper Weardale meets the criteria, laid down in Ragg and Bibby's work, defining their area of slope deposit. Upper Weardale is in certain areas above 600m (the area of prime concern in their work) and for the most part it lies between 450 and 600m (zone of materials of "indeterminate nature" - Ragg and Bibby, 1966). Points below 450m in the upper reaches of the dale can be classified as "valley floor" although such an altitudinal classification does include some steep slopes adjacent to the river flood plain. Progressing eastwards the 450m contour effectively delimits the high land which forms the broad rounded watershed area. The similarities between Upper Weardale and Broad Law (Ragg and Bibby's area of study) thus prompted a consideration of the similarities between the deposits described. It was the initial impression of the present author that these deposits were in many cases very similar and the realisation of this was the basis for a decision not to attempt a map of the deposits, it being impossible to eliminate a subjective classification of materials if a satisfactory map were to be compiled from field observation. The deposits in Upper Weardale were further assessed for similarity to those on Broad Law by the author's site examination of both sets of material. Discussion with Bibby confirmed the author's opinion that this type of hillslope deposit accumulating in a valley bottom would have many of the attributes of till and may be mapped as such if it were only briefly inspected by a mapmaker. It was considered that this early introduction of the technique "classification by affirmation" (V.B. Proudfoot's terminology) was not appropriate to this study.

4.3 Types of Superficial Material in Upper Weardale

The description of categories of superficial material in Upper Weardale was necessarily an important component of Atkinson's study of pedogenesis in this region. The present author therefore attempts to consider this primary classification in the context of a geomorphological study.

Atkinson recognises three main classes of superficial deposit in Upper Weardale namely

> "1. the upland regolith on ridges and interfluval crests
>
> 2. solifluction deposits on slope flanks and valley sides
>
> 3. till and riverine alluvia in valley bottoms."

This categorisation is presented with the statement:

> "Whilst the possibilities for polymorphism are substantial and all in fact may be the present day expressions of a single genetic feature (e.g. a Saale till sheet) ; each has received distinctive fashioning in the geomorphic history, at least since Zone I and probably for much longer." (Atkinson, 1968, p. 29).

The present author has a prime interest in the polymorphic nature of these deposits and their distinctive fashioning. Evaluating each deposit type recognised by Atkinson is a considerable task in view of the many unknowns in the diagentic effects of Late- and Post-Glacial climate. Indeed geomorphology has not developed a full evaluation of the effects of different climates existing in the present day (see

Leopold, Wolman and Miller, 1964).

4.31 Upland Regolith

Definition of this material is on the basis of its stratigraphy. The typical section, is similar to those described by Ragg and Bibby (1966) and Tivy (1962). It may be simply described as a surface layer of sub-angular "rubble" in a sandy matrix, frequently of Carboniferous sandstone fragments, overlying a layer of fine sandy or silt loam containing small angular stone fragments. The lower of these layers becomes increasingly stony with depth as bedrock is approached.

Atkinson examined the stone orientation and particle size distribution of this material. In general there is found to be no preferred orientation in such deposits and a tendency for stones to be vertically aligned. The grain size curves show a typically unimodal distribution for the stone layer and a bimodal curve for the underlying finer horizon. Stratification can be attributed to the effect of winter frost causing the upheaving of the stones, leaving fines below them during the thaw period (Atkinson, 1968).

Whilst these criteria offer an excellent basis for classification of the deposits according to recently acting processes, they do not provide a basis for detailed comment on the geomorphic history of the material. The properties outlined can, of themselves, give no immediate indication of the earlier stages in the genesis of the material. The orientation of stones in such a frost worked material would be most unlikely to reflect transport by a glacier some 20,000 years previously. The evidence offered by the presence of sandstone may be interpreted either to mean that the deposit has been produced in situ, or within ice overriding a watershed - as suggested by Vincent (1969, p. 287) in certain cases of topographic control of ice movement. If Vincent's hypothesis is accepted wasting of the ice mass would leave a mantle of glacially processed bedrock on the watershed area (see Fig. 4.1). The change brought about in the bedrock by its contact with the ice can only be conjectural. The processes of glacial action are not fully enough understood to permit any clear statement of the nature of the material resulting from the types of processing which would ~~result~~ occur in this case. The deposit derived from this material could have all the attributes of the upland regolith described by Atkinson.

4.32 Solifluction Deposits on Slope Flanks and Valley Sides

Atkinson's description of this material is excellent. It is quoted here as the basis for a discussion of the most commonly occurring superficial deposit of Upper Weardale.

> "The most widespread relict of Andersson (1906) - type flowage during depergelation is a dark grey (10YR4/1) compact tenacious solifluction deposit which forms one of the most important parent materials in the Dale. It is intensely gleyed, either uniformly or in the form of ochreous mottling, and has a high content of stone-sized fragments derived from local rocks. In fact it has many of the attributes of a glacial till which has undergone considerable congeliturbation since deposition." (Atkinson, 1968, p. 47).

This material described elsewhere (Falconer, 1966) as "... a 'pudding' deposit consisting of sandstone 'currants' in a matrix of greyish silty clay ..." is very variable in its characteristics. The gleying commonly found both on the valley floor and on the adjacent

VINCENT'S MODEL OF STRONG RELIEF CONTROL ON ICE MOVEMENT AND THE RESULTING DEBRIS DISTRIBUTION

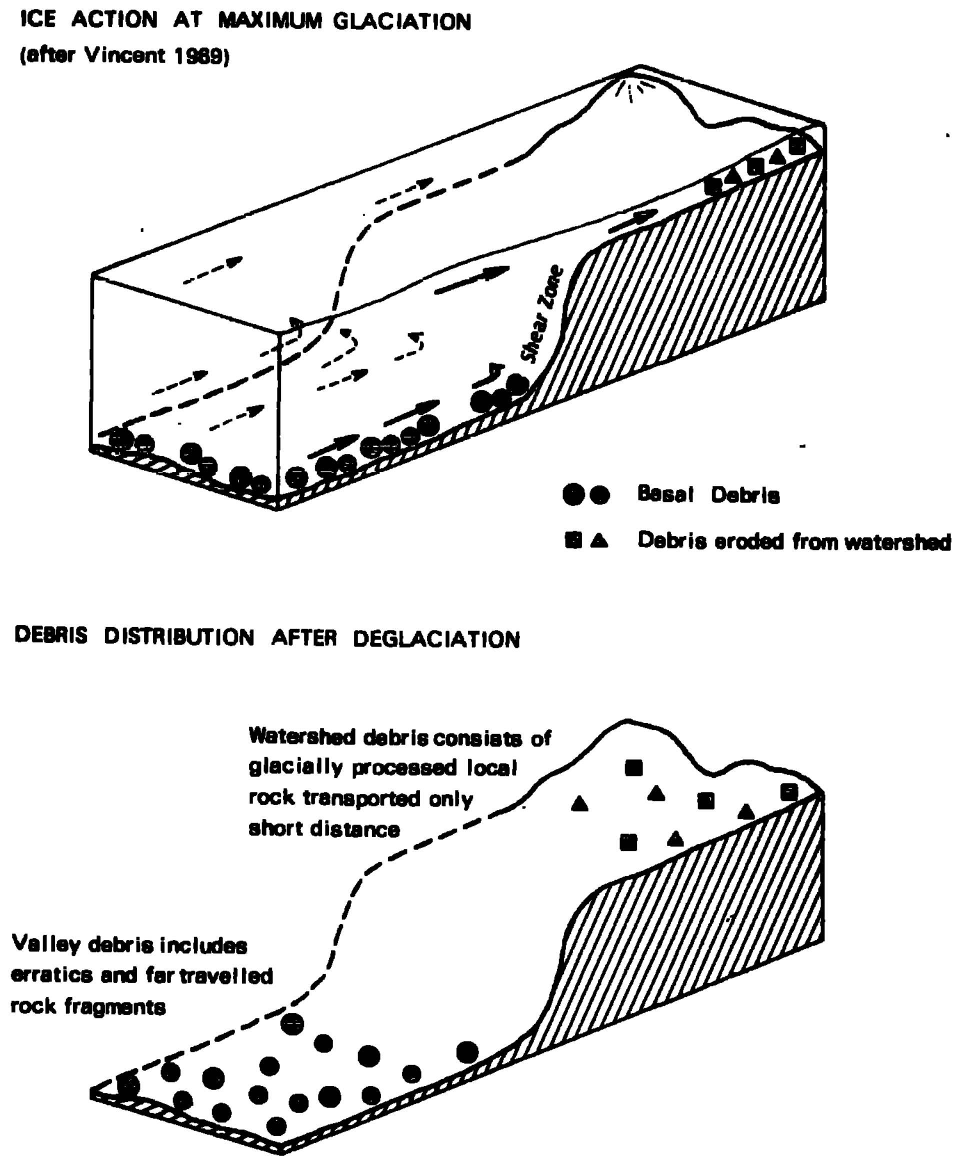


Figure 4.1

slopes gave colour changes over short distances. Certain examples of this material underlying the upland regolith in areas of very little slope posed certain problems of interpretation for the present author.

Atkinson makes some useful comments on the structure of this material stating that its general morphology indicates the importance of turbulent rather than laminar flow. That this flow existed indicates to the present author the increasing possibility that the general succession of post-Pleistocene events will not necessarily be in correct sequence in any stratigraphic section. Turbulent flow structures indicate that incorporation of material and super-position of incorporated material may take place with little control. No defined patterns need be associated with either the stratigraphy produced nor the distribution of these sites within the appropriate slope zones.

It is this material which can be equated to the material of "indeterminate nature" (Ragg and Bibby, 1966) in many cases. Ragg and Bibby consider it may result (on the slopes of Broad Law, S. Scotland) from an accumulation of slope-washed and soliflucted upland regolith ultimately having many of the characteristics of till. This material clothes much of the Weardale landscape and may be found at many sites. It is also found at depth in locations on the watershed areas and in sections in the valley floor deposits (see Appendices I and II).

Atkinson describes frost-sorted periglacial forms from several locations in this material and the author saw many examples of fossil stone stripes, and frost wedges during three seasons of field work. Continuous sections of this material are visible alongside many of the tracks and roads within Weardale. Of particular note is the long exposure alongside the third class road from Allenheads to Rookhope in the area above the village of Rookhope itself. Piggott's (1962) work suggests an aeolian origin for material over Carboniferous limestone in Derbyshire. This was investigated by Atkinson in Weardale and he concludes that there is no evidence for such process in the area.

Throughout these deposits the stone layer, found about 12" below the surface, is a major feature. Whenever it was possible to make use of a power auger for sampling, the stone layer proved to be particularly resistant! Many man hours were expended in clearing the larger stones (up to 12" long in some cases) to permit the use of the powered auger unit. The presence of cutanic sheathing in many cases leads the author to endorse Atkinson's view that this stone layer represents the effect of periglacial congelifraction in the area. The depth of the layer may be attributed to colluvial material accumulating in late and post-Glacial times. It is also probable in many cases that the stone layer is very similar to the surface layer found in the upland regolith. Cases where cutanic sheathing is present tend to confirm the operation of the frost-heave process.

Atkinson also records the effect of present climate which is classed as "humid-tundra" and is considered responsible for surface features particularly in the organic surface horizons.

4.33 <u>Till</u>

The till of Weardale was recorded and described by Dwerryhouse (1902) as "a thick deposit of blue Boulder Clay with striated stones". Good exposures of this are rare and invariably associated with contamination. When this boulder-clay dries it becomes a browner colour and has a characteristic ped structure which no doubt accounts for Dwerryhouse's use of the term "prismatic Boulder Clay" in his further descriptions of the material. Atkinson concludes that an important property distinguishing the till from the solifluction deposit is the nature and orientation of the stone content, he accepts Dwerryhouse's description of the till and amplifies it to note that the structure of the till "... is generally massive, becoming prismatic on dehydration."

Atkinson uses the stone content of the till as a major criterion for distinguishing it from slope deposit. He claims that in slope deposits fragments of limestone occur only immediately downslope of local outcrops and that sandstones predominate and are generally subangular and seldom smoothed and striated. "Till by contrast contains large numbers of sandstone and limestone erratics. The content of limestone pebbles and boulders is often high and well rounded, polished and striated stones are characteristic." (Atkinson, 1968). Stone orientation in the till fabric also gives a west-east component in the till whereas the slope deposit has no preferred orientation.

Surface exposures or near surface exposures of these materials do meet the criteria listed by Atkinson. There would be little point in duplicating his work within the context of the present study. However, at depth the present author found layers of stony clay including sandstone and limestone in a dense grey-clay matrix with many of the signs of slope deposit - including indications of turbulent flow. This material had the stone content of till and yet the characteristics of slope deposit. In other cases the sandstones and limestones (some striated) were found in a matrix of silty-clay which was of a lighter-grey colour.

For the purposes of the field study the deposits which Atkinson considers to be unmistakably till i.e. smoothed and striated sandstones and limestones in a blue silty-clay matrix were noted as till. Samples where there was some doubt as to the real nature of the deposit were unclassified. Orientation is sufficient criterion to differentiate these deposits only in certain areas of the valley as in many cases "downslope" is also "west-east" hence creating some element of doubt as to the conclusiveness of this diagnostic tool. These points together with the large number of "unclassified" deposits encountered in the field survey and the additional probability of minor influences of ice processing (as suggested by Vincent's hypothesis) in the upland regolith left the present author very sceptical of the value of deductions based on maps of superficial deposits in Weardale. The layering of superficial deposits found at many sites was considered sufficient reason to beware of any mapped delimitation of superficial deposit as layers of slope deposit may in some cases be thin, in other cases, several feet thick. It is from the total layering and the analysis of the deposits that an understanding of the area must be gained. In this context Atkinson's classification of soil parent material has to be treated with caution for the layers below the C horizon may be of considerable geomorphological significance.

4.4 Conclusion

Atkinson's classes of soil parent material provide a useful framework for investigating the nature of the superficial deposits in Upper Weardale. The classification is limited in its geomorphological significance in that it is concerned with description of parent material and not designed to reveal the geomorphological history of the area. In this latter context the classification does not involve sufficient uncertainty in the case of "upland regolith" which may be the product of post-Pleistocene processing of glacially deposited material (accepting Vincent's hypothesis of topographic control of glacial movement).

The classification also is too conclusive in its clear distinction between solifluction deposits and till. This is a criticism of the classification as a geomorphic tool not a criticism of its pedological value, for the parent materials of a soil must surely fall into the classification of "till" or "solifluction deposit". Soliflucted till becomes superfluous in pedogenetic studies for in these circumstances a raft of till transported downslope, may overlie solifluction deposits and a zone of "unclassified" material but it nonetheless forms a "till" parent material for soil genesis.

Chapter 5

Project Design

This study is concerned with the application of a limited number of techniques to illuminate the geomorphological history of Upper Weardale. Difficulties in clearly establishing the relationship between solifluction deposits and till provided a major item for investigation. Inter-layering of these deposits which made mapping difficult also had to be investigated in detail. In addition there was the possibility of ice overriding a watershed and thereby creating ice processed local bedrock which may ultimately become upland regolith (as in Fig. 4.1 above). At this juncture it becomes apparent that the study is not a study of till and its properties, but a more broadly based investigation of the suite of superficial deposits existing in the study area.

The consequence of this is to create a need for some analytical procedures capable of differentiating the environments of deposition of the materials. It is not the purpose of this investigation to concern itself primarily with the properties of glacial till and comment upon them (thereby undertaking a classification of the deposit prior to its investigation) but rather to see what meaning, if any, may be drawn from a systematic analysis of the sediments within an upland area of a specific North Pennine Valley.

Philosophically this approach is neither more nor less sound than assigning a terminology to a deposit in the field and then mapping this deposit and returning to the laboratory to analyse it. In areas where deposits may be easily differentiated this latter procedure has obvious benefits. Upper Weardale, as demonstrated above, does not have this advantage. Given that the deposits are not easily differentiable into distinct, geomorphologically significant groups it is hoped that the significance of these deposits can be meaningfully assessed in a different manner. This can most easily be exemplified by a series of flow diagrams. (See Figs. 5.1 and 5.2).

5.1 Structure of the Investigation

In Figure 5.1 the flow diagram attempts to summarise the major steps in the presentation of many papers in Pleistocene geomorphology. The present author wishes to emphasise the links which therefore exist between the primary step of field mapping and any subsequent hypothesis. In order to map deposits it is necessary to classify them. This classification, implicit in the mapping process, is necessarily subjective. Terminology in geomorphology is such that any deposit from Pleistocene to Recent times is classifiable only in terms which have genetic implications "till" implies clearly the action of glacial process, "alluvium" the action of streams, whilst the latter may be confirmed by direct observation in the present environment the former cannot be.

Topographic mapping is more objective in its nature (see Howarth, 1968) and is not the subjective tool spoken of in this context. Other examples of objective analysis of topographic maps followed by subjective analysis can be cited. Those pertinent to the present study are the parts of Maling's thesis (1955) dealing with profile analysis and spot-height data, Atkinson's altimetric frequency analysis (1968), and Peel's mapping of overflow channels in Northumberland (Peel, 1949).

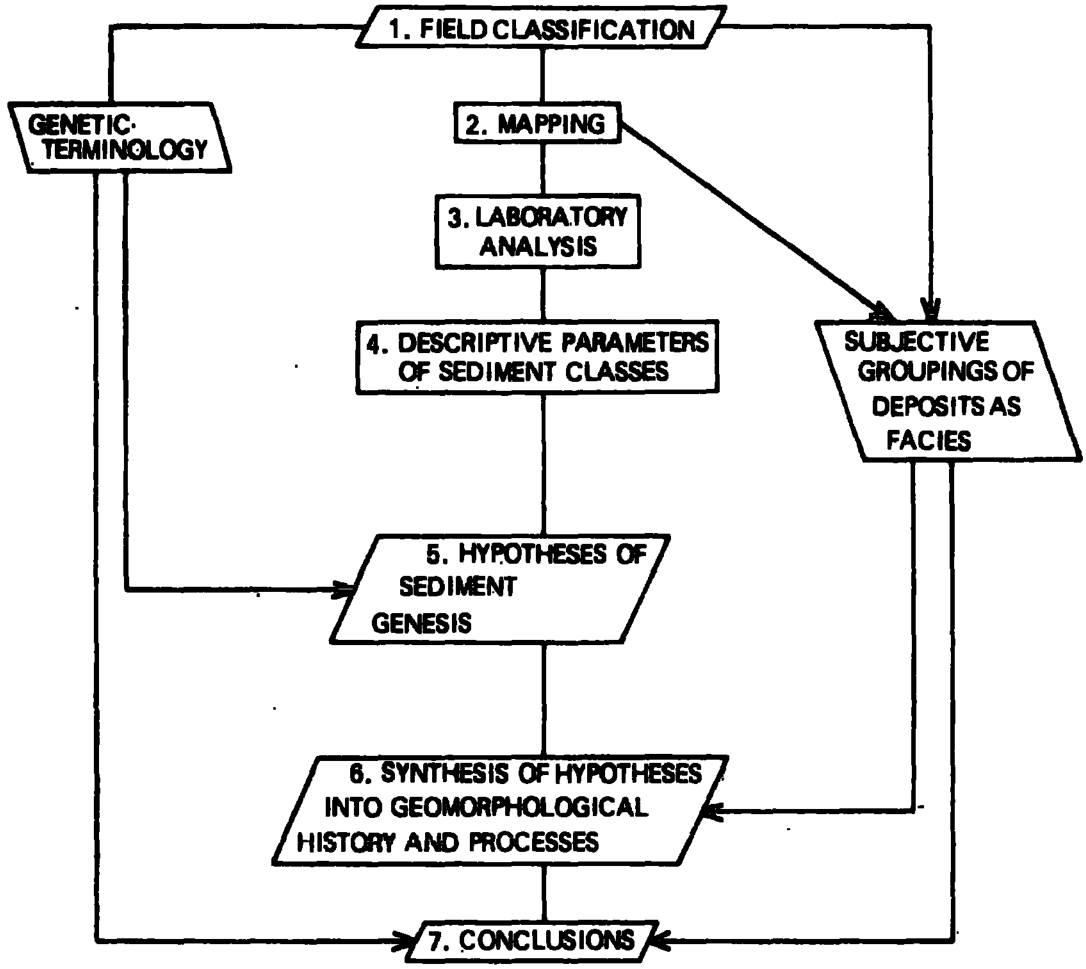
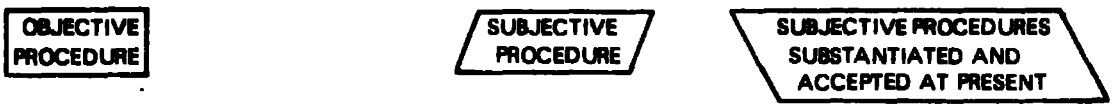


Fig. 5.1. Flow diagram of the structure of typical investigations of Pleistocene geomorphology



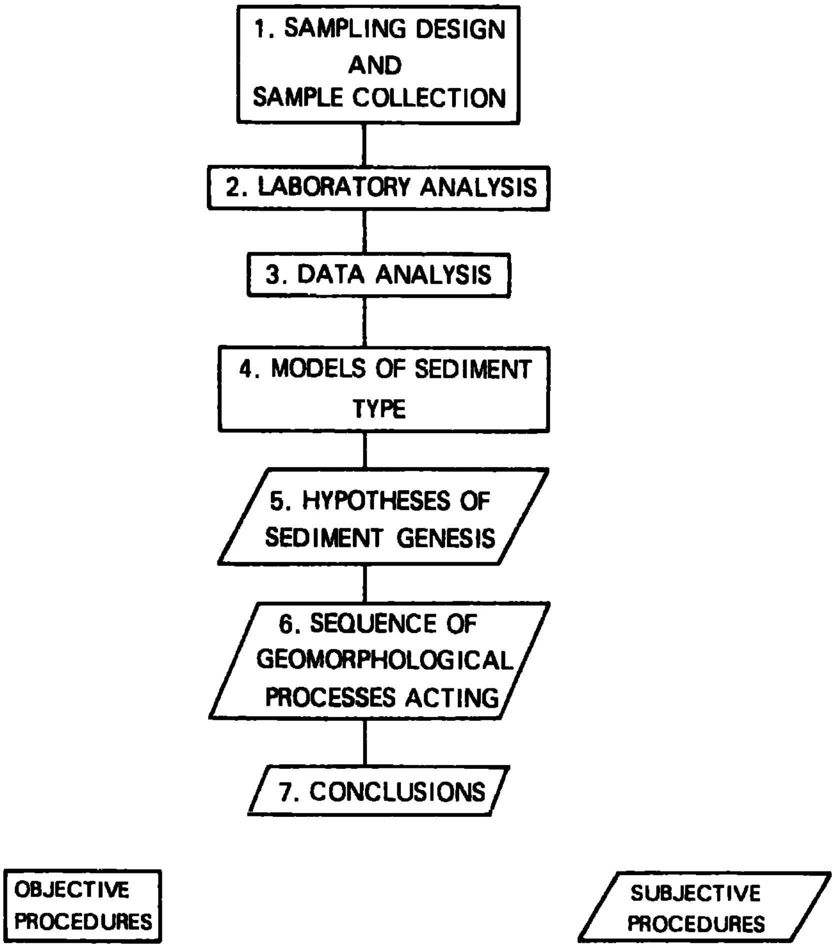


Fig. 5.2. Flow diagram of the structure of the investigation of superficial deposits in Upper Weardale.

Work on the use of altimetric frequency analysis (see Clarke, 1966) and much of the work by Savigear on defining slope categories (1962, *et seq.*) falls into the more truly scientific framework of data collection and analysis. Regrettably many Pleistocene studies rely heavily on pre-definition of deposits for the interpretation of the significance of the laboratory data.

The sequence of events detailed in Figure 5.1 needs some clarification. Subjectivity is, of itself no impediment to understanding. It is, however, an increasing hinderance to the development of scientific geomorphology. The ultimate impasse introduced by subjectivity may be exemplified by reference to the confrontation of "experts" seeking to interpret the same section of superficial deposits. If they should disagree about the nature of the deposit confronting them there can be no definitive statement of the nature of that deposit. Such a situation does not arise frequently as the nature of most commonly occurring deposits is understood sufficiently for the field classification to be a relatively easy procedure. However, when such a disagreement arises it may only be resolved by more objective analyses (e.g. stone counts, orientations etc. to define tills).

In an area such as Upper Weardale where a difficulty exists in the classification of the superficial deposits the subjective method would ideally require the presence of, for example, Dwerryhouse, Maling and Atkinson together with the present author, at any time when a deposit was to be classified. This would then produce situations in which any disagreement could be resolved by recourse to laboratory procedures and the field classification could proceed, with mapping of the deposits as the logical product of the work. Regrettably it is not possible to assemble this group and it seems that in order to produce data which are of value to the succeeding generations of Pleistocene geomorphologists it is necessary to provide some measures of the properties of the materials under discussion. As has been indicated above, in areas where the deposits are easily identifiable into distinct groups these considerations do not apply.

The sequence of events shown in Figure 5.1 therefore requires that the area in which it is implemented is one where Pleistocene deposits may be easily differentiated. Published work on the Pleistocene frequently includes some sedimentological analysis, however there seems to be a confusion between the application of genetic terminology to deposits in order to produce a map of superficial materials and the more legitimate use of topographic maps which are objective and can lead to valid analysis and conclusions about geomorphology. If the sequence in Figure 5.1 were to commence with the compilation of a detailed topographic map, or the analysis of such a map, and concern itself with landform rather than sediment, using the latter as an amplification of the deductions made it would, in fact, be parallel to the sequence of events illustrated in Figure 5.2 in which subjective assessment of the data is a final stage and involves no initial subjectivity - hence producing a clear separation between data and its interpretation. By introducing maps of deposits compiled in the field the data obtained are dependent upon the subjective assessment of the material in the field and in this respect the final conclusion would be necessarily prejudiced. Regrettably, the classifications used in the field mapping have genetic implications, consequently, before any sediment is sampled its genesis is "established". This is illustrated in Figure 5.1 by the link between stage 1 and stage 5 and in turn the influence of these two moulds any conclusions which are reached.

Similar links exist between the field classification and the synthesis of geomorphological history and these links inevitably have a significant influence on the conclusion (see Fig. 5.1). One may only conclude that the field classification is in essence the whole of the content of such work, the intermediate stages offering only description and amplification of the original concept. That this description and amplification is brought about by laboratory techniques and hence is "quantitative" in character, is a reflection of current fashion rather than of scientific merit. Work originating in regions where the field classification of deposits is not in dispute is therefore validated in stage 1 of Figure 5.1. Atkinson's comments cited above (Chapter 3.3) and the author's difficulty in establishing a definitive field classification for Upper Weardale indicate that such procedures are not applicable to this present study.

5.2 Geological Data and Statistical Methods

Krumbein and Graybill (1965) have surveyed the field of statistical method in geology. This, together with the work of Miller and Kahn (1962) and Griffiths (1967) now provides a clear exposition of statistical methodology and its application to geology and hence geomorphology. King (1966) provides additional summaries of these types of techniques and their application, specifically within geomorphology.

Geography is becoming increasingly oriented to statistical method and quantitative analysis. Techniques to handle large bodies of data have existed for some time and a factor in the sudden increased use of these techniques is the ready availability of the computer. Within the general field of geography there can be no doubt that energetic promotion of these computerised techniques by Chorley and Haggett (see 1965, 1967 *et seq.*) has been a major cause of their increasing use.

Figure 5.2 shows the sequence of events which may be followed in the general application of statistical method. Statistical inference is based upon the analysis of a sample derived from some population whose characteristics are unknown. The sample itself is the source of knowledge about the population and all required parameters are measured from the sample. It is necessary therefore to obtain a sample, measure its properties and from these data draw conclusions about the nature of the target population. These conclusions, if considered in the context of comparable data may provide a basis for the construction of models for the sediment type and thus the evaluation of the processes depositing the material.

Knowledge of the energy environments relates to the processes acting in the deposition of a sediment (see Klovan, 1966) thereby providing a basis for theorising about the genesis of the sediment sampled. If samples can be demonstrated to be the product of differing processes, the sequence of these sediments in a stratigraphy gives some measure of the sequence of the processes acting thereby providing a basis for the development of a geomorphological history.

Both Figure 5.2 and the brief summary above represent the adaptation of the statistical method to the case of superficial deposits in Upper Weardale. It may be argued that this represents a subjective decision to undertake such a programme of study. This view is valid. It is parallel to the view of Griffiths that no truly random sample exists. Griffiths cites random sampling as the ideal sampling procedure but cites the opinion that random sampling "is one of the most difficult concepts to reduce to operational practice." (Johnson, 1949, pp. 187 ff.).

5.3 Selection of Parameters for Study

An examination of the deposits in Upper Weardale in order to produce some insight into the geomorphology of the area requires the collection of data which will elucidate the processes involved in the deposition of the sediments. Techniques such as stone orientation and mineralogy are designed to differentiate tills derived from different areas of bedrock. The study of provenance of minerals within glacial tills demonstrates this clearly (Imbrie and Van Andel, 1964). Stone orientation is also of value in determining directions of ice movement and this may be related to the identification of different till sheets. (West and Donner, 1956, Andrews and Smith, 1966). Other than confirming the fact that ice moved through Weardale there seems to be little value in such techniques at this stage in this project. Stone orientations undertaken by the author (see Chapter 10) are of limited value in the full understanding of the geomorphology of Weardale although their confirmation of Atkinson's and Dwerryhouse's observation that ice moved in a west-east direction within Weardale is a welcome demonstration of the former presence of an active glacier.

Mineralogy, in view of the absence of exotic erratics in Upper Weardale is unlikely to yield data of great value. That this was so is confirmed by Vincent's analysis of a sample of "till" (defined below) from Upper Weardale which was not reported to have any content of minerals originating outside the boundaries of the Upper Weardale study area. This does not appear to yield data which are diagnostic of genetic process. King (1966) presents a considerable amount of evidence that particle size analysis is capable of producing such data. Many sedimentologists have used particle size data to differentiate deposits laid down under distinctly separate environments (vide Krumbein, 1934, Krumbein and Pettijohn, 1938, Folk and Ward, 1957, Mason and Folk, 1958, Shepps, 1953, Passega, 1964 etc.). Particle size analysis applied to glacial deposits has met with varied success as a tool to discriminate between different till sheets. The work of Young (1966) on the tills of Fala, Midlothin (S. Scotland) provides a useful comment on the results obtained from this use of particle-size analysis.

> "Particle size analysis has been shown to be a useful index for differentiating and characterising tills, usually in association with other criteria, by Stauffer (1937), White and Shepps (1952), Dreimanis and Reavely (1953), Krumbein (1953), Murray (1963), Shepps (1953, 1958), Shaffer (1956), Arneman and Wight (1959), Kaiser (1962) and Willman, Glass and Frye (1963): all those workers have prosecuted their studies in North America. On the other hand, evidence has been published by Järnefors (1952) in Sweden, Holmes (1952) and Flint (1955) in America and Andrews (1963b) in Canada which shows that particle size analysis did not reveal any difference between tills although other criteria analysed suggested that the tills examined were strikingly different." (Young, 1966, p. 40).

To this must be added the conclusions of Beaumont (1967) and Vincent (1969) that particle size analysis is a poor discriminator between tills. However, if the particle size data may be used to differentiate environments of deposition then the ambiguity resulting when it is applied to materials produced by similar environments of deposition is not altogether surprising. Further consideration of the use of particle size data in geology, especially that advocated by Klovan (1966), indicated that data on particle size composition of the deposits in Upper Weardale should produce valuable ~~technique~~ criteria for differentiating deposits created in a glacial environment from those produced in a colluvial environment. A technique demonstrated to be capable of discriminating between depositional environments is the major requirement in a study of Upper Weardale. Klovan's technique appears to offer this and the data required are particle size distribution curves. The parameter chosen for measurement was, therefore, particle size distribution. It should be noted that in subsequent work Klovan has modified his view and now maintains that particle-size data can form a useful first step in identifying processes but a more detailed study of provenance is necessary if <u>environments</u> of deposition are to be determined (see Solohub and Klovan, 1970). The present author considers that there is a great need for the "useful first step" to be taken in an analysis of a terrestrial environment such as Upper Weardale.

5.4 <u>Assessing the Value of the Factor Analysis Model</u>

In any study of this type it would be inappropriate to proceed without testing the applicability of the technique to be used. Klovan

(1966) has demonstrated the success of the Q-mode factor analaysis programme for differentiating the depositional environments of Barataria Bay. For the purposes of this study it is necessary to evaluate the technique for a suite of deposits in a totally different environment. In order to do this successfully it seems appropriate to analyse samples the nature of which could easily be subjectively assessed.

The present author, before adopting Klovan's technique of applying factor analysis to grain-size data, undertook a preliminary study. This study was based on the premise that Q-mode factor analysis of the particle-size data of deposits would provide an acceptable result. Until this preliminary study was undertaken there was no basis on which to assess the method to be used nor any reason for designing a sampling procedure for an unproven technique. Therefore, <u>before</u> the main part of this project was designed a small sample of deposits was analysed using the Q-mode analysis technique. The results are presented below. The apparent value of this technique (see below) was considered a suitable basis for further investigation and the formal structure of the main study and the description of the techniques are contained in the subsequent pages.

In order to establish the value of the technique it was necessary to include field samples which could be readily identified in a conventional manner. The implication of this is that samples "recognised" as till, solifluction/colluvial material and regolith should be subjected to particle-size analysis, the data thus obtained, fed into the Q-mode factor analysis programme proposed by Klovan and the results considered. Successful use of the procedure is impossible to define.

It can be argued that samples of "till" should load most highly on the same factor, samples of regolith and colluvial/solifluction material loading most highly on other, separate, factors. However the loading of a "solifluction" deposit (field definition) on the "till" factor (if such can be recognised) presents a problem. This could equally be interpreted as the deficiency of the programme or of the field classification. In defence of the programme it can only be stated that such a programme is an objective procedure.

5.41 Particle-size Classes

In order to proceed with the evaluation of the factor analysis technique for the Upper Weardale deposits it was necessary to adopt some method of grouping the particle size data into classes. Klovan used a class interval of 1 phi unit for the size of his data from 1 phi to 10 phi units and a terminal category of less than 10 phi units. The selection of size classes is an important problem examined below (see Chapter 7). For the purposes of this brief assessment of the technique 1 phi unit categories were used to cover the range 1-9 phi units with terminal categories of less than 9 phi units and more than 1 phi unit. The data are presented as Table 5.1.

5.42 The Factor Analysis Results

Table 5.3 shows the percentage explanation of the total variance achieved by the first six factors generated. The programme, designed to generate factors until a close approach to a 100% explanation of the variance is achieved thus indicates that the proportion of the variance

TABLE 5.1. Particle Size Data for Purposive Sample

PERCENTAGES IN PHI UNIT CATEGORIES

Sample No.	<1	1	2	3	4	5	6	7	8	8+
P1	8.6	8.3	22.6	22.5	12.3	5.3	0.5	2.3	3.7	14.6
P2	6.0	1.3	0.8	3.8	14.1	17.8	8.6	8.4	5.2	34.0
P3	4.5	0.4	0.6	2.3	13.1	23.2	11.5	4.8	7.1	32.5
P4	29.3	2.6	2.9	6.2	17.1	11.6	5.6	4.2	2.9	17.6
P5	45.2	5.1	5.6	6.3	9.9	10.9	3.8	1.5	1.3	10.4
P6	90.3	2.4	2.5	2.0	0.8	0.4	0.4	0.4	0.4	0.4
P7	17.0	14.2	26.6	10.2	2.1	2.2	1.8	4.3	3.1	18.5
P8	54.8	6.3	10.1	6.9	8.6	0.8	2.2	0.4	1.1	8.8
P9	12.8	13.2	19.7	15.2	11.9	5.5	3.7	3.8	4.4	9.8
P10	28.6	9.2	10.1	6.4	6.5	5.2	4.7	8.5	3.9	16.9
P11	16.0	7.7	12.1	14.2	13.8	4.1	2.9	5.1	3.5	20.6
P12	14.0	2.4	4.4	5.2	8.4	17.9	13.5	9.9	6.2	18.1
P13	36.4	3.9	3.3	4.1	8.3	14.8	9.4	6.4	4.6	8.8
P14	25.0	3.2	1.9	2.0	14.4	9.3	9.7	7.8	2.9	23.8
P15	43.8	4.4	3.8	2.9	11.9	7.2	5.8	6.4	5.2	8.6
P16	56.4	5.6	4.1	3.2	6.7	6.0	7.5	5.5	2.2	2.8
P17	18.6	2.2	8.8	8.4	8.9	7.9	6.6	8.3	4.6	25.7
P18	21.0	5.9	6.3	6.2	10.9	5.3	6.2	7.3	4.6	26.3
P19	14.8	5.2	8.4	10.7	9.2	7.7	9.2	9.2	4.9	20.7
P20	3.0	7.2	2.9	3.9	2.0	11.4	13.4	10.8	6.4	12.0
P21	48.0	4.3	3.5	4.1	16.1	6.8	3.1	3.3	3.2	7.6
P22	31.1	2.9	6.6	18.2	12.4	6.2	2.5	5.6	2.8	11.7
P23	28.8	6.0	10.2	11.0	6.0	5.7	6.9	5.6	6.2	13.6
P24	28.4	6.1	2.6	2.5	6.4	6.1	8.3	12.2	6.2	21.2
P25	73.4	4.6	6.9	5.1	5.3	1.4	1.5	1.0	0.6	0.2
P26	21.5	5.1	7.3	8.5	2.4	7.0	6.4	6.5	6.1	29.2
P27	18.4	3.9	6.6	9.3	9.4	6.7	5.7	8.1	4.2	27.7
P28	5.3	1.3	3.6	16.4	24.6	14.9	10.9	5.4	3.7	13.9
P29	20.6	5.1	7.3	7.5	11.4	9.9	8.5	9.7	6.3	13.7

Sample No.	<1	1	2	3	4	5	6	7	8	8+
P30	22.0	3.7	6.4	6.7	9.4	4.8	6.8	6.2	5.8	28.2
P31	27.9	7.1	10.1	9.1	7.8	6.2	4.9	5.1	3.2	18.6
P32	77.2	2.2	2.6	1.5	1.8	1.1	2.1	0.3	0.8	10.4
P33	23.3	6.2	7.2	6.1	5.6	7.3	6.5	6.8	5.0	26.0
P34	31.6	14.1	12.3	8.8	1.6	5.6	3.3	3.5	2.4	16.8
P35	10.4	11.3	12.0	8.3	7.2	4.1	6.9	3.8	6.4	29.6
P36	35.8	35.2	11.0	2.5	5.8	1.7	1.9	4.0	0.9	1.2
P37	13.7	11.6	13.6	10.9	10.4	5.7	4.2	5.7	3.8	20.4
P38	15.6	11.1	11.3	10.3	8.8	5.1	3.8	6.8	3.2	24.0
P39	7.3	6.5	8.0	10.3	10.2	5.7	7.4	6.5	5.4	32.7
P40	11.0	14.9	24.8	13.1	3.8	2.3	2.7	3.4	3.2	20.8
P41	12.6	5.9	5.5	6.2	12.7	13.9	10.4	6.6	8.3	17.9
P42	18.4	3.1	4.3	5.9	11.4	6.1	7.8	5.8	7.4	29.8
P43	0.3	0.6	2.7	1.5	7.3	11.2	15.2	12.4	8.8	40.0
P44	20.8	4.5	8.7	11.7	13.6	5.8	6.7	4.2	4.0	20.0
P45	8.1	5.5	9.8	6.9	17.6	6.7	8.3	8.9	5.3	22.9
P46	35.6	6.6	8.1	8.3	21.2	5.9	5.3	3.3	0.7	5.0
*P47	40.5	31.9	14.7	7.0	5.9	0.0	0.0	0.0	0.0	0.0
*P48	16.0	50.3	31.1	1.8	0.8	0.0	0.0	0.0	0.0	0.0
*P49	2.3	5.5	37.1	40.2	14.5	0.0	0.0	0.0	0.0	0.0
*P50	0.0	0.42	1.1	31.5	24.6	22.8	19.5	0.0	0.0	0.0
*P51	62.0	53.6	11.8	1.5	1.1	0.0	0.0	0.0	0.0	0.0
*P52	34.8	11.9	12.7	16.1	26.5	0.0	0.0	0.0	0.0	0.0
*P53	16.9	11.2	18.2	20.7	34.0	0.0	0.0	0.0	0.0	0.0

* Samples from Breidamerkursandur. S.E. Iceland.

TABLE 5.2

Key to Table 5.1

PURPOSIVE SAMPLE

Sample No.	Grid Reference	Depth (cms)	Field Classification
P1	805435	100	S
P2	"	125	T
P3	"	150	T
P4	"	175	T
P5	"	200	R
P6	"	225	R
P7	806434	25	S
P8	"	190	R
P9	821443	150	S
P10	"	200	T
P11	823437	75	T
P12	"	100	T?
P13	"	125	T
P14	"	140	T
P15	"	160	R
P16	"	185	R
P17	902394	100	T
P18	985352	300	T
P19	985381	45	S?
P20	"	80	T
P21	"	110	R
P22	"	140	R
P23	985392	75	S
P24	"	135	S
P25	"	210	R
P26	003367	45	S?
P27	"	90	S?
P28	"	135	T?
P29	"	180	S?

Sample No.	Grid Reference	Depth (cms)	Field Classification
P30	003367	225	T
P31	054383	150	T
P32	067384	150	R
P33	068377	120	T
P34	068384	75	R
P35	"	120	S
P36	"	210	R
P37	074345	50	T
P38	"	105	T
P39	173358	150	T
P40	205394	90	S
P41	"	110	T
P42	"	150	T?
P43	236363	90	Clay (see text)
P44	244335	75	T?
P45	"	135	T?
P46	Broad Law)		
P47	Iceland I)		
P48	Iceland II)		
P49	Iceland III)		
P50	Iceland IV)	See Figure 5.4	
P51	Iceland V)		
P52	Iceland VI)		
P53	Iceland VII)		

where R = Regolith
S = Solifluction
T = Till
? = uncertain classification

each group being defined after Atkinson 1968

TABLE 5.3

EXPLANATION ACHIEVED BY SIX FACTOR SOLUTION
TO PURPOSIVE SAMPLE DATA

	Cumulative Explanation of Total Variance (%)
Factor 1	72.86
Factor 2	86.10
Factor 3	92.81
Factor 4	96.75
Factor 5	98.35
Factor 6	99.21

attributable to each factor is as listed in the right-hand column of Table 5.3. Because Factor 5 is the dominant factor in the explanation of 1 sample (P48) the 5 factor explanation is accepted (Klovan personal communication). These five factors had the following relationship to field classification (see Table 5.4).

TABLE 5.4

No. of samples with dominant loading on each factor

Field	Total No.	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Till	18	13	5	0	0	0
Solifluction	6	2	1	3	0	0
Regolith	11	0	11	0	0	0
Solifluction??	4	3	1	0	0	0
Till??	5	4	0	0	1	0
	44	22	18	3	1	0

Table 5.5 lists the loadings of each sample on each of the five factors generated. Communality, a measure of the explanation of the sample achieved by the use of the set of factors (5 in this case), is also stated. A communality of 1.0000 is a perfect explanation. That the majority of samples (51) should have communalities higher than 0.9000 in this example attests to the mathematical validity of this five factor explanation.

In this preliminary stage it appears that the technique is an excellent discriminator of regolith samples and a useful tool in the designation of the Till and doubtful classifications (Till? and Solifluc-

TABLE 5.5. Purposive Sample Varimax Factor Matrix

COMMUNALITY AND LOADINGS FOR FIVE FACTORS

Sample No.	Communality	1	2	3	4	5
P1	0.9891	0.4857	0.1870	0.8067	0.2403	0.0984
P2	0.9810	0.9660	0.0774	0.0328	0.2018	-0.0033
P3	0.9495	0.9401	0.0441	-0.0270	0.2506	0.0133
P4	0.9799	0.6447	0.6828	0.1459	0.2768	0.0057
P5	0.9839	0.3816	0.8894	0.1625	0.1305	0.0615
P6	0.9993	0.0906	0.9915	0.0540	-0.0714	-0.0085
P7	0.9780	0.5224	0.3609	0.6832	-0.1288	0.3024
P8	0.9941	0.2600	0.9299	0.2440	-0.0018	0.0484
P9	0.9912	0.4666	0.3427	0.7034	0.2621	0.3043
P10	0.9852	0.6116	0.6914	0.3148	0.0191	0.1836
P11	0.9813	0.7052	0.3933	0.5380	0.1801	0.0858
P12	0.9306	0.8307	0.3533	0.0712	0.3156	0.1054
P13	0.9729	0.4747	0.8264	0.0572	0.2254	0.1029
P14	0.9857	0.7939	0.5685	0.0593	0.1646	0.0397
P15	0.9928	0.3930	0.8968	0.0939	0.1419	0.0695
P16	0.9947	0.2291	0.9612	0.0796	0.0718	0.0821
P17	0.9978	0.8718	0.3374	0.3282	0.0805	0.0982
P18	0.9894	0.8291	0.4823	0.2505	0.0467	0.0675
P19	0.9851	0.8219	0.3787	0.3534	0.1841	0.0865
P20	0.9218	0.5831	0.7268	0.0472	0.1130	0.1964
P21	0.9857	0.3315	0.9111	0.1166	0.1747	0.0402
P22	0.9810	0.4638	0.7309	0.4045	0.2558	-0.0507
P23	0.9826	0.5549	0.7193	0.3724	0.0961	0.0961
P24	0.9792	0.7288	0.6547	0.0829	0.0103	0.1115
P25	0.9997	0.1120	0.9842	0.1335	-0.0111	0.0248
P26	0.9867	0.8334	0.4558	0.2732	-0.0903	0.0408
P27	0.9933	0.8579	0.4105	0.2929	0.0547	0.0053
P28	0.9949	0.6630	0.1356	0.2802	0.6765	-0.0278
P29	0.9772	0.6959	0.5738	0.2542	0.2863	0.1308
P30	0.9936	0.8364	0.4825	0.2473	0.0020	0.0051

Sample No.	Communality	1	2	3	4	5
P31	0.9990	0.6360	0.6718	0.3581	0.0575	0.1079
P32	0.9980	0.2120	0.9689	0.0628	-0.0999	-0.0180
P33	0.9981	0.8064	0.5286	0.2439	-0.0282	0.0898
P34	0.9888	0.5132	0.7093	0.3861	-0.0718	0.2609
P35	0.9872	0.8590	0.1968	0.4112	-0.0473	0.1984
P36	0.9856	0.1585	0.6991	0.2735	0.0094	0.6299
P37	0.9958	0.7330	0.3412	0.5199	0.1196	0.2396
P38	0.9895	0.7804	0.3680	0.4518	0.0409	0.1980
P39	0.9872	0.9249	0.1099	0.3386	0.0432	0.0559
P40	0.9931	0.5859	0.2183	0.7120	-0.0708	0.3004
P41	0.9826	0.8312	0.3366	0.1782	0.3447	0.1669
P42	0.9869	0.8912	0.3927	0.1895	0.0500	-0.0066
P43	0.9903	0.9923	-0.0719	0.0195	0.0100	-0.0020
P44	0.9912	0.7233	0.5212	0.3914	0.2061	0.0246
P45	0.9614	0.8578	0.1816	0.3291	0.2707	0.1052
P46	0.9672	0.3393	0.8050	0.2724	0.3463	0.0995
P47	0.9801	0.1056	0.7721	0.3361	0.0064	0.5097
P48	0.9941	0.0608	0.2857	0.4491	-0.0897	0.8361
P49	0.9633	0.0810	0.0381	0.9441	0.2488	0.0460
P50	0.9652	0.2797	0.0431	0.3383	0.8733	-0.0898
P51	0.9976	0.0900	0.9212	0.1925	-0.0849	0.3109
P52	0.9979	0.2009	0.8049	0.4433	0.2797	0.1868
P53	0.9685	0.2577	0.4578	0.6423	0.4696	0.2438

tion??). It must be recognised that a purposive sample designed to evaluate the applicability of this programme does not provide a large number of samples of doubtful field classification. 20% of this purposive sample consisted of deposits not immediately classifiable in the field.

5.43 Interpretation of Results

Table 5.5 indicates that 5 of the 18 samples classified in the field as till are more highly correlated with Factor 2 which appears to be the factor representing regolith. Investigation of the field description (see Appendix I) shows that these samples are in all cases overlying shale. This would then account for the clay rich nature of these sediments and it becomes a problem of assessing this material. Reference to Vincent's model (Fig. 4.1) would indicate that samples close to bedrock may be glacially processed bedrock. A closer considera-tiontion of these samples shows that their loadings on Factor 1 are similar in magnitude to their loadings on Factor 2. A reasonable conclusion therefore appears to be that Factor 1 represents the influence of glacial processing, Factor 2 represents the influence of bedrock. In the case of the samples identified in the field as till but demonstrated by Q-mode factor analysis to be related to regolith we may describe the material as glacially processed bedrock, the influence of both bedrock and glacial processing being of the same order of magnitude in each case. (see Table 5.5).

5.44 The Universal Applicability of the Model

In order to test the general applicability of the factor analysis model samples of material from outside the Upper Weardale study area were incorporated in the body of data. These include samples from an area currently undergoing deglacierization (Breidamerkursandur, S.E. Iceland) and samples of material described by Ragg and Bibby (1965) as the "subjacent layer" in their Broad Law study. The locations and field descriptions of the samples from S.E. Iceland are given as Figure 5.3.

These samples, although considered as an integral part of the evaluation of the technique and therefore constituent members of Table 5.5 are here considered separately because of their special nature. In addition a sample of clay from the Wear valley to the west of the study area was added to the sample to see what, if any, correlation this had with the major factors generated. Reference to Table 5.5 and Table 5.2 shows that the samples from Iceland which might reasonably be expected to be well explained by the glacial process factor are loading on every other factor except the glacial factor (Factor 1). The reason for this is probably contained in the conclusions of Beaumont (1967) and Vincent (1969) both of whom view the local bedrock as an important controlling influence on the nature of the deposits produced by a glacier. The fact that the Icelandic samples are extracted from an area of volcanic rocks is probably a major reason why they show no correlation with the till of Upper Weardale where the bedrock is a particularly argillaceous sedimentary material.

The sample of material from Broad Law loading on Factor 2 serves only to confirm the opinion formed by field examination that the

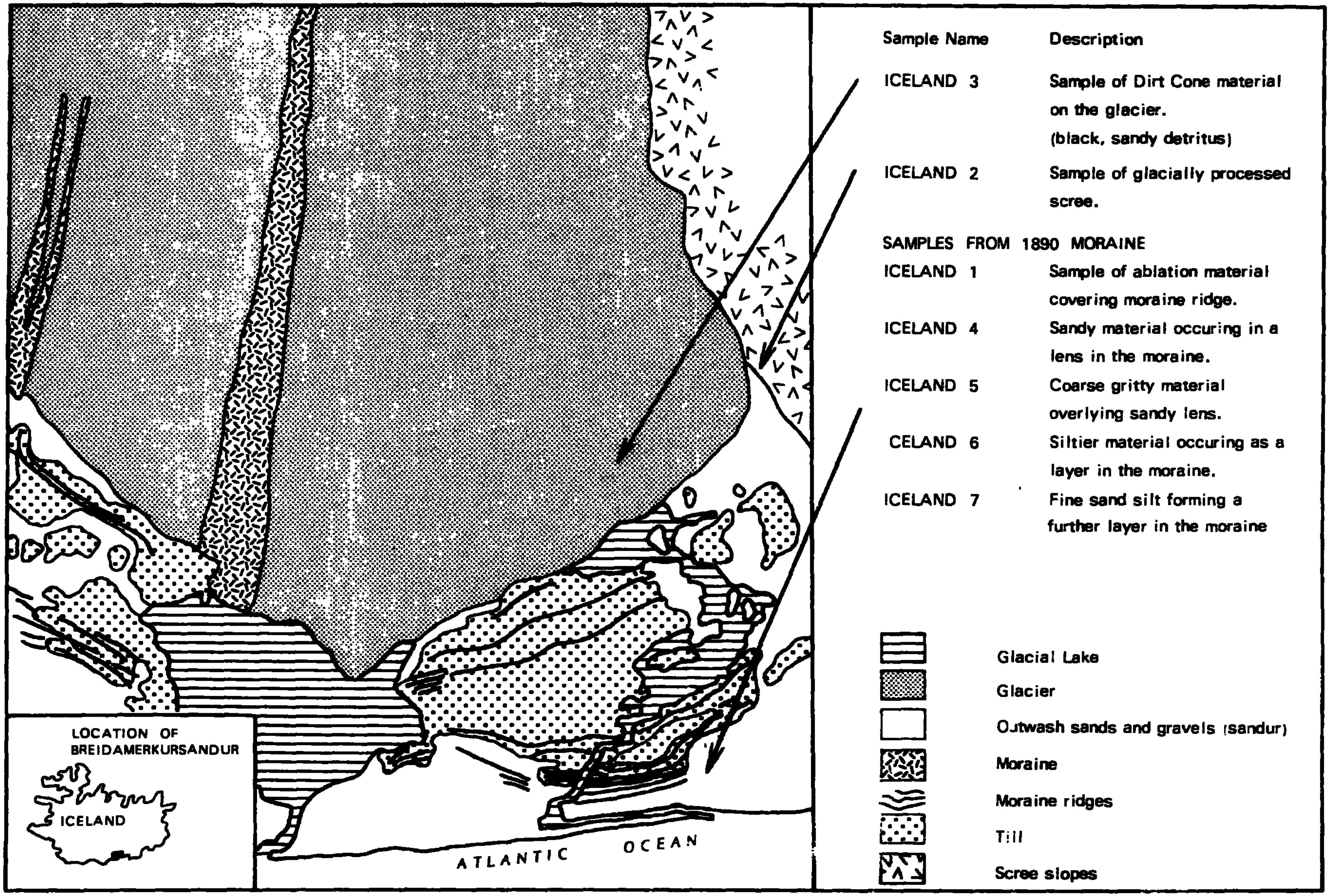


Figure 5.3 Location of Iceland samples

regolith material in the two areas is similar. Since both areas are developed in coarse gritstones the bedrock is similar. The sample of clay from the Wear valley west of the study area poses some problems of interpretation. (Sample No. P43). A careful examination of its factor loadings reveals that it loads almost completely on Factor 1. No other factor offers any "explanation" above 0.0216. This pattern is not true for any other sample in Table 5.5. It is probable that extremely high clay content may produce a high loading on Factor 1. The significance of this is considered in the subsequent chapters.

5.5 Sampling Design

The sample of deposits used to evaluate the factor analysis model was a purposive sample by the definition of Krumbein and Graybill (1965). Such a sample has little intrinsic statistical merit. In order to proceed with the analysis of the sediments in Upper Weardale it was necessary to design a sampling procedure. Griffiths, and Krumbein and Graybill, advocate the use of simple random sampling but caution that the sampling procedure requires careful adherence to the following sequence:

> "1. Development of the conceptual geologic model, definition of the population of interest, choice of variables to be measured, and sources of variability that need to be taken into account.
>
> 2. Translation of the conceptual model into a statistical model in which the mathematical structure of an observation explicitly influences the several sources of variability.
>
> 3. Selection of a sampling plan adapted to the statistical model."
>
> (Krumbein and Graybill, 1965, p. 164)

5.51 The Model

Conceptually the geological model may be stated as follows:

It is proposed that the particle size characteristics of a sediment are sufficiently sensitive to the environment of deposition that they can reveal a polygenetic history. Symbolically this may be defined as:

$$\Sigma\phi = f(\delta)$$

where $\Sigma\phi$ is the total particle size distribution of a sediment and γ is the agent of deposition. The conceptual model for Upper Weardale requires the action of three processes (accepting Atkinson's tripartite classification of the soil parent material) namely the glacial process, the solifluction or colluvial process and bedrock disintegration producing regolith. This more complex model then has the component parts

$$\Sigma\phi' = f(\gamma)$$
$$\Sigma\phi'' = f(\chi)$$
$$\Sigma\phi''' = f(\rho)$$

where $\Sigma\Phi$ is the characteristic particle size distribution produced by the environment, and γ , χ and ρ represent glacial, colluvial and subaerial environments respectively. The model for any one sample then becomes

$$\Sigma\Phi = A\Sigma\phi' + B\Sigma\phi'' + C\Sigma\phi''' + e$$

where A, B and C are constants $\Sigma\Phi$ is the sample at any specific site and e is the error term. This is a statement of the factor analysis model (see Chapter 7) and thus fulfils the second point of Krumbein and Graybill (1965) and the model to be tested as stated above (5.4).

5.52 Additional Parameters Measured

Recent theses concerned with the analysis of glacial deposits (Young, 1966, Beaumont, 1967, Vincent, 1969) also included measurement of Carbonate content and pH values. Other properties measured, apart from mineralogy were Colour, Iron Content, Organic Carbon content and Coal content. Of these Carbonate content and pH values were considered to be of direct value to this work, colour was considered to be of minor importance since gleying could equally affect both till and solifluction deposits and the colour of till in the field was very much a consequence of its water content. Iron content was not measured, the inclusion of ironstone nodules in the Carboniferous shales would make this a very variable constituent depending on the abundance of these nodules in the locally occurring bedrock. Colour being considered of minor importance meant that iron content, primarily a colouring agent, was not considered significant.

The absence of coal in Weardale with the exception of a seam less than 2" thick rendered the investigation of this property pointless. The outcrop of the coal seam is so restricted in the upper part of the dale that the discovery of coal in any deposit would be remarkable. No coal has ever been reported in Upper Weardale boulder clay and the present author did not discover its presence at any site in the dale.
A measure of the quantity of organic material present is obtained in the preparation of the samples for particle size analysis - this being the loss of weight resulting from treatment with hydrogen peroxide. This treatment is designed to remove organic material and was considered to be of possible significance. Three additional parameters were therefore

measured, Carbonate Content, pH and Organic content.

5.53 Variability to be Examined

Variables to be measured have been discussed above. For the sake of completeness, point 1 of the Krumbein and Graybill (1965) sequence requires a definition of these parameters. In the rigorous design of this project particle size is the main parameter to be studied. Sources of variability are contained within the samples of sediment themselves. However, it is important to define the fact that the variability to be studied is contained within the existing sediments and NOT aggregates of them. The variability with which this study is concerned is also variability both in a horizontal and a vertical plane. Variability in the horizontal plane (lateral variability) is of interest in both the ultimate evaluation of the distribution of the deposits and in the areal variation of the forces producing them. Variability in the vertical plane is of interest in that it demonstrates what layering, if any, exists at an individual sample site. The importance of this in any evaluation of a suite of deposits is that it permits the investigator to draw some tentative conclusions about the chronology of events. If certain processes can be deduced from the analysis of variance of the deposits the stratigraphy will then give some indication of the sequence in which these processes acted.

5.54 The Sampling Plan

Sampling is perhaps the most controversial and difficult element within any geological study. Griffiths (1967) devotes a whole chapter of his book to this only to conclude,

> "Extensive information on sampling exists, and the literature on sampling applied to geological populations is steadily growing, but until specific experiments aimed primarily at solutions to geological sampling problems are completed, no very exact guide of general use can be expected."
> (Griffiths,1967, p. 30)

Miller and Kahn (1962) carefully avoid the problem by treating sampling only as a component of statistical mapping and detailing methods of grid sampling as a basis for tests of variance. The final decisions in the design of the present project were taken on the basis of the work of Griffiths and the detailed considerations of sampling given by Krumbein and Graybill.

Krumbein and Graybill summarise the typical flow diagrams relating geological target populations to sample populations and their summary is produced as Figure 5.4. The target population for this study is the suite of deposits collectively forming the "superficial deposits of Upper Weardale". However, considerations of the nature of the area have already demonstrated that the samples obtained from the deposits of Upper Weardale are of a compound nature which may be typified by the model discussed above.

In this study the requirements of the sampling plan are defined by the following criteria:

(1) Every type of superficial deposit must have an equal chance of being sampled.

(2) The layering of the surficial deposits (if layering exists) must also be sampled to permit the development of a geomorphological history.

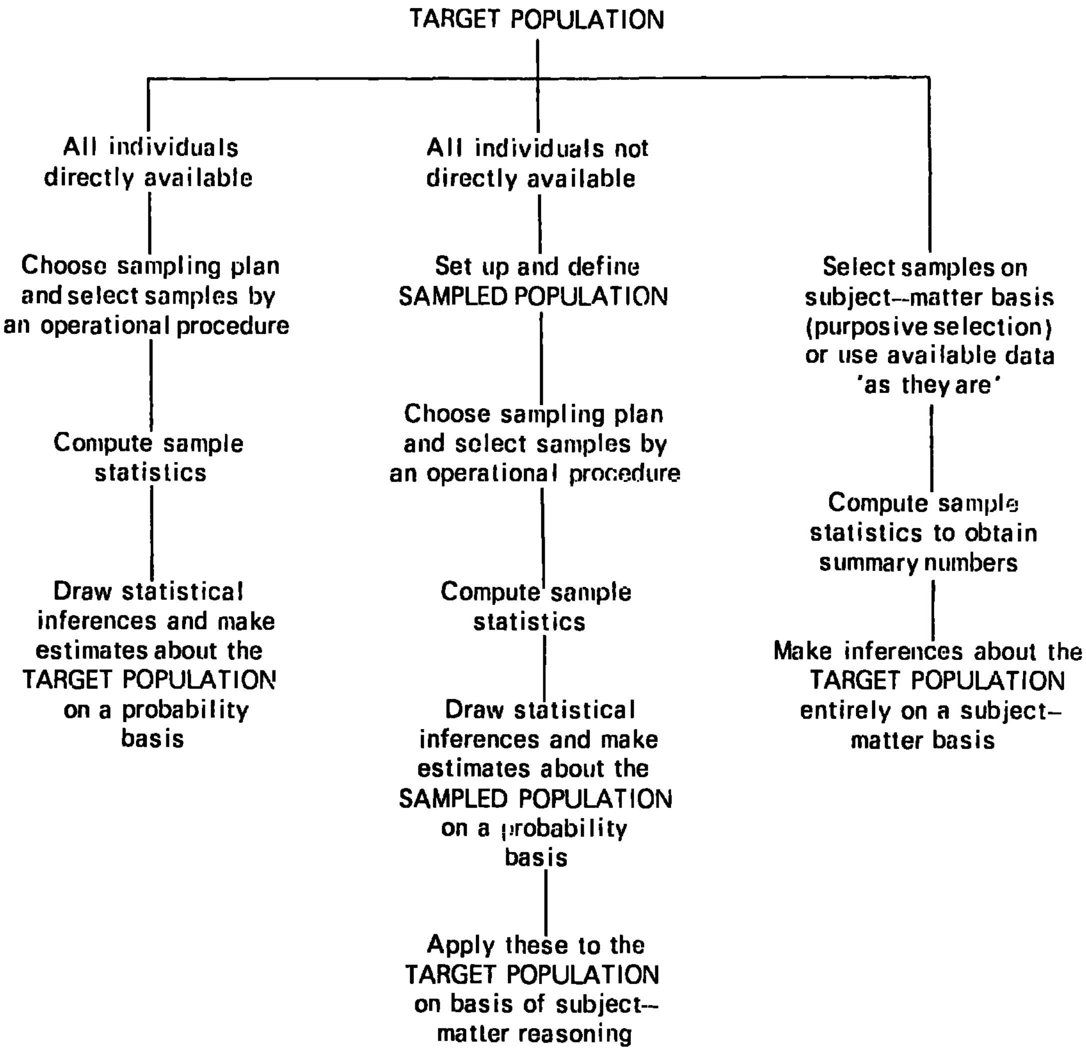


Fig. 5.4 Relationship of target population to sample population for three commonly occurring situations in geological studies.

(3) The sampling procedure must preserve the particle size characteristics of each individual type of superficial deposit for the analysis of variance.

(4) The number of individual samples obtained should be of a size compatible with the time available for processing them.

Certain considerations of the type of sampling are applicable here. Unlike many geological sampling situations this project is not concerned with the variability of a single stratigraphic unit. Thus it is concerned with three dimensional variability. For sampling within the area - a two dimensional design would seem to be best using a simple random sample. Difficulties in mapping the deposit at the surface mean that there exist no suitable criteria for designing stratified random samples. Analysis of variance within the surface layer would also be of little value as till is often found at depth and the surface layer is more the concern of the pedologist. In this context therefore nested sampling designs are of no particular value.

Using a simple random sample does imply that the population is uniformly available and therefore any randomly chosen site may be sampled. Griffiths points out that in geological sampling restrictions of accessibility apply and it is only possible to sample an "available" population. This he defines as the exposures existing within the study area. In Upper Weardale bedrock is quite close to the surface, and much of the area is unfenced moorland. The author therefore decided that the target population of the superficial deposits was available in so far as it was possible to inspect the deposits at any one point by digging an inspection pit. It then was apparent that there were no restrictions on the basically desirable procedure of taking a random sample.

The structure of this sample site designation then became simply a recourse to random number tables using two three-digit numbers as the eastings and northings respectively of grid co-ordinates. Numbers occurring outside the area of study were discarded. Because the grid is capable of defining an infinite series of points within the area it was considered that the three digit grid reference (accurate to 10 metres) provided sufficiently accurate definition of the sample site. Each sample was defined by a randomly chosen distance east of the origin (Grid point NY 800300) and a randomly chosen distance north of this same point. Thus each location had an equal chance of being selected, subject only to field error in the location of the chosen point as defined by grid co-ordinates. The distribution of sample sites is shown in Figure 6.1 and a list of the randomly selected co-ordinates is given as Table 6.1.

For the need to obtain data on the stratigraphy of the sediments there was no immediately applicable procedure. The randomly located sample sites provided a sample of the stratigraphy if the layers of material present were recorded, thus providing a random sample of the layering present in the superficial deposits. To this point the sample is theoretically sound. Problems arise in the designation of layers at each site. In so far as geologic studies recognise strata initially as visually distinct layers of sediment it was considered consistent with the aims of this study to record the visually distinct layers encountered in each inspection pit.

If the analysis of variance model is to be applied successfully then data for each layer are required to define the layers for analysis. It is therefore necessary for a sample of each layer to be taken. Statistically this procedure does not detract from the randomness of the sample design although it introduces an element of subjectivity in the designation of layering. In order to reduce this subjectivity a differing number of samples was taken at each site. Either one or two samples were taken from each layer. Two or more were taken at sites where there appeared to be only one layer present in order to test for homogeneity. In Appendices I and II, a field description is given for each sample taken. This means that in some cases it appears that the section is multi-layered. Reference to the dominant factor (and its loading) reveals the cases where the same factor dominates throughout the section and thus, the samples indicate only variability within one deposit type. Three of the stated requirements are therefore satisfied:-

Randomly chosen sampling sites mean that each type of site has an equal chance of being chosen. Sampling the layers which are visibly differentiated in the inspection pit dug at the sampling site and multi-sampling of apparently homogeneous zones mean that the sampling design is capable of detecting stratigraphy. The two aforementioned provisions in combination, mean that each and every deposit has an equal chance of being sampled and the characteristics of each deposit are preserved as neither channel nor bulked samples are to be taken.

The fourth criterion was established as an external parameter. The purposive sample used to evaluate the factor analysis model gave a measure of the time required. In the purposive sample 50 individual samples were processed. To obtain particle size data on one sample alone requires approximately 3 days (see Vincent, 1969, p. 164). Thus the use of one field season and the subsequent laboratory time (6 months) in the obtaining and processing of the purposive sample placed a limit of about 12 months on the total time available to the present author. Some economies of time are possible by running sample preparations simultaneously but the saving is not much more than 20% because of the need for careful hydrometer analysis and the availability of the accessory equipment.

In total it was agreed that about 100 samples could be taken. Experience from the purposive sample indicated that an average of 3-4 samples had to be taken from each site as in many cases in the west of the dale the solid rock was very close to the surface and only one sample could be taken. This indicates that samples from 30 sites would provide adequate material to meet the discussion of number of samples by Krumbein and Graybill. They state

> "A remaining question, not yet touched upon, is that of the number of samples to be collected. There is no simple answer, inasmuch as time and cost factors must be considered."
>
> (Krumbein and Graybill, 1965, p. 164)

5.6 Conclusion

With an apparently successful pilot study to evaluate the application of the factor analysis model, and the establishment of a suitable sampling design it is necessary to consider other basic procedures. Sample collection and processing and the nature of the data thus produced, all of course, established prior to the processing of the purposive sample data need a more detailed consideration. That the description of sampling and processing procedures follows the discussion of the sampling design based on data they produced is only a reflection of the logical ordering of the major project description. The procedures are discussed in the following chapter.

Chapter 6

Particle Size Analysis

This chapter is necessarily a re-statement of the techniques used by Vincent (1969) and Beaumont (1967) in their investigations. The value of this is to introduce some limited standardisation in the reporting of results and thus enable comparison of the results to be made. Both Beaumont and Vincent comment on the relatively insignificant use made of particle-size analysis in British studies of glacial geomorphology. A brief synopsis of the uses of particle size analysis has been presented above (Chapter 5.3).

In a similar study Vincent (1969, p. 162) is able to categorise uses of particle size analysis in the following manner. Firstly, for purposes of correlation and discrimination, secondly, for studies of weathering, and thirdly, for interpretation and genetic significance. Of these groups only the second, the use of particle size analysis for weathering studies, is legitimately divorced from the other two in terms of the application of the work. To use any data for correlation and discrimination whilst disregarding the interpretation of the data and its genetic implications would seem at best to be disregarding a valuable information resource.

6.1 Particle Size Analysis as an Indicator of Environments of Deposition

The use of particle size analysis as a primary method of detecting sediments deposited in certain environments is a geological procedure which has been in use for many years. Much of the work done in the field was directly attributable to W.C. Krumbein and his early application of descriptive statistics to particle-size data. The early manual of laboratory procedures in sedimentary petrography by Krumbein and Pettijohn published in 1938 is still in current use. This text is in two distinct parts, Part One by Krumbein himself is devoted entirely to "Sampling, Preparation for Analysis, Mechanical Analysis, and Statistical Analysis".

Krumbein's success with these techniques and his specialisation in this field of study continues to the present day. The original text (Krumbein and Pettijohn, 1938) devoted 267 pages to a description of sampling techniques, laboratory procedures for mechanical analysis, and statistical processing of the data. This treatise did not involve major consideration of actual investigations it being primarily concerned with the presentation of techniques.

Since that date sedimentary petrography - or sedimentology as it is now known - has advanced rapidly many of the advances being the direct result of Krumbein's own work and the work of his students. Much of the work in the first two decades following the publication of the manual of sedimentary petrology was directed towards the establishing of descriptive statistics applicable to particle size data. The simpler measures such as mean, median and modal grain size, standard deviation, skewness and peakedness of the cumulative grain size curve were all included in the initial work.

The use to which these measures have been put in subsequent work is well summarised by King (1966), whose book provides a useful synthesis of this type of work in the section devoted to sediment analysis.

It is soon apparent that the majority of such work has been restricted to samples of coastal material particularly beach sands and extensions of this work to fluvial environments in some cases. The present work applies such measures to the suite of deposits in Upper Weardale. In so doing it necessarily involves an examination of the relationships of these measures and hence produces work for comparison with that done in the adjacent areas by Vincent and Beaumont.

6.2 Methods and Problems of Analysis

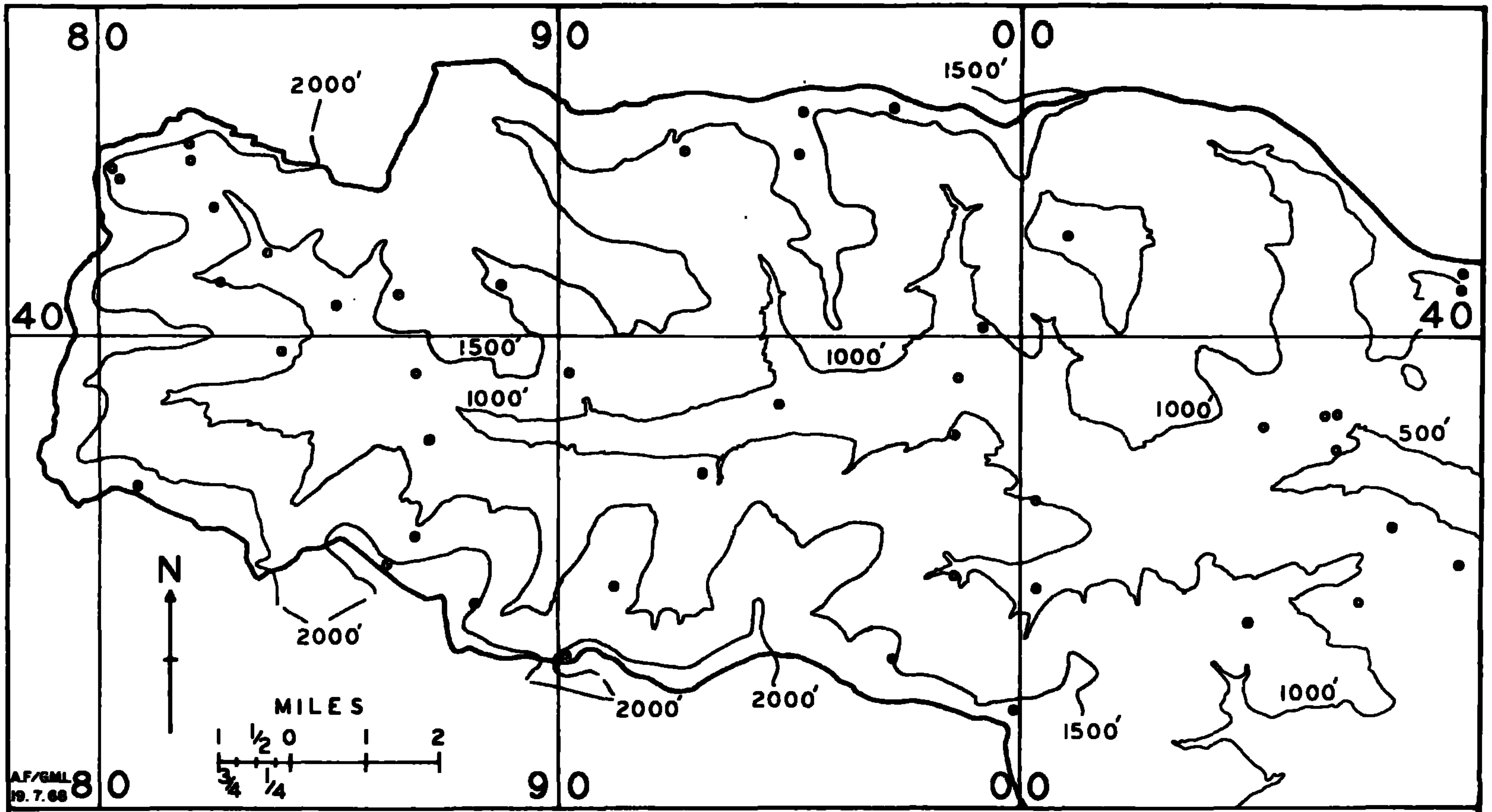
Sampling at the sites chosen in the random sample design is the first difficulty encountered. Table 6.1 lists the grid references of sites selected from random number tables and these are shown on Figure 6.1. They also form a directory to Appendix II which includes the sections and field notes from this sampling stage of the work. The quantity of the deposit to be taken as a sample and the way in which it is to be taken are both sampling problems. McClellan (personal communication 1969) indicates that there is a need to sample a glacial deposit so that the large particles - boulders and coarse gravels etc. form a part of the sample. He reasons that without this portion of the size curve the mechanical analysis of the sediment is probably meaningless.

Young (1966) also considers this problem in detail. Many of his remarks are particularly lucid and pertinent to this present discussion. He claims that most field scientists admit the need to take as large a sample as possible but then in actual studies they resort to the collection of a "small bagful" of the material sampled. Wentworth (1926) suggested a sample of 32kg as adequately representative of a

TABLE 6.1 List of Sites Chosen by Random Number Procedure

	Grid Reference
1	NY 808370
2	NY 825428
3	NY 826413
4	NY 836419
5	NY 840397
6	NY 852407
7	NY 865410
8	NY 862353
9	NY 869360
10	NY 873379
11	NY 883346
12	NY 888413
13	NY 903331
14	NY 912348
15	NY 927440
16	NY 931373
17	NY 947386
18	NY 952440
19	NY 952449
20	NY 962334
21	NY 962450
22	NY 992403
23	NY 997342
24	NZ 003348
25	NZ 010423
26	NZ 049341
27	NZ 080362
28	NZ 095353
29	NZ 097408
30	NZ 097493

Descriptions of the deposits and their layering at each site are given in Appendix II



UPPER WEARDALE

DISTRIBUTION OF SAMPLE SITES

• Random Sample

• Purposive Sample

Figure 6.1

deposit. Detailed studies indicate a requisite sample size as large as 50kg (Hörner, 1944) quartered down to 1500gms for laboratory work, this view was endorsed by Järnefors (1952) who maintains that this is the minimum acceptable size of sample. Other workers disagree. Holmes (1952) considers that a 15-20lbs sample is adequate, Dreimanis and Reaveley (1953) used samples of 1-2lbs and Shepps (1953) samples of 1.5kg-2.5kg. Work by Davis (1958) and Block (1960) used samples of 100/150lbs and 50lbs respectively. Young himself used samples of till weighing 100/120lbs.

Vincent adopts the published guide of the British Standards Institute (1961) Methods of testing soils for civil engineering purposes (B.S. 1377) given below, and selects a sample size of 2kg as being of manageable proportion.

TABLE 6.2

Size of Sample Required for Analysis

Maximum Size of Material Present in Substantial Proportions	Minimum Weight of Sample to be taken for Sieving	
Inches	lbs	kg
2½	110	50
2	77	35
1½	33	15
1	11	5
3/4	4.5	2

Beaumont (1967) also takes this decision and therefore both restrict their data to the particle range below 20mm. (c. 3/4"). The present author also adopts this basic restriction thereby changing the project to a consideration of the matrix of the superficial deposits of Upper Weardale. However, this restriction is accepted by most standard procedures of mechanical analysis because of the problems of handling large samples in the field and in the laboratory.

At the site the sampling of each layer was of the type described as a grab sample (Krumbein and Graybill, 1965) as this type of sample met the requirements of the project. "Grab samples, ... retain their individual variability as long as they are not combined into composite samples by placing two or more in one bag-" (Krumbein and Graybill, 1965, p. 62). As the grab samples were placed in polythene bags each large enough to contain about 4kg of field sample and the weight of the grab sample was about 4 kg there was little possibility that composite samples could be created by error. Polythene bags provide excellent sample containers and have the advantage that fines are not easily lost from them. Each grab sample bag was labelled with grid reference, depth and date of sampling and the polythene bag closed by use of a hand-stapler.

When returned to the laboratory these samples were dried in a constant temperature oven at 110°C and a representative 2000grm sample was obtained by quartering. A further 1000grms was gently broken up in a mortar using a rubber tipped pestle and this material was passed through a No.8.B.S. sieve. The material passing the No.8 sieve was used for chemical analyses. The total particle size range analysed was from 20mm to 0.001mm and the procedures used were those detailed by British Standard procedure B.S.1377, specifically wet and dry sieving for coarse analysis and hydrometer for finer materials to clay size. The average time required for the analysis of an individual sample was about 3 days.

6.3 MECHANICAL ANALYSIS DATA

The data obtained from the British Standard Procedure for testing soils are in the form of size classes with irregular intervals. The standard set of sieves used and the time intervals for taking hydrometer readings give individual point readings for the following particle sizes.

All figures in millimetres

20.0
13.0
9.7
6.0
4.7
3.2
2.0
1.2
0.6
0.4
0.3
0.2
0.15
0.10
0.075
0.062
0.046
0.038
0.027
0.016
0.013
0.0090
0.0066
0.0048
0.0043
0.0022
0.0014
0.0010

British Standard Procedure requires the plotting of the individual size values with the percentage of the material finer than the stated size on semi-logarithmic paper. The logarithmic scale being used for the particle size categories and the arithmetic scale for the percentage of material finer than the stated size. Both Beaumont (1967) and Vincent (1969) present their data in this way. The data from the present survey are not tabulated in this manner.

In sedimentology it is conventional to plot particle size curves on arithmetic probability paper. This is done for each sample taken and these plots are included in Appendix I and Appendix II together with description of the sites sampled in this survey. For general information all the sample size curves are drawn together on one graph as Figure 6.2. The tabulated data (see Table 7.2) provide sufficient information for the construction of size curves on semi logarithmic paper for reporting purposes. This is not undertaken here as the conventional plots given in the appendices provide the necessary illustration. Only in this specific case is the British Standard Procedure for particle size analysis not fully implemented.

Raw data in the form of presentation used in Table 7.2 are available for the purposes of comparison, however, for comprehension and illustration this table is of little value. Consequently Table 6.3 presents the data in a more usual form giving percentages of gravel, sand, silt and clay for each sample. This information is presented using the categories recommended by the British Standards Institute.

Medium Gravel	20mm	-	6mm	GRAVEL
Fine Gravel	6mm	-	2.0mm	
Coarse Sand	2.0mm	-	0.6mm	
Medium Sand	0.6mm	-	0.2mm	SAND
Fine Sand	0.2mm	-	0.6mm	

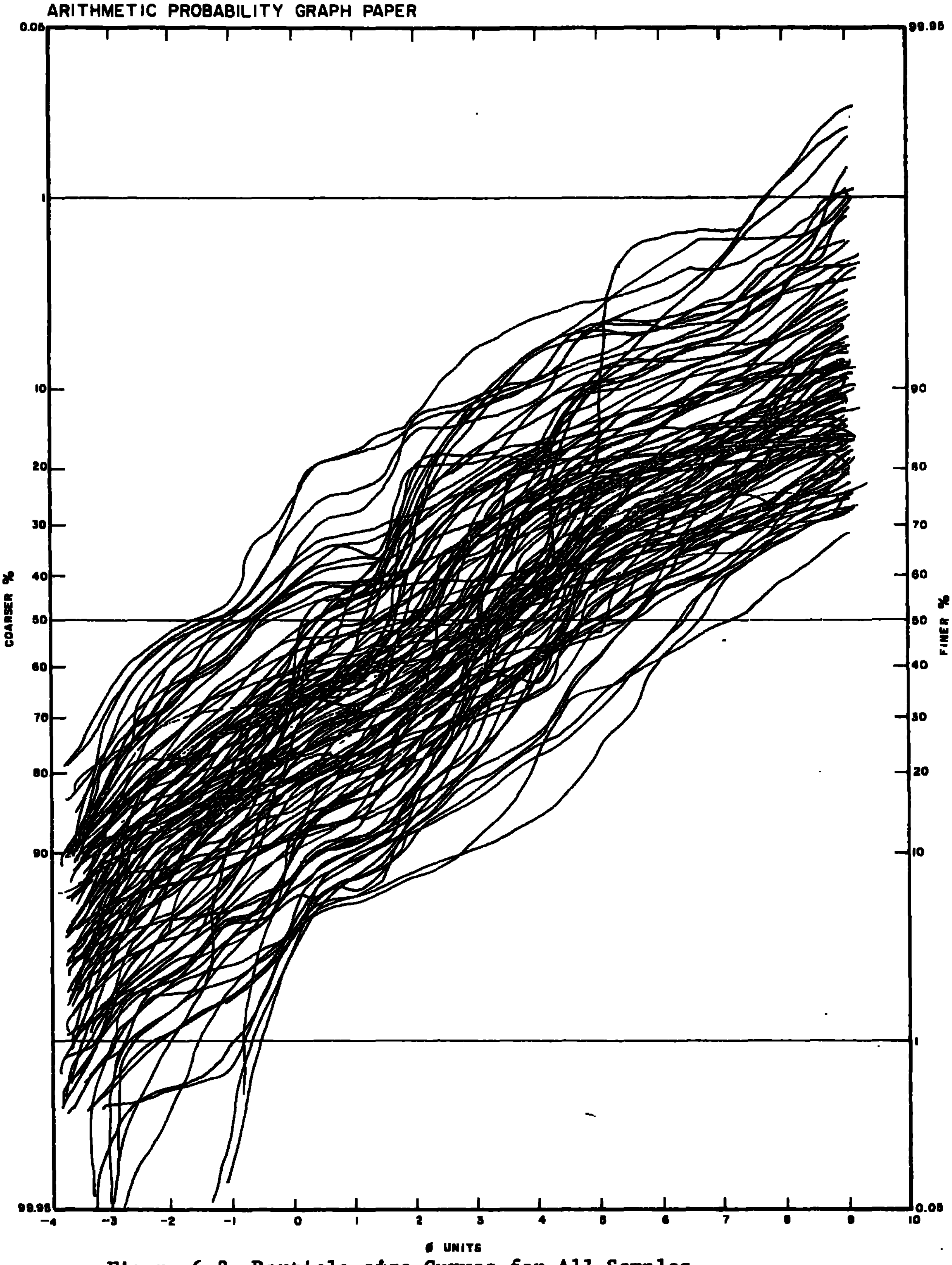


Figure 6.2 Particle-size Curves for All Samples

TABLE 6.3

PARTICLE SIZE DATA (GRAVEL, SAND, SILT, CLAY)

Part 1 PURPOSIVE SAMPLE

SAMPLE NO.	GRID REF	DEPTH CMS	PERCENTAGE GRAVEL	SAND	SILT	CLAY
P1	805435	100	2.5	59.5	19.2	18.8
P2		125	2.0	9.9	48.9	39.2
P3		150	21.4	3.3	33.9	41.4
P4		175	21.0	20.0	38.5	20.5
P5		200	30.5	31.7	26.1	11.7
P6		225	80.5	16.7	1.4	1.4
P7	806434	25	2.4	65.6	10.4	21.6
P8		200	31.0	47.6	12.6	8.8
P9	821443	150	2.9	58.0	24.9	14.2
P10		200	16.5	37.7	25.0	20.8
P11	823437	75	8.2	41.8	25.9	24.1
P12		100	5.5	20.5	49.7	24.3
P13		125	20.0	27.7	38.9	13.4
P14		140	14.5	17.5	41.2	26.8
P15		160	38.5	26.4	21.3	13.8
P16		185	41.0	28.3	25.7	5.0
P17	902394	100	5.0	33.0	31.7	30.3
P18	985352	300	12.5	26.9	29.7	30.9
P19	985381	45	10.5	28.6	35.3	25.6
P20		80	6.5	37.5	37.6	18.4
P21		110	36.6	22.9	29.7	10.8
P22		140	18.5	40.3	26.7	14.5
P23	985392	75	21.0	35.0	24.2	19.8
P24		135	16.8	22.8	33.0	27.4
P25		210	61.0	29.0	9.2	0.8
P26	003367	45	10.6	31.8	22.3	35.3
P27		90	12.4	25.8	29.9	31.9

SAMPLE NO.	GRID REF	DEPTH CMS	PERCENTAGE GRAVEL	SAND	SILT	CLAY
P28	003367	135	3.5	22.7	56.2	17.6
P29		180	10.2	30.3	39.5	20.0
P30		225	14.5	24.3	27.2	34.0
P31	054383	150	18.3	35.9	24.0	21.8
P32	067384	150	47.0	36.6	4.9	11.5
P33	068377	120	15.7	27.1	26.2	31.0
P34	068384	75	13.9	52.9	14.0	19.2
P35		120	1.4	40.6	22.0	36.0
P36		210	1.8	82.7	13.4	2.1
P37	074345	50	0.0	49.8	26.1	24.1
P38		105	0.0	48.3	24.5	27.2
P39		270	25.9	43.6	19.6	10.9
P40	173358	150	3.5	28.5	29.9	38.1
P41	205394	90	4.4	59.4	12.1	24.1
P42		110	5.7	24.5	43.6	26.2
P43		150	8.3	23.4	38.5	29.8
P44	236363	90	0.0	5.1	46.1	48.8
P45	244335	75	15.5	30.2	31.1	23.2
P46		135	3.4	26.9	41.5	28.2

PARTICLE SIZE DATA (GRAVEL, SAND, SILT, CLAY)

Part 2 RANDOM SAMPLE

SAMPLE NO.	GRID REF	DEPTH CMS	PERCENTAGE GRAVEL	SAND	SILT	CLAY
R1	808370	22	1.9	73.9	16.4	7.8
R2		30	13.5	62.1	15.0	9.4
R3		90	0.4	9.9	45.5	44.2
R4		180	5.4	56.9	26.8	10.9
R5	825428	90	21.8	40.1	18.7	19.4
R6		110	26.8	54.6	9.8	8.8
R7		160	27.1	44.3	15.7	12.9
R8	826413	45	32.3	25.2	18.9	23.6
R9		70	25.6	40.8	14.1	19.5
R10		225	6.3	34.6	34.9	24.2
R11	836419	22	30.0	17.3	51.9	0.8
R12		45	9.7	32.2	46.8	11.3
R13		60	4.7	17.7	45.4	32.2
R14	840397	30	17.8	32.2	30.5	19.5
R15		60	16.8	33.1	29.9	20.2
R16		90	15.8	28.2	29.7	26.3
R17		450	8.3	15.2	46.5	30.0
R18	852407	30	13.5	58.6	26.9	1.0
R19		60	29.4	35.3	20.1	15.2
R20		90	13.3	30.6	31.8	24.3
R21		105	24.2	33.9	29.4	12.5
R22		150	16.6	35.7	32.9	14.8
R23		180	19.8	39.6	26.2	14.4
R24	862353	75	0.2	42.6	43.0	14.2
R25		105	2.3	19.1	50.6	28.0
R26		120	18.1	30.6	41.3	10.0
R27		180	20.0	31.3	41.3	7.4

SAMPLE NO.	GRID REF	DEPTH CMS	PERCENTAGE GRAVEL	SAND	SILT	CLAY
R28	865410	22	2.9	31.5	38.2	27.4
R29		45	2.0	24.0	32.4	41.6
R30		120	33.5	36.6	22.3	7.6
R31		195	5.4	33.8	41.7	19.1
R32	869360	60	21.1	47.5	20.3	11.1
R33		75	45.2	35.9	14.2	4.7
R34		150	14.4	24.8	35.6	25.2
R35	869394	30	12.0	36.6	32.8	18.6
R36		60	14.6	37.7	21.7	26.0
R37		90	53.1	23.0	12.3	11.6
R38	873379	60	21.3	42.7	21.8	14.2
R39		180	13.0	31.1	23.9	32.0
R40	883346	30	3.8	49.6	28.7	17.9
R41		360	25.8	38.4	20.9	14.9
R42		90	10.4	41.3	24.3	24.0
R43	888413	90	10.9	43.3	27.0	18.8
R44		165	22.0	38.9	21.5	17.6
R45		195	6.0	35.8	41.1	17.1
R46	903331	90	12.1	60.7	21.4	5.8
R47		105	15.0	60.9	11.1	13.0
R48	912348	22	26.2	53.7	16.9	3.2
R49		90	18.0	60.5	18.2	3.3
R50	927440	30	50.0	32.2	9.1	8.7
R51		45	57.0	32.3	6.9	3.8
R52	931373	60	18.7	39.4	30.2	11.7
R53		75	49.6	28.4	14.7	7.3
R54		180	45.7	33.4	15.4	5.5
R55	947386	30	3.8	37.4	32.7	26.1
R56		60	15.8	40.5	28.9	14.8
R57		90	18.6	35.1	30.7	15.6

SAMPLE NO.	GRID REF	DEPTH CMS	PERCENTAGE GRAVEL	SAND	SILT	CLAY
R58	952440	75	25.8	23.8	22.4	28.0
R59		150	50.1	33.3	11.6	5.0
R60		240	22.3	49.7	21.1	6.9
R61		300	45.1	34.4	13.3	7.2
R62		30	0.7	33.5	36.6	29.2
R63		35	0.3	53.8	30.1	15.8
R64		45	5.8	37.7	45.3	11.2
R65		75	2.8	61.7	21.7	13.8
R66	962334	15	16.5	45.4	21.8	16.3
R67		30	42.7	28.9	11.8	16.6
R68		75	48.0	29.6	13.8	8.6
R69		240	52.2	38.3	7.8	1.7
R70	962450	30	6.7	50.5	25.5	17.3
R71		60	8.6	72.8	16.5	2.1
R72	992403	90	8.0	37.1	31.1	23.8
R73		120	12.7	33.1	23.5	30.7
R74		150	15.8	48.1	22.5	13.6
R75	997324	30	3.0	60.8	18.6	17.6
R76		45	5.8	56.6	19.2	18.4
R77		90	35.3	42.3	15.5	6.9
R78	3348	15	45.3	43.6	7.8	3.3
R79		90	18.3	68.3	10.1	3.3
R80		120	45.4	31.5	18.3	4.8
R81	10423	22	18.5	64.4	8.2	8.9
R82		60	79.9	10.6	3.9	5.6
R83		150	30.3	57.9	6.4	5.4
R84	49341	22	50.2	44.8	4.3	0.7
R85		45	40.0	50.8	7.0	2.2
R86		60	37.5	46.8	5.5	10.2
R87		120	15.7	42.1	29.0	13.2

SAMPLE NO.	GRID REF	DEPTH CMS	PERCENTAGE GRAVEL	SAND	SILT	CLAY
R88	80362	22	11.1	60.2	14.5	14.2
R89		38	10.0	70.8	8.6	10.6
R90		60	9.1	84.0	5.1	1.8
R91	95353	22	12.5	80.7	4.3	2.5
R92		45	20.2	49.6	15.1	15.1
R93	97408	45	22.1	37.3	23.4	17.2
R94		15	12.8	55.9	19.9	11.4
R95	97493	60	26.2	46.0	21.6	6.2
R96		270	16.1	37.7	37.0	9.2

Coarse Silt	0.06mm - 0.02mm		
Medium Silt	0.02mm - 0.006mm	SILT	
Fine Silt	0.006mm - 0.002mm		
Clay	less than 0.002mm	CLAY	

These categories provide a simpler summary of the data obtained. These data are presented in three groups the purposive sample data forming one group, the random sample data a second group, and the combined samples a third group. Histograms showing gravel, sand, silt and clay percentages are presented as Figure 6.3. These diagrams are for all samples taken from Upper Weardale and indicate that less than 20% gravel was the predominant amount reported from all samples (87 out of 139 samples which had a gravel content) although an extreme variation in gravel content from 0.0% to 80.5% is demonstrated. Variability in the sand content is equally great (3.3% to 84.0%) although the total data indicates a more nearly normal distribution about a modal group in the 30%-40% sand content.

Both silt and clay content show a much less extreme range. Silt ranges from 1.4% to 56.2% and clay 0.7% to 44.2%. Silt has an approximately normal distribution about a modal group in the 20-30% class, clay has a predominant number of samples reporting less than 20% content. Thus, the entire suite of deposits can be considered to be made up of a sand content in the 30-40% range on silt content in the 20-30% range and a gravel or clay content usually below 20%. When considering this type of data it provides some indication of a "typical" deposit from Upper Weardale. Whilst in a genetic sense this is only a gross generalisation it does provide some framework in which to consider

HISTOGRAMS OF GRAVEL, SAND, SILT AND CLAY CONTENT OF ALL SAMPLES TAKEN FROM SUPERFICIAL DEPOSITS IN UPPER WEARDALE

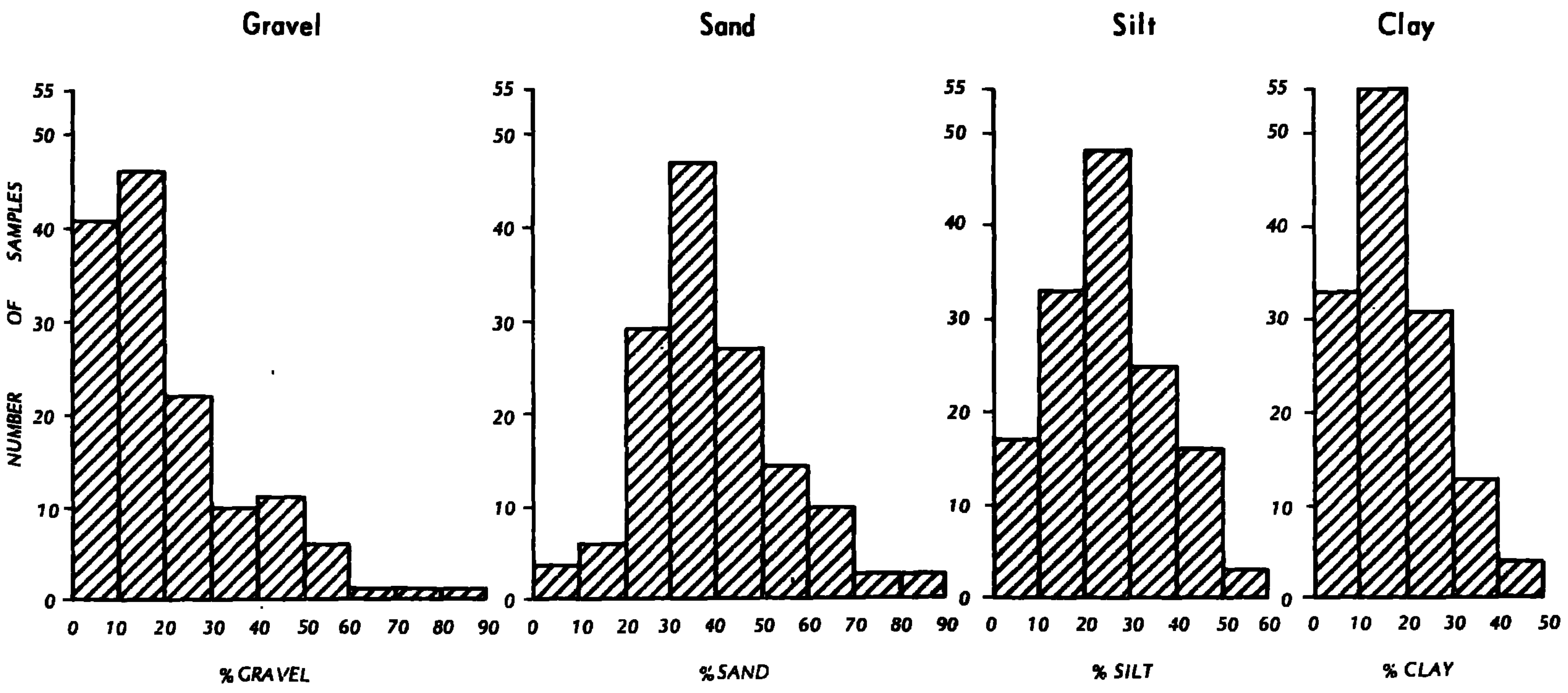


Figure 6.3

the nature of all samples taken from the area. Necessarily it indicates the nature of the superficial deposit generated in the region, and on this basis it is possible to introduce stochastic measures of similarity.

Figures 6.4 and 6.5 present the particle size data in two groups. Figure 6.4 presents the gravel, sand, silt and clay histograms for the purposive sample data, Figure 6.5 provides the same information for the random sample data. It is apparent that gravel, sand, silt and clay content does differ between these samples, and using chi-square tests for differences of mean values of gravel, sand, silt and clay the only significant difference is between the purposive and random samples (significant at the .95 level). The conclusion to be drawn from this result is that the purposive sample does not provide a valid sample of the whole suite of deposits. The reason for this is implicit in the sample name. Purposive sample collection was to test a technique and its ability to differentiate till samples from others. Consequently till and till-like samples were in the majority hence the tendency for this sample differ from a sample of the whole suite of deposits in the valley. In brief the purposive sample was biased because it included more than a representative amount of clay till. The nature of the data indicates that this difference would occur, on average 5 times in 100 samplings of the material even if no bias were involved. The present author concludes that the purposive sample was, therefore not unrepresentative of the deposits in Upper Weardale although it would be dangerous to use it alone as a truly representative sample.

HISTOGRAMS OF GRAVEL, SAND, SILT AND CLAY CONTENT OF THE PURPOSIVE SAMPLE TAKEN FROM THE SUPERFICIAL DEPOSITS OF UPPER WEARDALE

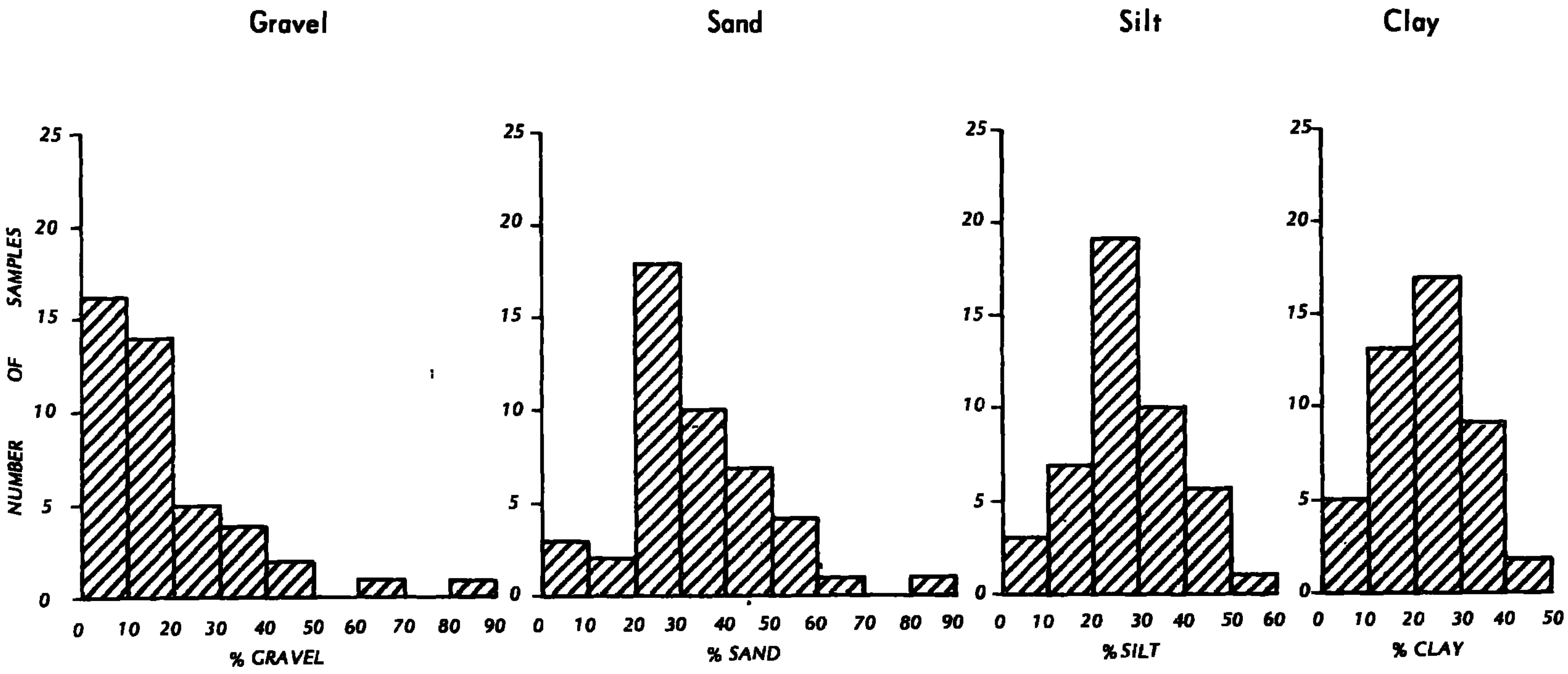


Figure 6.4

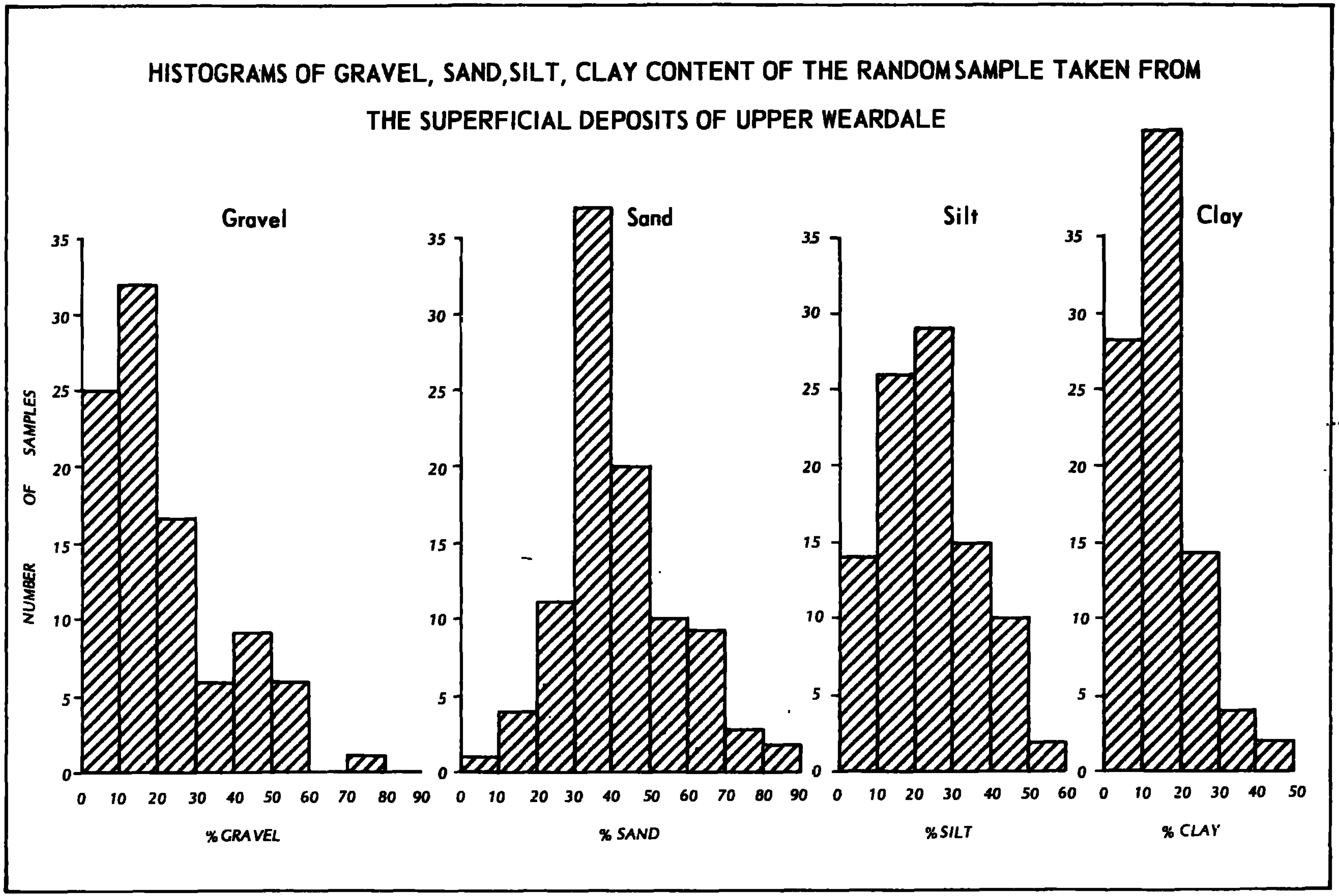

HISTOGRAMS OF GRAVEL, SAND, SILT, CLAY CONTENT OF THE RANDOM SAMPLE TAKEN FROM THE SUPERFICIAL DEPOSITS OF UPPER WEARDALE
Gravel
Sand
Silt
Clay
NUMBER OF SAMPLES
% GRAVEL
% SAND
% SILT
% CLAY

Figure 6.5

6.4 Characteristics of the Particle Size Data

The data presented in Table 7.2 and Figure 6.2 are in an elementary form. The further "refinement" of these data into categories of gravel, sand, silt and clay does not meet the conventional pattern of data transformation into the categories of sand, silt and clay for the construction of a triangular diagram frequently used in data presentation both by geomorphologists (Vincent, 1969, Beaumont, 1967) Pleistocene geologists (Dreimanis and Reavely, 1953) and soil scientists (Atkinson, 1968). The data are, therefore recalculated excluding the 'gravel' category to provide sand, silt and clay data for plotting on triangular diagrams. These recalculated data are presented as Table 6.4.

At this point the data are being considered as field data or, more correctly "ground truth information". The statistical measures produced are therefore descriptive. Consequently the triangular diagram presented as Figure 6.6 shows the plot of all data by field classification and particle size composition (sand, silt, clay range only). The result certainly parallels that experienced by Vincent who comments "... no meaningful groups emerge" when he examines a plot of all his data on three-coordinate graph paper (Vincent, 1969, p. 171). In an attempt to summarise the content of this diagram (Figure 6.6) the same data are presented as histograms of sand, silt and clay content as Figure 6.7. Figures 6.8 and 6.9 present the purposive and random sample data in histogram form for sand, silt, clay data but the pertinent triangular graphs have been omitted as they offer a similar structure to Figure 6.6 and no clarification results. Figure 6.10 attempts a clarification of the data presentation by separating the field classification

TABLE 6.4

PARTICLE SIZE DATA (SAND, SILT, CLAY)

Part 1 PURPOSIVE SAMPLE

SAMPLE NO.	GRID REF.	DEPTH CMS.	PERCENTAGE SAND	SILT	CLAY
P1	805435	100	61.0	19.7	19.3
P2		125	10.1	49.9	40.0
P3		150	4.2	43.1	52.7
P4		175	25.3	48.7	25.9
P5		200	45.6	37.6	16.8
P6		225	85.6	7.2	7.2
P7	806434	25	67.2	10.7	22.1
P8		200	69.0	18.3	12.8
P9	821443	150	59.7	25.6	14.6
P10		200	45.1	29.9	24.9
P11	823437	75	45.5	28.2	26.3
P12		100	21.7	52.6	25.7
P13		125	34.6	48.6	16.7
P14		140	20.5	48.2	31.3
P15		160	42.9	34.6	22.4
P16		185	48.0	43.6	8.5
P17	902394	100	34.7	33.4	31.9
P18	985352	300	30.7	33.9	35.3
P19		45	32.0	39.4	28.6
P20		80	40.1	40.2	19.7
P21		110	36.1	46.8	17.0
P22		140	49.4	32.8	17.8
P23	985392	75	44.3	30.6	25.1
P24		135	27.4	39.7	32.9
P25		210	74.4	23.6	2.1
P26	003367	45	35.6	24.9	39.5
P27		90	29.5	34.1	36.4
P28		135	23.5	58.2	18.2
P29		180	33.7	44.0	22.3
P30		225	28.4	31.8	39.8

SAMPLE NO.	GRID REF.	DEPTH CMS.	PERCENTAGE SAND	SILT	CLAY
P31	054383	150	43.9	29.4	26.7
P32	067384	150	69.1	9.2	21.7
P33	068377	120	32.1	31.1	36.8
P34	068384	75	61.4	16.3	22.3
P35		120	41.2	22.3	36.5
P36		210	84.2	13.6	2.1
P37	074345	50	49.8	26.1	24.1
P38		105	48.3	24.5	27.2
P39		270	58.8	26.5	14.7
P40	173358	150	29.5	31.0	39.5
P41	205394	90	62.1	12.7	25.2
P42		110	26.0	46.2	27.8
P43		150	25.5	42.0	32.5
P44	236363	90	5.1	46.1	48.8
P45	244335	75	35.7	36.8	27.5
P46		135	27.8	43.0	29.2

PARTICLE SIZE DATA (SAND, SILT, CLAY)

Part 2 RANDOM SAMPLE

SAMPLE NO.	GRID REF.	DEPTH CMS.	PERCENTAGE SAND	SILT	CLAY
R1	808370	22	75.3	16.7	8.0
R2		30	71.8	17.3	10.9
R3		90	9.9	45.7	44.4
R4		180	60.1	28.3	11.5
R5	825428	90	51.3	23.9	24.8
R6		110	74.6	13.4	12.0
R7		160	60.8	21.5	17.7
R8	826413	45	37.2	27.9	34.9
R9		70	54.8	19.0	26.2
R10		225	36.9	37.2	25.8
R11	836419	22	24.7	74.1	1.1
R12		45	35.7	51.8	12.5
R13		60	18.6	47.6	33.8
R14	840397	30	39.2	37.1	23.7
R15		60	39.8	35.9	24.3
R16		90	33.5	35.3	31.2
R17		450	16.6	50.7	32.7
R18	852407	30	67.7	31.1	1.2
R19		60	50.0	28.5	21.5
R20		90	35.3	36.7	28.0
R21		105	44.7	38.8	16.5
R22		150	42.8	39.4	17.7
R23		180	49.4	32.7	18.0
R24	862353	75	42.7	43.1	14.2
R25		105	19.5	51.8	28.7
R26		120	37.4	50.4	12.2
R27		180	39.1	51.6	9.2
R28	865410	22	32.4	49.3	28.2
R29		45	24.5	33.1	42.4
R30		120	55.0	33.5	11.4
R31		195	35.7	44.1	20.2

SAMPLE NO.	GRID REF.	DEPTH CMS.	PERCENTAGE SAND	SILT	CLAY
R32	869360	60	60.2	25.7	14.1
R33		75	65.5	25.9	8.6
R34		150	29.0	41.6	29.4
R35	869394	30	41.6	37.3	21.1
R36		60	44.1	25.4	30.4
R37		90	49.0	26.2	24.7
R38	873379	60	54.3	27.7	18.0
R39		180	35.7	27.5	36.8
R40	883346	30	51.6	29.8	18.6
R41		360	51.8	28.2	20.1
R42		90	46.1	27.1	26.8
R43	888413	90	48.6	30.3	21.1
R44		165	49.9	27.6	22.6
R45		195	38.1	43.7	18.2
R46	903331	90	69.1	24.3	6.6
R47		105	71.6	13.1	15.3
R48	912348	22	72.8	22.9	4.3
R49		90	73.8	22.2	4.0
R50	927440	30	64.4	18.2	17.4
R51		45	75.1	16.0	8.8
R52	931373	60	48.5	37.1	14.4
R53		75	56.3	29.2	14.5
R54		180	61.5	28.4	10.1
R55	947386	30	38.9	34.0	27.1
R56		60	48.1	34.3	17.6
R57		90	43.1	37.7	19.2
R58	952440	75	32.1	30.2	37.7
R59		150	66.7	23.2	10.0
R60		240	64.0	27.2	8.9

SAMPLE NO.	GRID REF.	DEPTH CMS.	PERCENTAGE SAND	SILT	CLAY
R61	952440	300	62.7	24.2	13.1
R62		30	33.7	36.9	29.4
R63		35	54.0	30.2	15.8
R64		45	40.0	48.1	11.9
R65		75	63.5	22.3	14.2
R66	962334	15	54.4	26.1	19.5
R67		30	50.4	20.6	29.0
R68		75	56.9	26.5	16.5
R69		240	80.1	16.3	3.6
R70	962450	30	54.1	27.3	18.5
R71		60	79.6	18.1	2.3
R72	992403	90	40.3	33.8	25.9
R73		120	37.9	26.9	35.2
R74		150	57.1	26.7	16.2
R75	997324	30	62.7	19.2	18.1
R76		45	60.1	20.4	19.5
R77		90	65.4	24.0	10.7
R78	3348	15	79.7	14.3	6.0
R79		90	83.6	12.4	4.0
R80		120	57.7	33.5	8.8
R81	10423	22	79.0	10.1	10.9
R82		60	52.7	19.4	27.9
R83		150	83.1	9.2	7.7
R84	49341	22	90.0	8.6	1.4
R85		45	84.7	11.7	3.7
R86		60	74.9	8.8	16.3
R87		120	49.9	34.4	15.7
R88	80362	22	67.7	16.3	16.0
R89		38	78.7	9.6	11.8
R90		60	92.4	5.6	2.0
R91	95353	22	92.2	4.9	2.9
R92		45	62.2	18.9	18.9
R93	97408	45	47.9	30.0	22.1
R94		15	64.1	22.8	13.1
R95	97493	60	62.2	29.3	8.4
R96		270	44.9	44.1	11.0

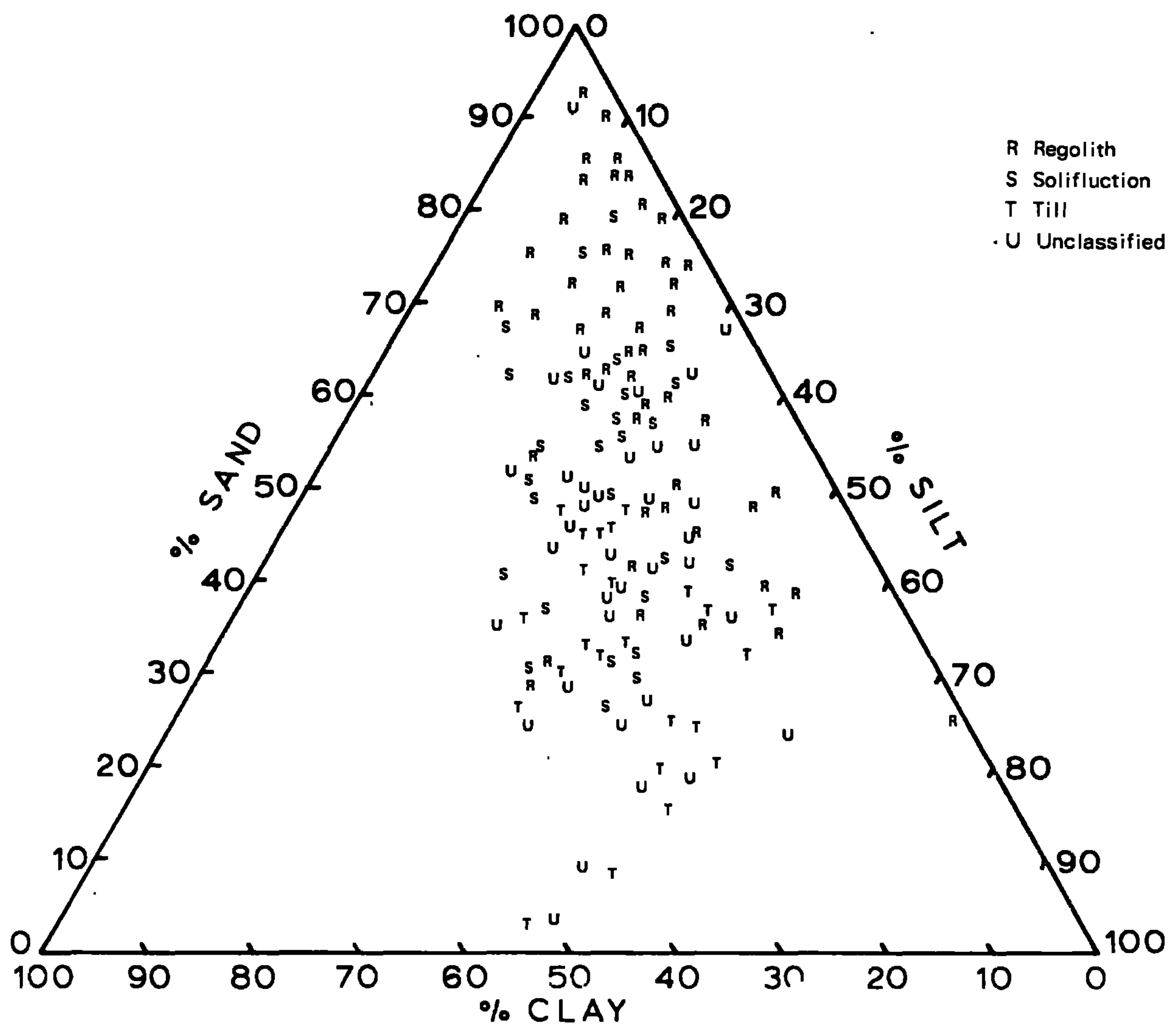


Figure 6.6 Triangular Diagram of All Samples by Field Classification

HISTOGRAMS OF THE SAND, SILT AND CLAY CONTENT OF ALL SAMPLES TAKEN FROM

THE SUPERFICIAL DEPOSITS IN UPPER WEARDALE

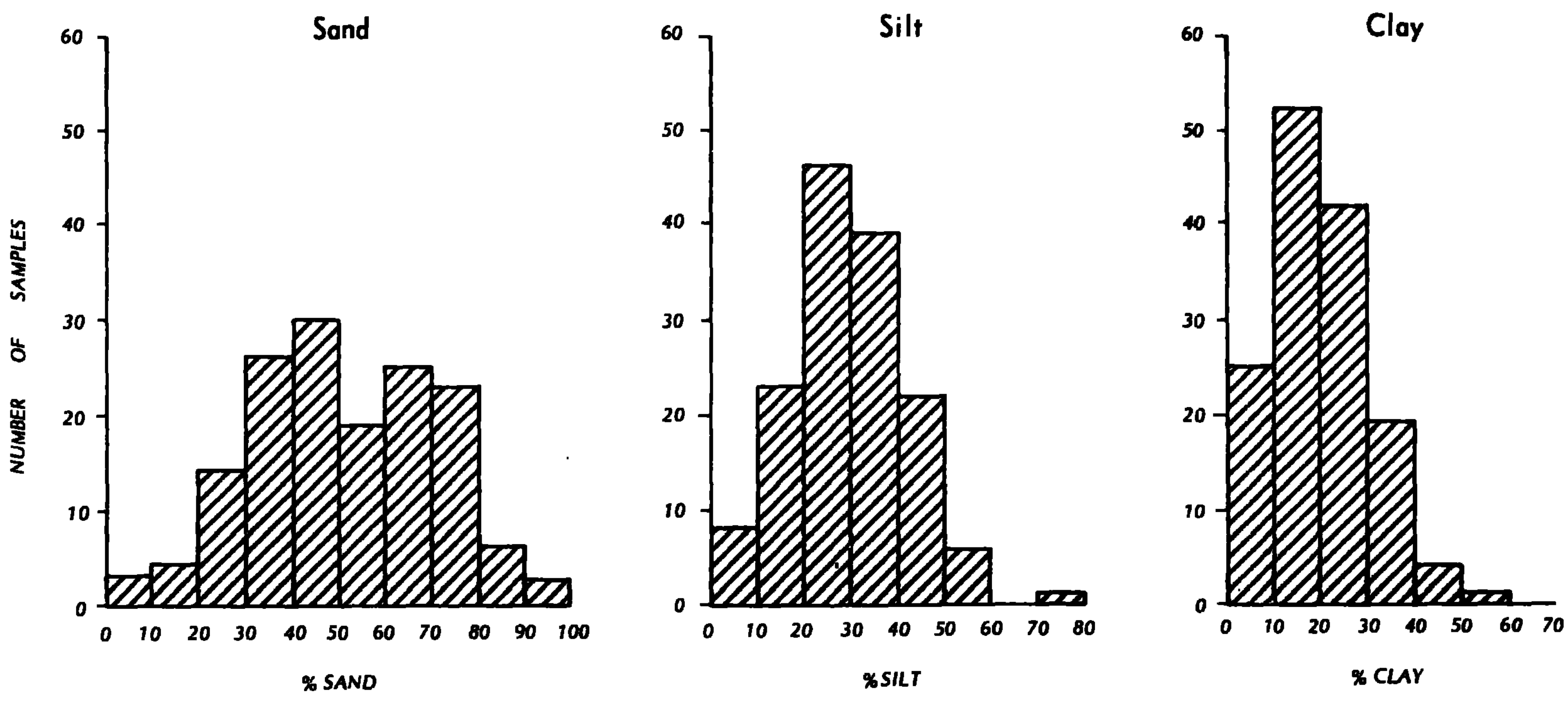


Figure 6.7

HISTOGRAMS OF THE SAND, SILT AND CLAY CONTENT OF THE PURPOSIVE SAMPLE TAKEN FROM THE SUPERFICIAL DEPOSITS IN UPPER WEARDALE

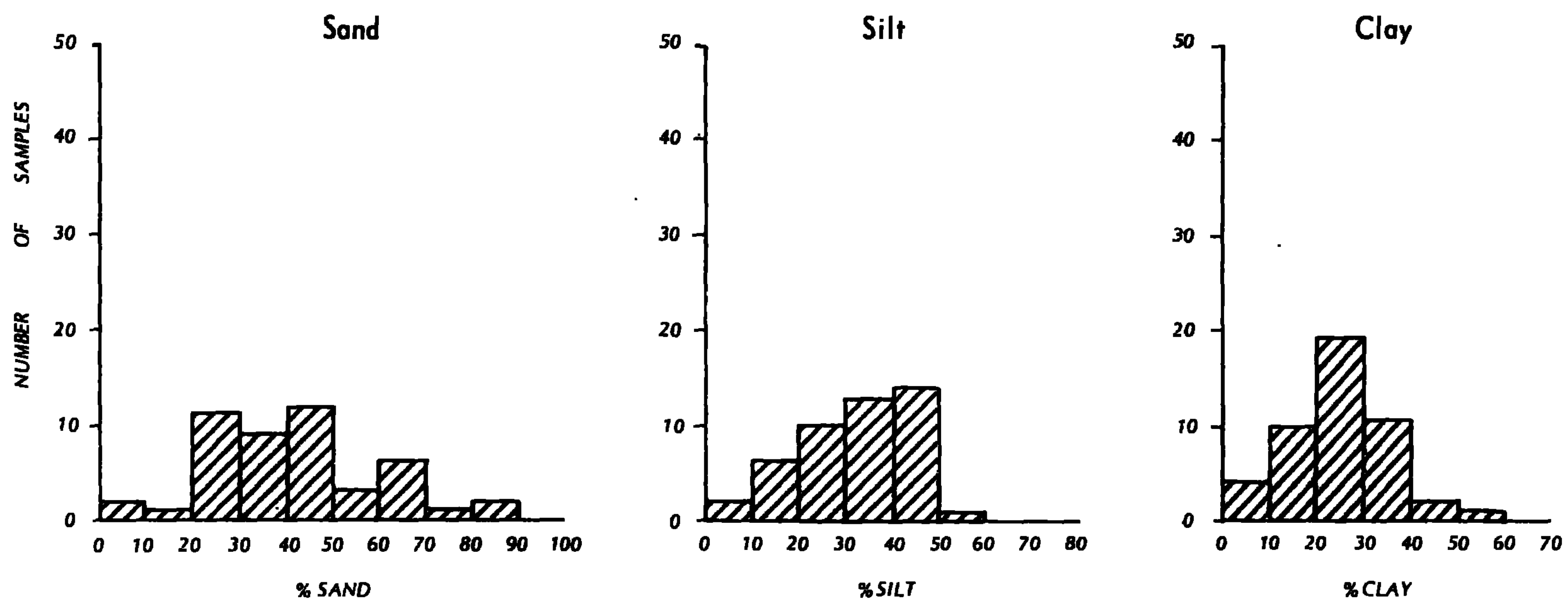


Figure 6.8

HISTOGRAMS OF THE SAND, SILT AND CLAY CONTENT OF THE RANDOM SAMPLE TAKEN FROM THE SUPERFICIAL DEPOSITS IN UPPER WEARDALE

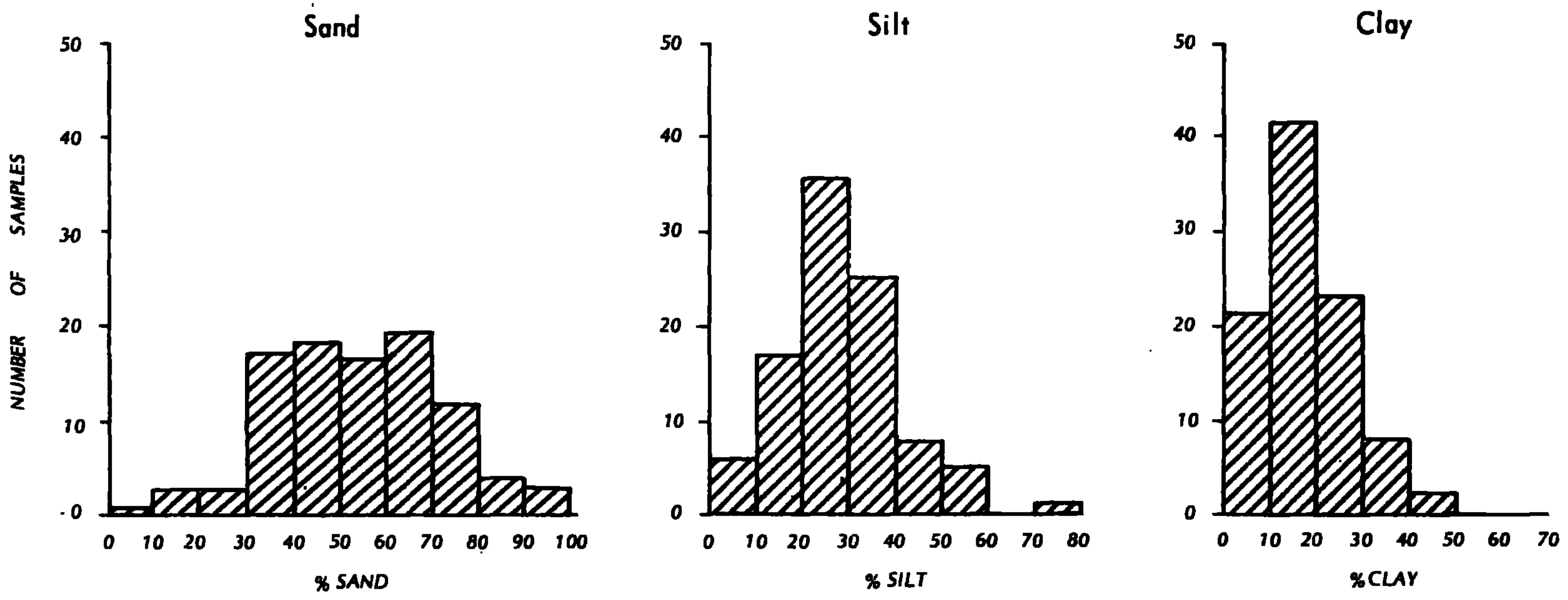


Figure 6.9

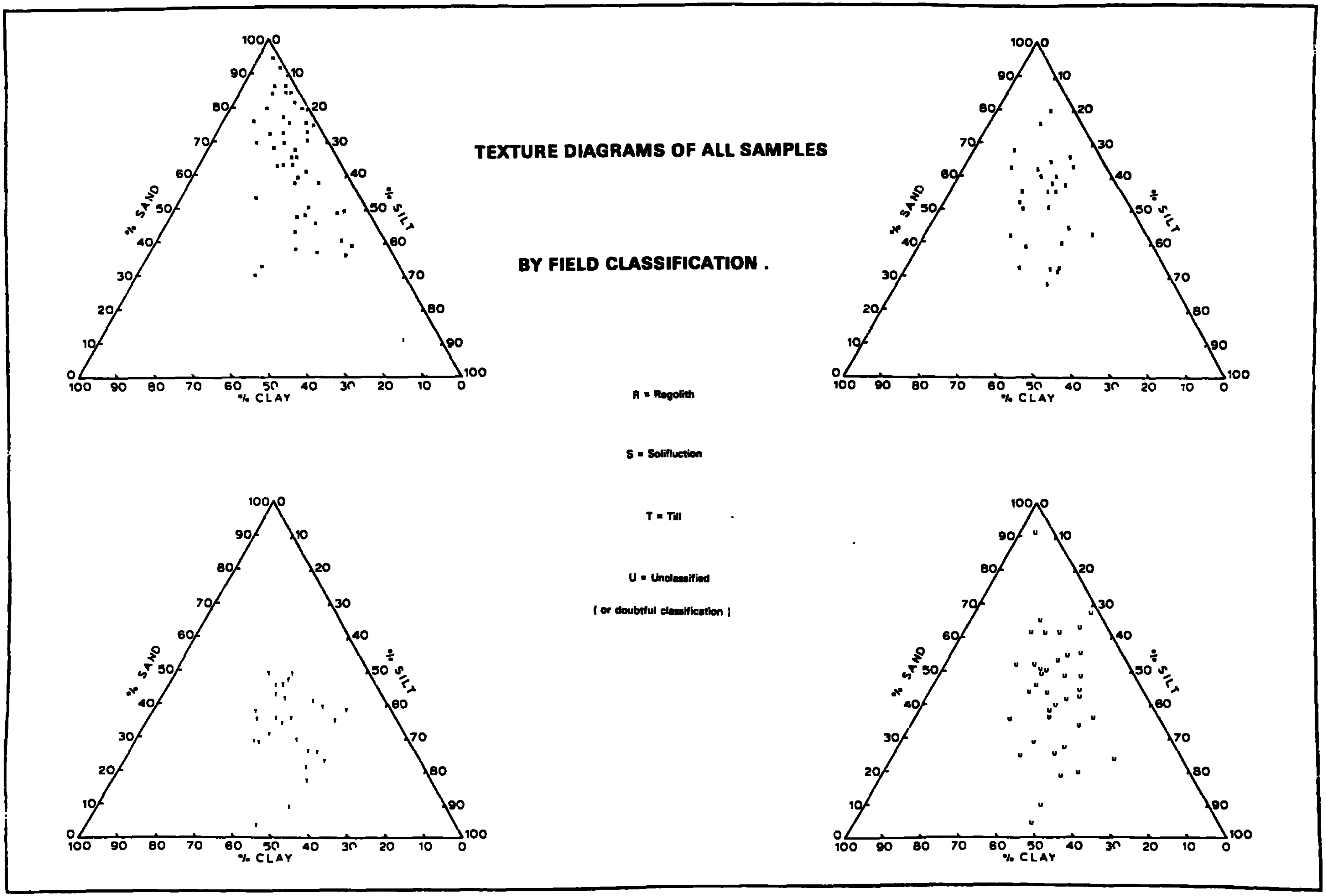

TEXTURE DIAGRAMS OF ALL SAMPLES
BY FIELD CLASSIFICATION .
% SAND
% SILT
% CLAY
R = Regolith
S = Solifluction
T = Till
U = Unclassified
(or doubtful classification)

Figure 6.10

of superficial deposits into component groups. Each is plotted on its diagram to give an area of the graph within which each of the field groupings occur. These areas are shown together in Figure 6.11. The field group classified as "till" is plotted on Figure 6.12 with the data of both Vincent's tills of the north-west Alston Block and Beaumont's Lower Till of County Durham.

It is apparent from Figures 6.11 and 6.12 that some consensus exists in the field recognition of till. Figure 6.12 demonstrates the relationships between sand, silt and clay content of the tills recognised in north-east England. There is, however, no presently available method of assessing the validity of the boundary members of this classification. Figure 6.11 indicates that some members of the "solifluction" and "regolith" categories from field classification have a higher sand content than till. Of these two categories some solifluction material appears to have higher silt content. Figure 6.11 therefore indicates that some deposits recognised in the present survey as solifluction deposits are similar to the sandier samples of Vincent's erratic free tills. Similarly a few samples of the Lower Till of County Durham with low clay content have textural characteristics comparable to the siltier regolith of the present author's field classification.

These apparent conflicts of classification do not yet have precise and objectively assessed parameters to clarify the situation further. However, it seems that materials derived in most cases from the same parent lithology (the Yoredale series) would demonstrate some textural similarities. Analysis of these similarities is therefore of great importance.

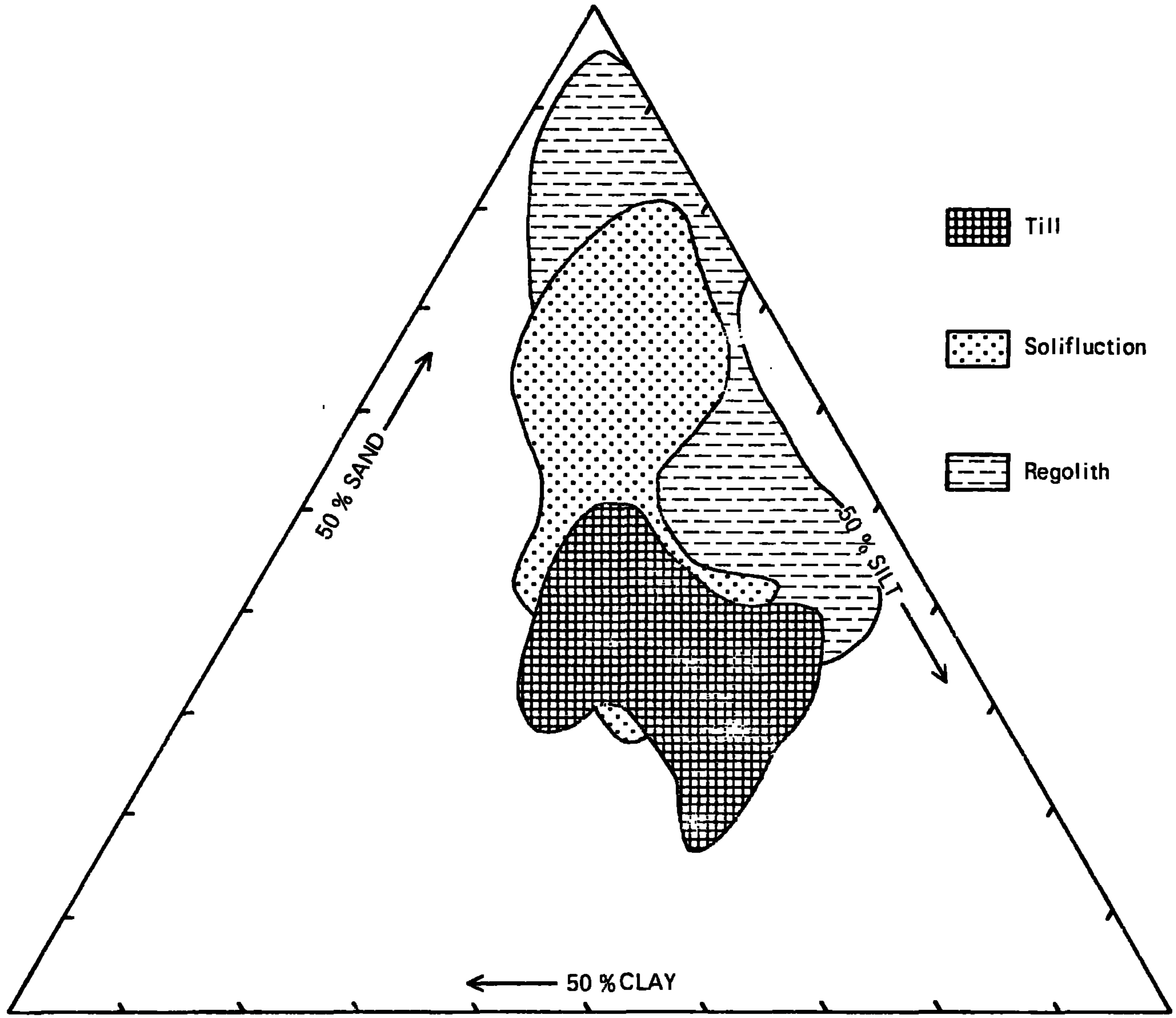


Fig. 6.11 Texture types included within the three part field classification.

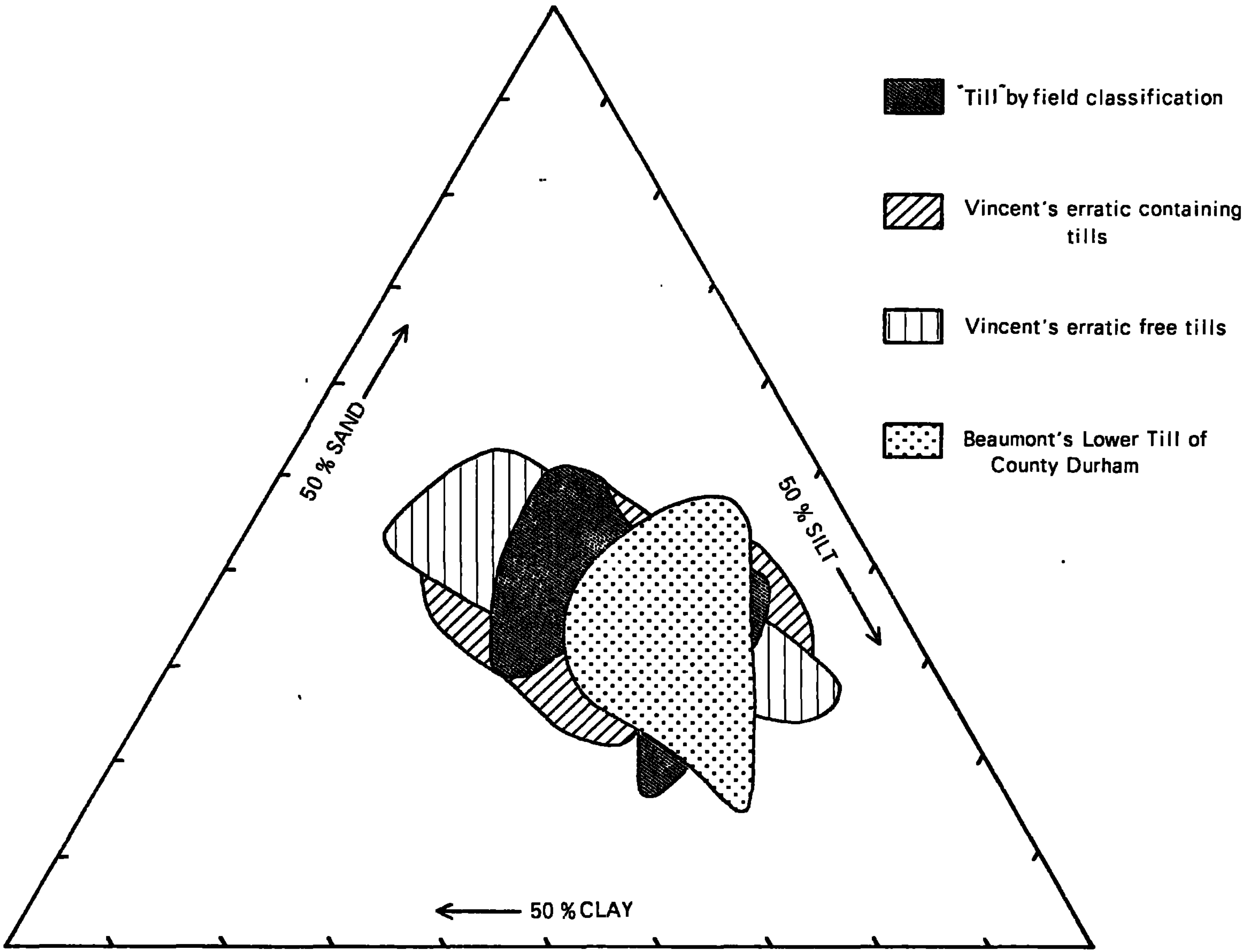


Fig. 6.12 Comparison of "Till" texture by field classification with till from adjacent areas .

6.5 Statistical Analysis of Particle Size Data

The British Standards Institute method of reporting particle size data on semi-logarithmic graph paper departs from established practice in sedimentology, and produces curves which are therefore of less value in assessing the nature of a deposit. Scrutiny of the typical slope of these curves led Beaumont to investigate a "break of slope" apparent in the curves for the samples of till he analysed in Eastern Durham. He demonstrated that this was associated with the change in the nature of the sediment from a dominance of rock fragments to a dominance of mineral grains. (Beaumont, 1967). Dreimanis demonstrates this also relating it to the bimodality observed in his analyses of tills in North America (Dreimanis, personal communication). The bimodality (and therefore the "break of slope") is more easily observed on the conventional cumulative size curves for sediments plotted on arithmetic probability graph paper.

It has long been recognised that sediments tend to be log normal in their cumulative size distribution. Krumbein and Pettijohn (1938) state this in their discussion of the grade scales which may be used in the presentation of particle-size data. They conclude that geometric scales offer advantages for statistical analysis and adopt the phi notation for particle size data. The phi notation is a logarithmic transformation of the data which uses the negative value of the base two logarithm of the particle size in millimetres. Stated numerically this is

$$\phi = -\log_2 (\text{size mm.})$$

Consequently 1 mm has a phi value of 0. As particle size increases from 1 mm phi values become negative. As size decreases from 1 mm phi values increase. This grade scale has the advantage that it avoids the use of fractions or extended decimals and for most published particle size data the results are positive. The result is that the phi scale provides a transformation of the data so that when it is used, original data plotted arithmetically become a logarithmic representation of the original values. The approximation to normal distribution in many sediments is best demonstrated by using probability paper on which the scale is adjusted so that a cumulative size curve for a normal distribution (using the phi scale for size categories) plots as a diagonal straight line.

King summarises this whole topic by reference to the conversion table for ϕ units from millimetres taken from Inman's 1952 paper. Her comments extend beyond the general points given above to comment on the use of arithmetic probability paper. She states that the ϕ and % coarser plotted on the ordinate and abscissa respectively

> "... can be plotted on ordinary graph paper, but in this case the curve at the top and bottom becomes very difficult to interpret. A normal sediment on this type of graph will be shown as an S-shaped curve, starting at the bottom left of the graph and extending to the top right. As the tail of the curve is of considerable importance in analysing the characteristics of a sediment, it is important that values of percentage coarser should be accurately read from this part of the curve. This can be done if the figures are plotted on arithmetic probability paper, the probability scale being used on the abscissa for plotting the percentage coarser values. This type of paper has the advantage that the normal distribution curve is a straight line on it, so that this provides a useful means of assessing the normality of the distribution at a glance. ... The values of

significant percentage coarser figures can be read direct from the graph, and the ones that are mainly used are the 5, 16, 25, 50, 75, 84 and 95% coarser figures." (King, 1966, pp. 278-279).

From these percentile figures various measures of the particle size distribution curve have been derived. All these measures are descriptive statistics attempting to "... furnish a series of numbers for each sample, as an aid in describing and classifying sediments." (Krumbein and Pettijohn, 1938, p. 228). This work therefore comes within the first of three viewpoints expressed by Krumbein and Pettijohn (1938). They claim that the viewpoint represented by one group of workers in sedimentology "has not concerned itself directly with statistical theory, on the ground that conventional devices furnish too few numbers for detailed work." (Krumbein and Pettijohn, 1938, p. 228). It is such a group which has applied various measures to particle size data to obtain "a series of numers" (descriptive statistics) "as an aid in describing and classifying sediments" (empirical description of subjectively established classifications).

That these descriptive statistics exist and are published for large numbers of data provides a basis for assessing their value in the present study. The use of these measures by Vincent (1969) and Beaumont 1967) provides the pattern on which the following section is based for purposes of standardisation and comparison.

6.51 Central Tendency

Median

The measure of central tendency most often used was the median diameter, that is, the 50% value on the cumulative frequency graph, which defines the size separating the sample into two equal portions by weight. The median however takes no account of the distribution of the grain size on either side of the 50% value.

Values of the median for this survey show an absolute range from −3.0 ϕ to 7.9 ϕ. Histograms of median values for all the data and for the purposive and random samples are presented as Figure 6.13. The mean value of the median of each of the members of the purposive sample is 3.81 ϕ with a standard deviation of 2.35. The mean value of the random sample median values is 2.58 ϕ with a standard deviation of 2.02. The total data have a mean value for the median of 2.98 ϕ with a standard deviation of 2.2026. Differences in the mean values of the median between the purposive and random samples are significant at the 99.6% level. That this should be so is a further reflection of the differences established in consideration of the gravel, sand, silt and clay contents. The purposive sample with a median size of 3.81 ϕ is clay rich hence the median tends to be in the finer particle size. The sandier random sample therefore has a median in a slightly coarser size range viz. 2.58ϕ.

These values for the whole suite of deposits are, predictably more extreme than the values established by Vincent for the tills of the north-west Alston Block. Comparisons of values and parameters however, are not appropriate at this stage, as the field assessment of the samples used in this study was not intended to be the basis of comparison and assessment of classes of data between these studies. The present data only represent the superficial deposits of Upper Weardale and therefore have an extreme variability encompassing all sediment types present in

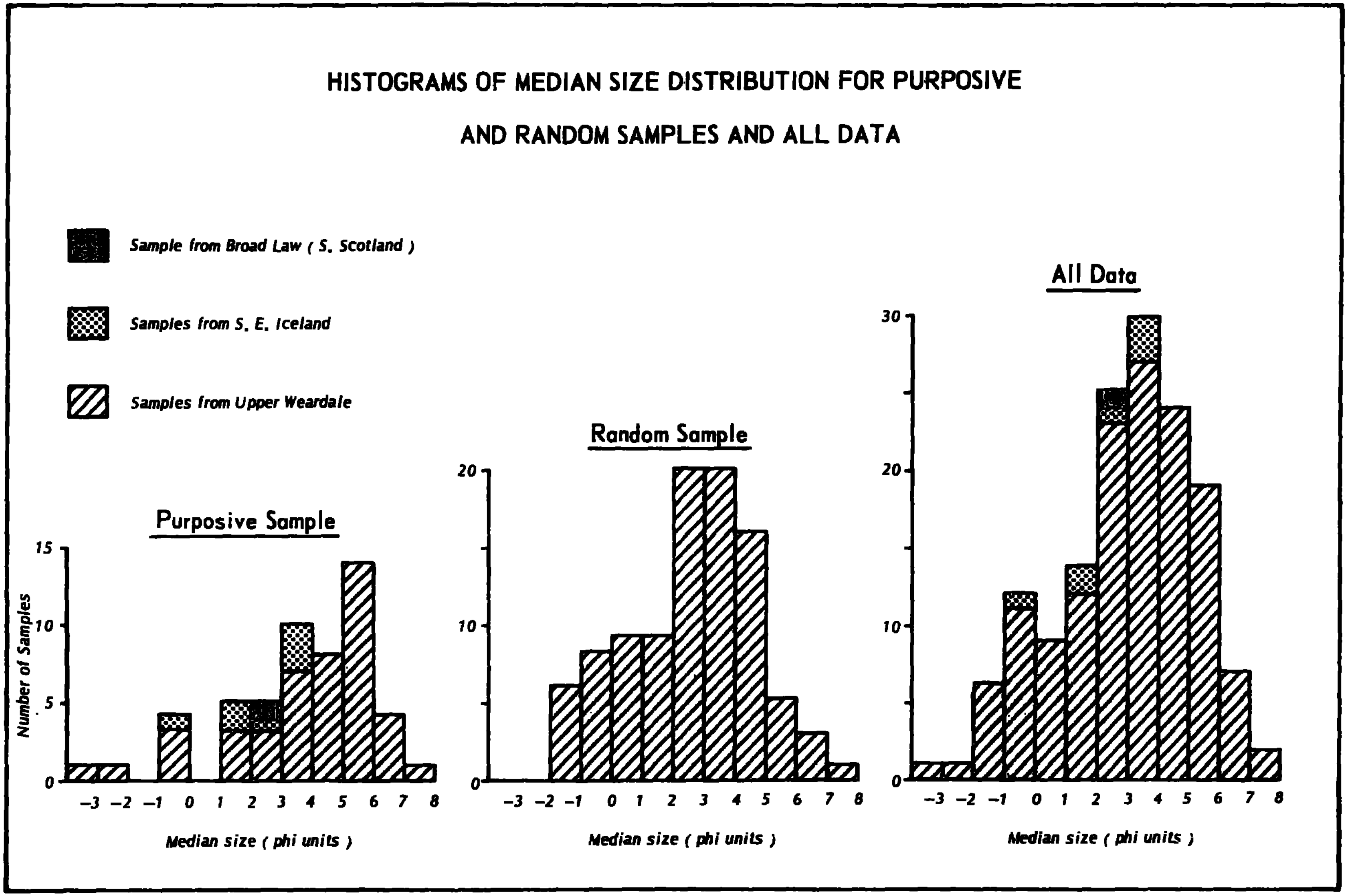

HISTOGRAMS OF MEDIAN SIZE DISTRIBUTION FOR PURPOSIVE
AND RANDOM SAMPLES AND ALL DATA
Sample from Broad Law (S. Scotland)
Samples from S. E. Iceland
Samples from Upper Weardale
Purposive Sample
Random Sample
All Data
Number of Samples
0
5
10
15
20
30
-3 -2 -1 0 1 2 3 4 5 6 7 8
Median size (phi units)

Figure 6.13

that area. Because of the doubt about the applicability of difference of means test where the data are not normally distributed these results were checked using the non-parametric chi-square test which showed that the purposive and random samples differed at the .995 level of significance.

Mean

The mean is the arithmetic average of the particle sizes occurring in the sample. Precise measurement of each particle to give the raw data for calculation of the mean is obviously not possible. In consequence several methods of obtaining the mean value have been established. All represent approximations to the required parameter and consequently it is possible to comment on the efficiency of each. Inman (1952) proposed a measure of the mean (expressed in phi units) which he defined as

$$M\phi = \tfrac{1}{2}(\phi 16 + \phi 84)$$

Folk and Ward (1957) subsequently modified this to offer a value defined as

$$Mz = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

McCammon (1962) analysed the efficiency of several such measures and produced the following assessment of them.

(i) $M\phi = \tfrac{1}{2}(\phi 16 + \phi 84)$ 74% efficient

(ii) $Mz = (\phi 16 + \phi 50 + \phi 84) / 3$ 88% efficient

(iii) $M\phi = \phi 5 + \phi 15 + \phi 25 + \phi 35 + \phi 45 + \phi 55 + \phi 65 + \phi 75 + \phi 85 + \phi 95$ $/ 10$ 97% efficient

He therefore proposed that equation (iii) be used to calculate the value of the mean grain-size. The particular value of the mean is that it is more suitable for further mathematical analysis than the median. If the distribution of the sample is symmetrical the mean and median values are coincident. In the majority of cases the sample curve is asymmetrical and the median and mean values differ. This difference can be used to compute the degree of asymmetry of the curve (see below).

All the above formulae use measures derived from the cumulative size curve. The techniques of particle-size analysis offer only the basic information for the construction of a particle-size curve. Consequently it is from this curve that other measures are determined. These measures are established graphically and are based on the intercept of the particle size curve and a specified percentile measure. Hence, in the above formulae, and all others dealing with the descriptive statistics of particle size data, $\phi 16$ is the ϕ value of the sixteenth percentile etc. The median therefore is the fiftieth percentile or $\phi 50$. It is also pertinent to note that the ϕ notation, representing a logarithmic transformation of the data gives a relationship between ϕ units and millimetres such that $M\phi$ gives the arithmetic mean of the sample in ϕ units which is also the geometric mean measured in millimetres.

Folk and Ward (1957) introduced their measure of mean size (in phi units) as a refinement of Inman's measure which is not satisfactory for asymmetrical or bimodal curves. Whilst the McCammon formula is the most efficient estimator of the value of the mean it is not always possible to read the 5th and 95th percentile values from the cumulative size curve. For this reason the Folk and Ward formula was adopted for measurement of the mean values.

Values of the mean for the total data and the purposive and random samples are presented as a series of histograms in Figure 6.14. Testing the difference of the distribution of mean values using the chi-square test reveals that the difference between the random and purposive samples is significant at the .995 level. This again can be seen as a reflection of the biased nature of the purposive sample described above. The range of values for the mean is from 5.87ϕ to -2.57ϕ slightly less extreme than the values of the median but still reflecting the diverse nature of the suite of sediments in Upper Weardale.

6.52 Sorting

The degree of sorting in a sample can give a useful indication of the nature of the deposit. In order to determine how well sorted a sediment is it is necessary to have a concept of 'sorting' which in the case of sedimentology is the general concept of log normal particle-size distribution. One measure of this is the standard deviation of the sample. An approximation to this was proposed by Inman (1952) called the phi deviation and defined

$$\sigma\phi = \tfrac{1}{2}(\phi 84 - \phi 16)$$

Again this formula is good for normally and close to normally distributed sediments but Folk and Ward (1957) suggest an improved measure called the Inclusive Graphic Standard Deviation and this is given by the formula

$$\sigma_1 = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

This gives a closer approximation to the standard deviation than Inman's

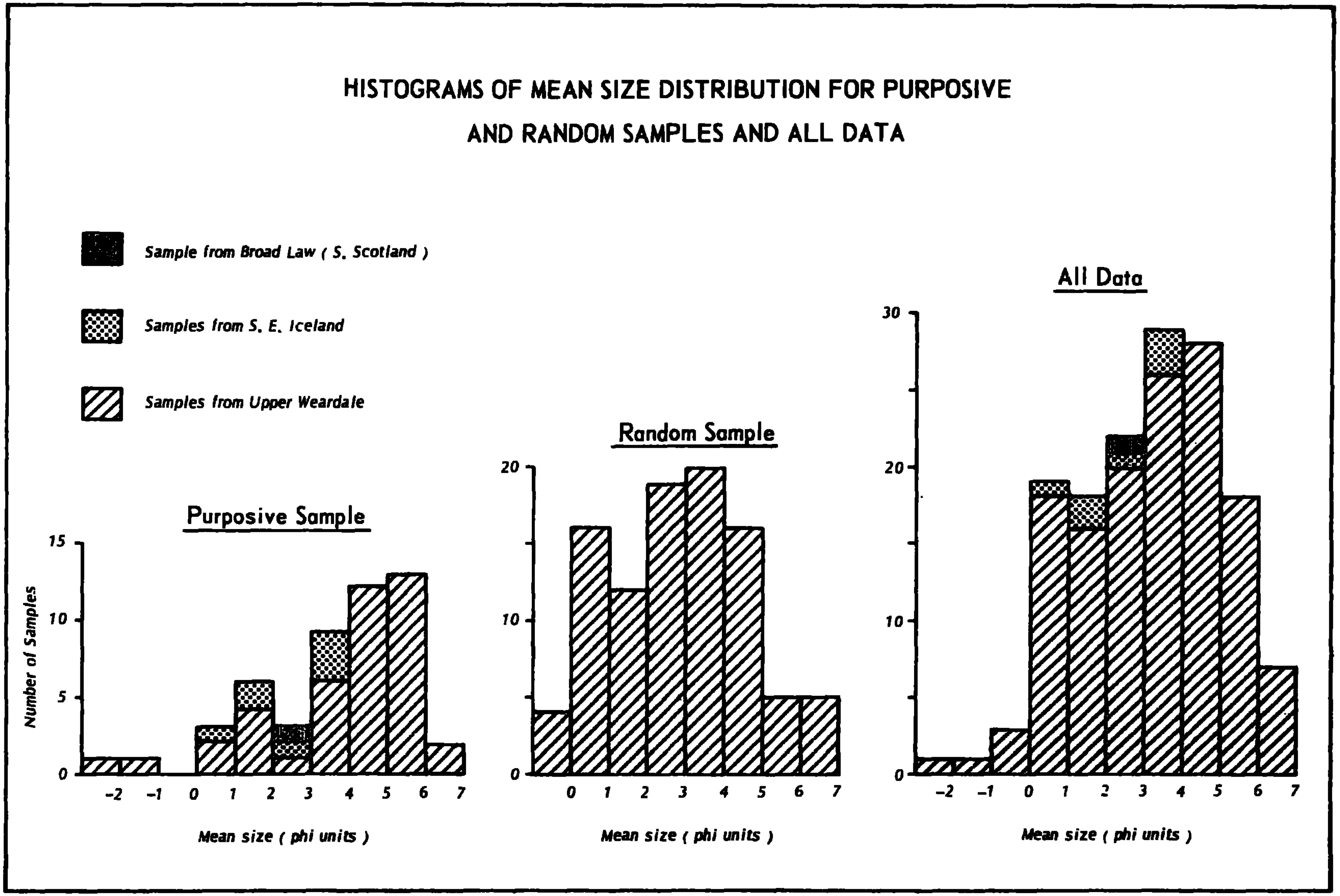

HISTOGRAMS OF MEAN SIZE DISTRIBUTION FOR PURPOSIVE
AND RANDOM SAMPLES AND ALL DATA
Sample from Broad Law (S. Scotland)
Samples from S. E. Iceland
Samples from Upper Weardale
Purposive Sample
Random Sample
All Data
Number of Samples
Mean size (phi units)
Mean size (phi units)
Mean size (phi units)

Figure 6.14

(1952) formula but both are superior to Trask's proposed measure (Trask, 1952)

$$\text{the Trask sorting coefficient} \quad So = \sqrt{Q_1/Q_3}$$

where Q_1 and Q_3 are the upper and lower quartiles of the distribution.

McCammon (1962) also evaluates the efficiency of sorting measures and produces the following conclusions.

Inman's ϕ deviation measure

$$\sigma\phi = \tfrac{1}{2}(\phi 84 - \phi 16) \qquad 54\% \text{ efficient}$$

Folk and Ward's Inclusive Graphic Standard Deviation

$$\sigma_1 = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6} \qquad 79\% \text{ efficient}$$

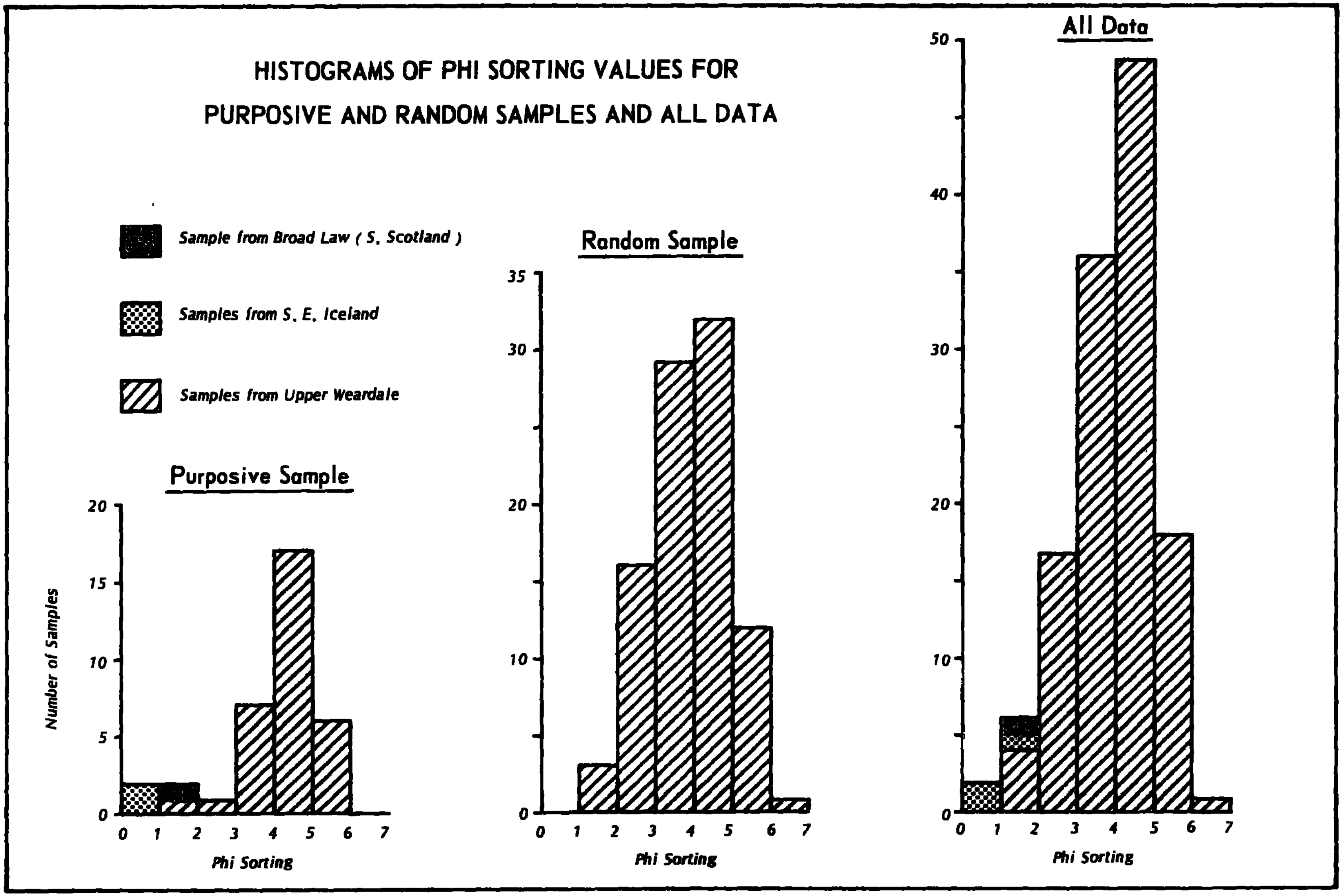
McCammon proposes a lengthy formula for greater efficiency in calculating sorting but the restrictions on the use of these measures resulting from the difficulty of obtaining accurate values of $\phi 95$ and $\phi 5$ for the particle size curves of till mean that this project was limited to the use of Inman's formula for the ϕ deviation measure.

The range of values for sorting in the deposits of Upper Weardale is from 6.2 to 1.5. Using the verbal description proposed by Folk and Ward (see Table 6.5). These deposits vary from poorly sorted to extremely poorly sorted. Histograms of their occurrence in the purposive and random samples and the total data from Upper Weardale are presented as Figure 6.15. Differences between the purposive and random samples in this case using the chi-square test, are significant at the .995 level. It may be concluded that the sorting of the deposits in Upper Weardale is generally poor but shows lower values for the random sample.

TABLE 6.5

Description of Sorting Values (after Folk and Ward, 1957)

Sorting Value	Description
less than 0.35	Very well sorted
0.35 - 0.5	Well sorted
0.5 - 1.0	Moderately sorted
1.0 - 2.0	Poorly sorted
2.0 - 4.0	Very poorly sorted
more than 4.0	Extremely poorly sorted



HISTOGRAMS OF PHI SORTING VALUES FOR
PURPOSIVE AND RANDOM SAMPLES AND ALL DATA
Sample from Broad Law (S. Scotland)
Samples from S. E. Iceland
Samples from Upper Weardale
Purposive Sample
Random Sample
All Data
Number of Samples
Phi Sorting
Phi Sorting
Phi Sorting

Figure 6.15

King (1966) points out that sorting appears to be dependent on the grain size of the material in some cases. Both Beaumont (1967) and Vincent (1969) have demonstrated a significant relationship between median size and sorting for glacial tills. In this context the present author investigated the relationship for the whole suite of deposits in Upper Weardale and found no significant relationship. The correlation coefficient (r) for all data was only 0.01.

6.53 Skewness

It was indicated above (6.51) that the difference between the median and the mean value for a particle size gave some measure of the departure of the curve from a normal distribution. This departure from the symmetrical normal distribution is called skewness. Inman (1952) defined this as

$$\alpha\phi = \frac{M\phi - Md\phi}{\sigma\phi}$$

or the difference between the mean and median expressed in units of the standard deviation of the curve. This value may be positive or negative as the median (phi) is less than or greater than the mean (phi). If the median is greater than the mean the skewness value is negative and the curve is skewed to the finer particle size range. If the median is less than the mean the skewness is positive and the distribution curve is skewed to the coarser particle size range.

Most workers recognise the limitations of Inman's measure of skewness which is concerned only with differences between measures of central tendency. Inman himself recognised this and suggests a second measure of skewness

$$\alpha_2\phi = \frac{\frac{1}{2}(\phi 5 + \phi 95) - Md\phi}{\sigma\phi}$$

to take into account the tails of the ~~situation~~ distribution

Folk and Ward (1957) suggest a modification of this to give a single measure called the Inclusive Graphic Skewness and defined as

$$Sk_1 = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$$

For this study Inman's (1952) measure is used because of the problems of establishing the $\phi 5$ and $\phi 95$ percentiles.

The histograms of the skewness values for the samples taken from Upper Weardale are presented as Figure 6.16. The range of values is from -o.52 to 0.72. Chi-square tests of the significance of the difference between the values indicates a difference between the purposive and random samples which is significant at the .995 level. This reflects the more positive values of skewness for the random sample indicating that they comprise coarser sediments.

6.6 Conclusions from the Particle Size Data

Throughout the latter section devoted to the use of descriptive statistical measures it is consistently stated that the efficiency of the measures used is not good. The reason for this is the difficulty encountered in determining the particle size composition of the extremes of the distribution curve especially in the case of a clay rich deposit. Inman (1952), Folk and Ward (1957) are only echoing the work of Doeglas (1946) when they place great emphasis on the nature of the "tails" of the particle size distribution curves in their analysis of sediments.

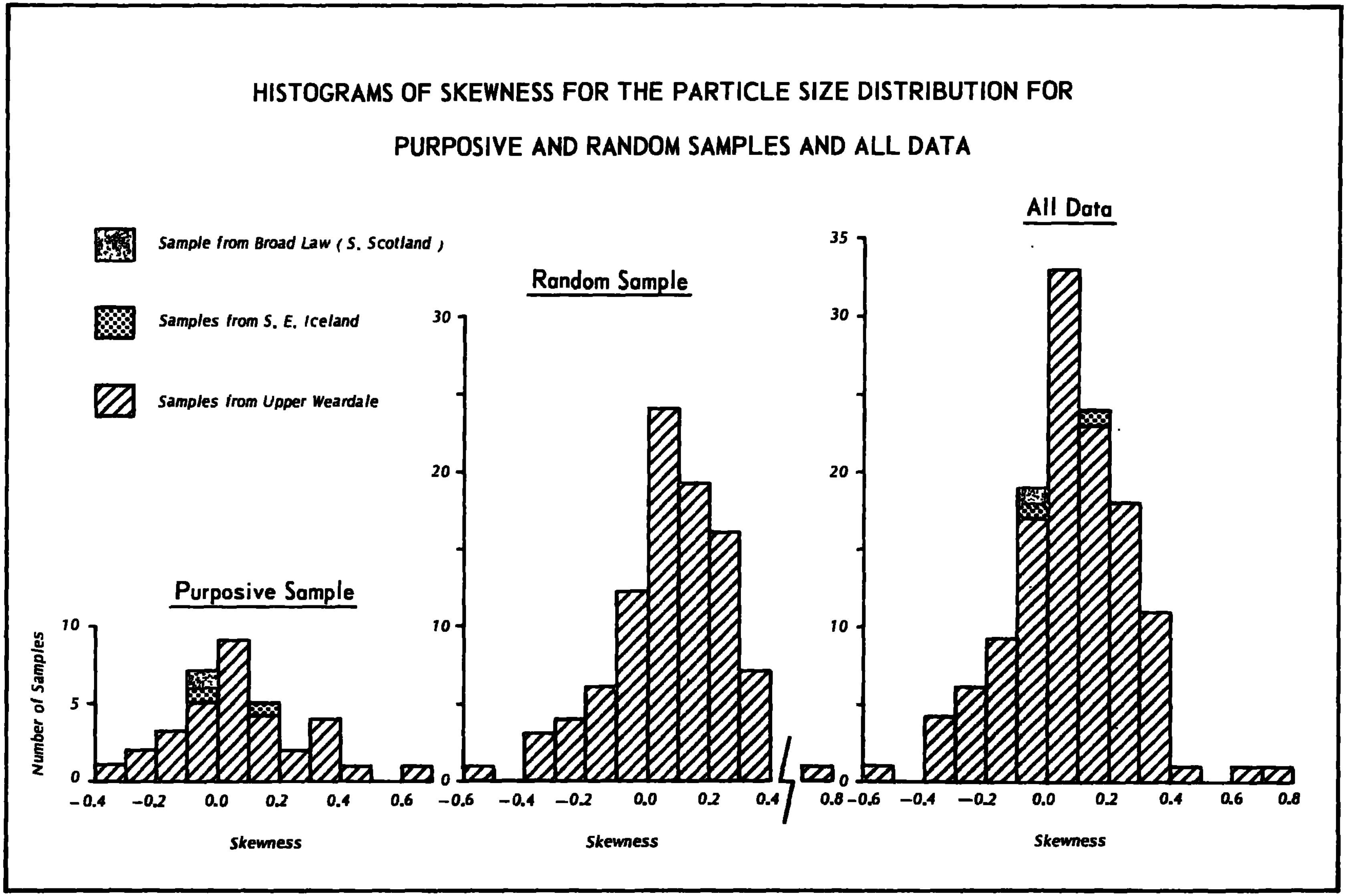

HISTOGRAMS OF SKEWNESS FOR THE PARTICLE SIZE DISTRIBUTION FOR
PURPOSIVE AND RANDOM SAMPLES AND ALL DATA
Sample from Broad Law (S. Scotland)
Samples from S. E. Iceland
Samples from Upper Weardale
Purposive Sample
Random Sample
All Data
Number of Samples
Skewness
Skewness
Skewness

Figure 6.16

The difficulties in analysing the clay fraction below a size of 0.001 mm are extreme. Consequently it is frequently impossible to use the more efficient measures of the particle size curve when investigating glacial deposits.

Of particular interest in the foregoing results is the clear indication that the purposive sample appears to have a bias towards clay rich deposits. The implications of this are far reaching. It seems to be clear that taking samples which the investigator considers to be "representative of the area" is not a reliable way of producing truly representative data. If this is true for a suite of deposits in a region it seems it may also be true for samples representing one type of deposit in a region.

The absence of any relationships between the mean grain size of a sample and the other descriptive statistics computed for all data seems to indicate that there are no intrinsic relationships which hold true for all deposits. This then indicates the importance of the relationships detailed by both Vincent (1969) and Beaumont (1967) between mean grain size and sorting and skewness values. The relationships they observe are demonstrably not true throughout suites of deposits in Upper Weardale. Consequently the order observed in glacial tills by Vincent (1969) and Beaumont (1967) is an indication of some existing properties of the material not sufficiently recognised in the typical description of till as "unstratified (glacial) deposits" (Embleton and King, 1968) or "a coarse strong soil" (Geikie, 1863).

There are very few parameters which purport to identify glacial till and fewer which claim to be criteria for the definition of solifluction deposits. In no cases where such criteria are implied (e.g. Young, 1965, Beaumont, 1967, Vincent, 1969, Washburn, 1969) are there any data showing that the criteria differ from the general case in the area from which the parameters are derived. The foregoing data describe the general nature and variability of a suite of deposits in Upper Weardale.

This description in the present case shows that there are no significant relationships between these sediment parameters for the whole group of deposits. Consequently any sub-division of the group of deposits which does demonstrate ordered relationships between the parameters is an improvement in the understanding of the deposits. The relationships between the parameters for any such group may be diagnostic of the deposit-type. The establishment of such groupings and consideration of the relationships between the deposit parameters are undertaken in the ensuing chapters.

Chapter 7

Factor Analysis

Techniques of factor analysis are being used increasingly in geography to produce groupings of variables which are significant in the explanation of the total variance of a data set. Papers dealing with this technique are numerous. (Goddard, 1970, Pocock and Wishart, 1969, Carson, 1969, Horton, 1968, Cox, 1968, Murdie, 1969). Within physical geography Carson (1969) offers a useful contribution to the published literature with his use of principal components analysis to determine the influence of certain parameters on slope development. Vincent makes use of factor analysis in his study of the tills of the N.W. Alston Block and produces results of particular value by using a combination of mineralogical, lithological and chemical variables in Q-mode analysis.

The analysis of superficial materials by standard data processing techniques has been neglected. Klovan's (1966) paper provides the major step forward in the analysis of environment type from particle size data. His work is based on that of Imbrie (1963), and their association and cooperation in the development of these techniques. Before embarking on a discussion of the results of factor analysis it is necessary to indicate the mechanics and philosophy of the technique itself. Much of this summary is based on Imbrie's 1962 monograph "Factor and vector programs for analysing geologic data". References to the original source material and the basic development of the technique owe much to the psychologists and their data processing breakthrough of the 1930s. Hotelling's 1933 paper is a remarkable step forward in this work.

Harman's text devoted to "Modern Factor Analysis" (1960) also provides a great deal of useful information for the purposes of clarification.

Krumbein and Garrison in a preface to Imbrie's monograph provide a concise summary of factor analysis. It is presented here as a basis for the ensuing discussion:

> "A principal advantage of factor analysis is that it permits condensation of a large number of observed variables into as few as three or four theoretical variables that contain essentially all the information in a much larger data set of original observations. For those problems in which clearly defined dependency relations may not be self-evident, factor and vector analysis provide a path to better understanding of the complex inter-relationships so commonly encountered in multivariate data."
> (Krumbein and Garrison: preface in Imbrie, 1962).

In data of the kind produced by the present author's investigation of Upper Weardale there are many variables. Sand, silt and clay content of a deposit may each be considered as variables, gravel, organic content, pH, carbonate content also may be considered in this way. So too can lithology, depth from which samples are taken and the elevation of the sample site and its position within the valley. There can be no doubt that this is a multivariate system. The relationships between these variables are often expressed qualitatively or simply guessed at. It appears that factor analysis by reducing the complex of information gathered to a small number of theoretical variables which contain the information from the initial data body, can contribute greatly to a real understanding of the important inter-relations of measured variables in Upper Weardale.

7.1 Background to Factor Analysis

The technique of factor analysis emerged early in the present century when Spearman and a group of investigators developed it as a means of reducing complex data in the measurement of intelligence levels to a manageable and comprehensible form. (See Spearman, 1904). Subsequently this technique was refined and generalised into a rigorous statistical technique for use with multivariate data. (See Thurstone, 1931, 1947, Holzinger and Harman, 1941). Hotelling (1933) also adopted this technique in a modified form to permit the analysis of statistical variables into principal components. Subsequent work by Harman (1960) introduced computerised forms of this procedure which speeded up the calculations and hence increased their desirability and availability for general use.

Imbrie (1963) states that factor analysis merits much wider attention because of the ingenious and powerful techniques which are used. It is possible to apply these techniques to two types of reasoning. One, devoted to a study of the relationships between variables is termed the R-mode analysis, the other Q-mode analysis, explores relationships between cases. In terms of a simple diagram of observations where C_i is any individual case (of a total of N cases) and V_j is any variable (of a total of n variables) measured for all cases, we have the matrix,

$$
\begin{array}{llll}
 & V_1 & V_2 & \cdots\cdots\cdots\; V_n \\
C_1 & X_{11} & X_{12} & \\
C_2 & X_{21} & X_{22} & \\
C_3 & & & \\
C_4 & & & \\
\cdot & & & \\
\cdot & & & \\
C_N & & &
\end{array}
$$

$C_1 \ldots\ldots C_N$ cases
$V_1 \ldots\ldots V_n$ = variables measured
X_{ij} = value of variable for case C_i variable V_j
where $1 \leq i \leq N$ and $1 \leq j \leq n$

R mode analysis therefore considers 'n' variables and analyses the variability within and between columns. Q-mode analysis considers the N cases as variables and analyses the variability within and between Rows. Comparison between the two modes of analysis is best achieved in tabular form.

Table 7.1

Comparison of R-mode and Q-mode Factor Analysis Procedures

R-mode	Q-mode
(1) r matrix	(1) cos θ matrix
(2) initial factor matrix	(2) initial factor matrix
(3) rotated factor matrix	(3) rotated factor matrix
(4) oblique vector resolution	(4) oblique vector resolution

Much of the published work to date makes use of R-mode analysis attempting to use variables and their associations as the basis for understanding the assembled data. The r-matrix is the measurement of the correlation coefficient 'r' between every possible pair of variables measured. In some published work outside the realm of physical geography and geology Q-mode analysis has been done using an r matrix as its initial step, the 'r' value being the correlation coefficient between every possible pair of cases. Two geologists, Imbrie and Purdy (1962) working on the application of Q-mode analysis to assess the correlation between cases (geologic samples) for stratigraphic purposes developed the use of a cos θ matrix.

The cos θ matrix, instead of calculating the product moment correlations between cases measures the cosine of the angle between any two cases in their common plane. Specifically each case with its 'n' observations for each of 'n' variables is considered as a unique vector in 'n' dimensional space. For two samples X_i and X_p in 'n' space the calculation of cos θ may be made from the formula

$$\cos \theta ip = \frac{\sum (X_{ji})(X_{jp})}{\left(\sum_{j=1}^{j=n} (X_{ji})^2 \sum_{j=1}^{j=n} (X_{jp})^2 \right)^{\frac{1}{2}}}$$

Imbrie and Purdy (1962) define this as the coefficient of proportional similarity and if the data are positive cos θ has the range 0-1. cos θ=0 for samples having nothing in common and cos θ=1 for samples which are identical in their composition with respect to the 'n' variables measured. This is preferred to the use of the correlation coefficient 'r' which measures the relationship of the values of two variables (i.e. the response of y to a change in x) but not the similarity of proportion in their composition. Mathematically this is a reflection of the use of the difference between each observation and the mean value for that variable (the '$x - \bar{x}$' term) in the calculation of 'r'. The subtraction of a constant from each of a series of numbers alters their proportions, hence cos θ is preferred as a measure of proportional similarity between cases.

7.2 Principal Component Factor Analysis

Step (2) included above in Table 7.1 represents a great advance in the application of factor analysis. In its infancy the technique could be used to derive "factors" from the data or to test data against factors supplied to the programme. Hotelling's (1933) paper developing the concept of principal component analysis greatly improved the operation of this technique. Simply stated principal components analysis treats an original data matrix (usually a correlation matrix) as a series of simultaneous equations and from these it extracts the "roots" or solutions for a series of unknowns. These unknowns are theoretical variables which are related to the total variance of each case in the original data matrix. The solution resulting is comparable to the solution of quadratic (or other) equations, the roots being ordered by size, the largest value being then used as factor I the major influence on the data, therefore giving the greatest explanation of the variance of the data. The other factors thus obtained add smaller amounts to the explanation of the variance thus it is possible to construct tables of cumulative explanation of the total variance. Thus it can be seen that the variance explained by Factor I + Factor II + Factor III + ... Factor N can be made to approach a 100% explanation of the variance. The constant addition of less significant factors in this way produces a situation in which a cut-off point may be determined by inspection. For example Vincent (1969) accepts an 81% explanation of the variance of his data matrix which is brought about by a three factor explanation of the data.

The factors generated in this way from Hotelling's (1933) principal components theory are thus used as the factors for continued explanation of the data. It is frequently found that the factors, stated with reference to some arbitrary axes, are not easy to evaluate. For this reason a varimax rotation procedure is used to rotate the factor axes so that they minimise the displacement of sample vectors from the axes themselves [Step (3) of Table 7.1]/ This is best illustrated by the diagrams presented in the paper by Imbrie and Van Andel (1964) and reproduced here as Figure 7.1

In essence the mathematical statement of the whole procedure can be reduced to

$$C = Av_1 + Bv_2 + Cv_3 + \dots Kvn$$

where A is the coefficient of variable v_1 for case C

B is the coefficient of variable v_2 for case C

etc.

This observed relationship defining C is then inter-related with all other observed relationships for all other cases (Q-mode analysis) $C_1 \dots C_N$ and C is ultimately restated as

$$C = aF_1 + bF_2 + cF_3 + \dots kF_n + e$$

where $F_1 \dots F_N$ are the explanatory factors, a, b, c ... k are the factor loadings (see Fig. 7.1) and C is the original case now re-stated in terms of $F_1 \dots F_n$. It should be carefully noted that these relation-

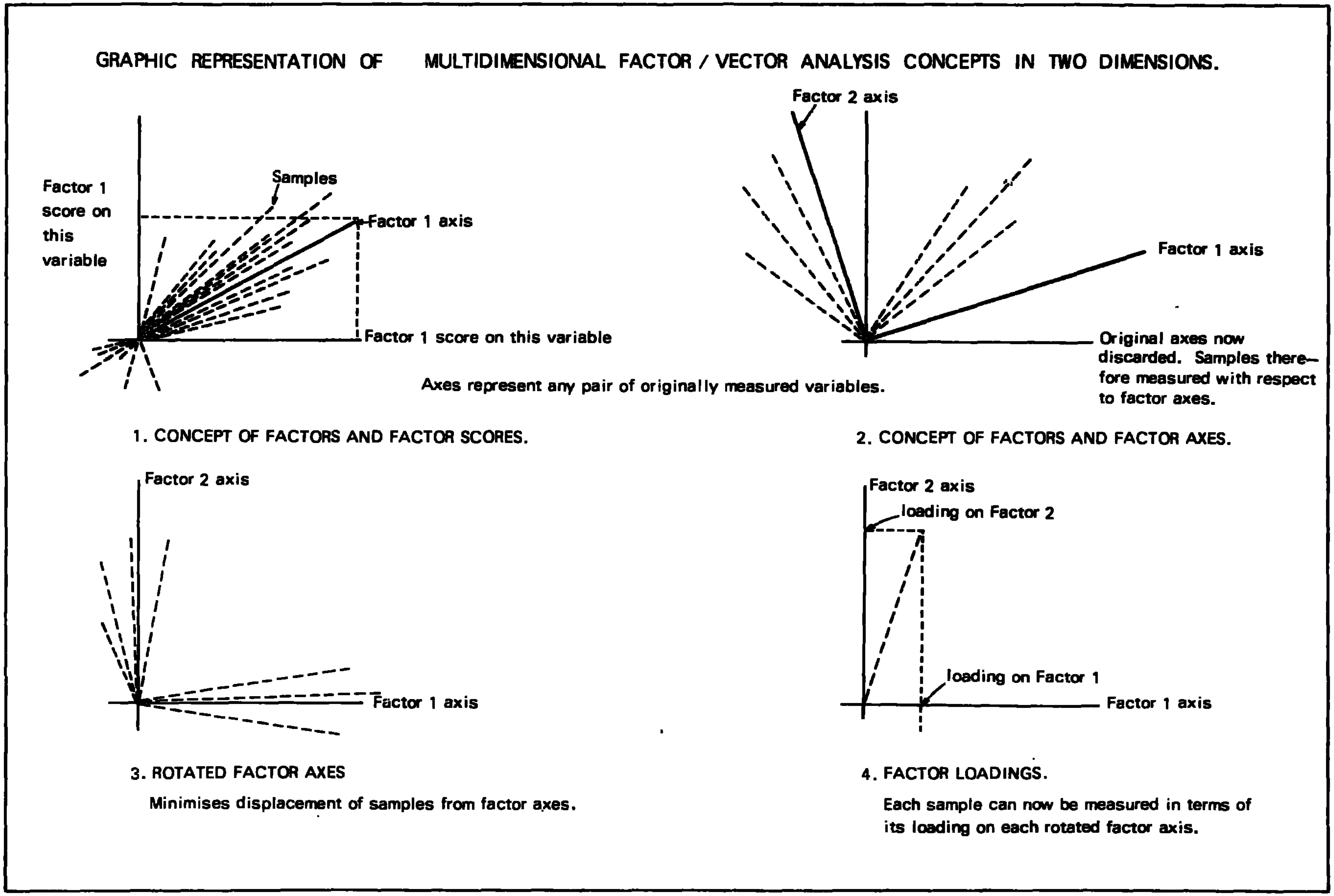

GRAPHIC REPRESENTATION OF MULTIDIMENSIONAL FACTOR / VECTOR ANALYSIS CONCEPTS IN TWO DIMENSIONS.
Factor 1 score on this variable
Samples
Factor 1 axis
Factor 1 score on this variable
Axes represent any pair of originally measured variables.
1. CONCEPT OF FACTORS AND FACTOR SCORES.
Factor 2 axis
Factor 1 axis
Original axes now discarded. Samples therefore measured with respect to factor axes.
2. CONCEPT OF FACTORS AND FACTOR AXES.
Factor 2 axis
Factor 1 axis
3. ROTATED FACTOR AXES
Minimises displacement of samples from factor axes.
Factor 2 axis
loading on Factor 2
loading on Factor 1
Factor 1 axis
4. FACTOR LOADINGS.
Each sample can now be measured in terms of its loading on each rotated factor axis.

Figure 7.1

ships between C and $F_1 \ldots F_N$ and C and $V_1 \ldots V_n$ are considered to be linear. In the event of the relationships being non-linear some appropriate transformation of the data is required. 'e' is the error term.

The four steps in the application of R and Q mode factor analysis given above (Table 7.1) include step (4) "oblique vector resolution". This is a technique not used in early applications of factor analysis and it is proposed by Imbrie (1963) because it relates the factors derived theoretically in the preceding steps of the calculation to actual cases from the initial data matrix. This is an optional calculation of value in certain circumstances but does not form a major element in the calculation procedure.

7.3 The Application of Factor Analysis in Geomorphology

Raw data are, in almost every case, extremely complex. In general it is the task of the scientist to discover simple general principles which underlie the data. Imbrie categorically states "In geology theories are commonly expressed in qualitative terms." (Imbrie, 1963, p. 2). He goes on to question the reason for this and says that in part the reason is the problem of ...

> "identifying the most meaningful parameters of a given domain. In physical sciences one commonly knows a priori many of the quantities that must be specified - mass, force, charge, distance, temperature, pressure, etc. - whereas in geology this is rarely the case. Factor analysis is therefore particularly useful in geology because it can be applied without a priori knowledge of number or nature of causal influences at work in a given body of data." (Imbrie, 1963, p. 2).

If we read geomorphology for geology in the above quotations the observations are still valid and the case for the use of factor analysis is clearly established. There remain the problems of which mode of analysis to apply and how to assemble the data for processing.

R-mode analysis examined by Imbrie is considered to be of less value than Q-mode analysis in geological data processing. It can, however be used to provide some useful geological information by indicating which variables interact to produce which type of deposit. In the case of a multivariate system this can be an important method of data analysis and it is this type of analysis used in regional geography to provide a series of factor score maps which show the influence of factors over an area, each factor being defined as a complex of certain variables.

Q-mode analysis considered by Imbrie to be a useful tool in the evaluation of geologic data has been demonstrated by Klovan (1966) to be even more powerful than Imbrie (1963) suggests. Imbrie sees geological data subjected to factor analysis with the purpose of describing and interpreting variations in the composition of the sediments (characterised by a set of 'n' measurements). He also clearly sees factor analysis as a useful method of condensing information so that rather than analysing many maps each showing values of one variable he examines a few maps each showing values of a factor which represents several variables.

If we consider this process with reference to geomorphology it is of greater value to be able to obtain maps of the areas of dominance of processes rather than co-variation of variables. It is difficult to measure processes in landscape genesis but Klovan's (1966) demonstration of the use of Q-mode analysis to determine sedimentary environments offers a useful basis on which it is possible to construct process hypotheses.

In the abstract of his paper Klovan (1966) states three advantages of his use of the Q-mode factor analysis technique to determine depositional environments from grain-size distributions. These are

> " 1. It makes use of the entire spectrum of the grain-size distribution.
>
> 2. It does not require arbitrary statistical descriptions of the grain-size distribution; hence the analytical method can be more objective.
>
> 3. It demands no a priori knowledge of the environmental and geographic location of the sediment samples for classifying them into environmentally distinct facies. This should make the technique particularly applicable to problems dealing with ancient sediments." (Klovan, 1966, Abstract).

7.4 Class Intervals in the Raw Data

With data of grain-size distributions there are certain constraints. The fact that each distribution sums to 100% means that we are dealing with a closed number system. However, there appears to be no satisfactory way of avoiding this as any measurement of grain-size distribution requires the use of a sample limited in size by the apparatus available to transport and analyse it. Consequently, as size determinations are done by weight retained on a sieve any standard method of analysis is only going to produce % data. Even if the figures are stated as weights rather than % of the total sample they are part of a closed system, the total in this case being the weight of the sample analysed rather than the 100% normally adopted.

Klovan (1966) points out that each class interval in a grain size distribution contains a specified amount of the sediment, this then forms a unique attribute of that particular sediment sample. Consequently each grain-size category forms a variable in the measurement of the particle-size data and therefore there are as many variables as class intervals. In his study Klovan (1966) uses 10 class intervals and therefore considers each sample to be a vector in 10 dimensional space-from which the cos θ matrix is generated for the ensuing Q-mode analysis.

In the case of the samples from Upper Weardale the 10 class intervals used were identical with the ones used by Klovan in his study. This gave the data for the test of the technique described briefly in Chapter 5. Data for this test are presented as Table 5.1 and the factor loadings resulting are presented as Table 5.5. It is apparent that the first of Klovan's stated advantages is somewhat negated by this procedure. The range of size in the analysis of the deposits from Upper Weardale is in excess of that for the sands analysed by Klovan (1966). Upper Weardale sediments are analysed in the range below 20 mm. Klovan uses phi unit categories thereby using a logarithmic transformation of his data required in cases of non-linear data. To adopt single phi unit categories for the Upper Weardale data is possible - producing a total of fifteen categories in the range from -4ø to 10ø+. It is also possible to use a broader category to produce fewer class intervals but still cover the same range of data. This latter solution was adopted and the data were grouped into 1.5ø unit categories. Ten such categories were used, these being specified in Table 7.2 which presents the data for all samples grouped by 1.5 phi unit categories.

TABLE 7.2

Particle-size Data Grouped into Categories

PERCENTAGE IN EACH SIZE CATEGORY

GRID REFERENCE	DEPTH	LARGER THAN -3.0ϕ	-3.0/ -1.5ϕ	-1.5/ 0.0ϕ	0.0/ 1.5ϕ	1.5/ 3.0ϕ	3.0/ 4.5ϕ	4.5/ 6.0ϕ	6.0/ 7.5ϕ	7.5/ 9.0ϕ	SMALLER THAN 9.0ϕ
805435	100	00.0	00.0	05.5	04.5	2995	32.5	05.6	02.4	04.9	15.1
	125	01.8	00.3	02.9	01.6	01.5	09.3	26.4	13.2	09.0	34.0
	150	03.7	00.5	00.3	00.2	00.8	04.0	32.3	14.2	09.7	34.3
	175	05.5	12.0	09.6	02.9	04.8	15.8	19.1	07.7	05.0	17.6
	200	07.3	17.5	17.0	05.4	08.7	11.9	15.2	05.0	01.6	10.4
	225	49.0	27.6	12.0	02.4	07.2	00.3	00.3	00.3	00.3	00.6
806434	25	00.0	01.2	06.8	11.5	38.3	11.2	03.3	04.1	05.1	18.5
	200	02.1	17.9	31.5	06.1	14.1	12.3	04.0	02.2	01.5	08.3
821443	150	00.0	02.0	06.9	06.5	30.3	22.9	10.2	04.6	06.8	09.8
	200	08.6	06.4	09.3	05.7	17.9	08.9	09.2	08.3	08.7	17.0
823437	75	05.5	01.5	06.3	03.7	18.8	21.3	10.8	05.9	05.6	20.6
	100	01.4	02.6	07.5	03.2	06.1	09.2	22.3	18.7	10.9	18.1
	125	04.8	10.9	17.3	05.0	05.6	07.8	19.4	12.6	07.8	08.8
	140	01.6	09.2	12.4	02.5	04.3	13.0	12.7	13.5	06.9	23.9
	160	08.3	15.4	16.3	05.8	06.2	10.4	11.6	08.7	08.7	08.6
	185	10.0	24.8	19.5	05.3	06.5	06.4	09.5	10.0	05.2	02.8
902394	100	00.0	00.0	12.0	04.3	13.3	12.8	12.4	10.2	09.3	25.7
985352	300	00.0	00.0	17.8	04.2	11.2	11.6	10.8	10.0	08.1	26.3
985381	45	08.9	01.4	02.7	02.2	13.2	15.9	11.7	13.9	09.4	20.7
	80	00.0	01.9	21.9	08.8	07.5	03.3	14.0	19.4	11.2	12.0
	110	26.6	07.7	10.5	05.2	05.8	17.2	09.8	04.9	04.7	07.6
	140	03.6	11.0	12.5	04.6	08.9	26.7	10.1	05.0	05.9	11.7
985392	75	11.8	07.6	06.6	04.8	14.2	16.0	06.7	10.1	08.6	13.6
	135	07.6	07.7	10.1	04.6	07.1	04.7	10.3	14.6	12.1	21.2
	210	42.4	14.4	12.9	04.2	11.0	09.5	02.3	02.1	01.0	00.2
003367	45	02.3	07.5	08.0	05.4	10.7	09.5	08.4	09.9	09.1	29.2
	90	06.6	04.4	05.0	03.0	09.9	15.1	10.3	09.3	08.7	27.7
	135	02.2	00.8	01.8	00.8	04.6	31.8	24.1	13.9	06.1	13.9
	180	04.5	04.7	07.8	04.7	11.3	21.8	16.0	13.4	11.1	13.7
	225	05.6	06.5	07.9	03.1	09.0	14.0	06.9	09.4	09.4	28.2
054383	150	09.8	06.0	07.9	05.5	15.9	12.9	1.02	08.5	14.7	18.6
067384	150	17.3	21.3	29.4	10.6	03.4	02.7	01.7	02.3	00.9	10.4

GRID REFERENCE	DEPTH	LARGER THAN -3.0ϕ	-3.0/ -1.5ϕ	-1.5/ 0.0ϕ	0.0/ 1.5ϕ	1.5/ 3.0ϕ	3.0/ 4.5ϕ	4.5/ 6.0ϕ	6.0/ 7.5ϕ	7.5/ 9.0ϕ	SMALLER THAN 9.0ϕ
068377	120	09.4	04.6	06.0	04.9	11.8	08.8	10.2	09.5	08.8	26.0
068384	75	07.0	05.3	11.7	10.2	23.8	09.6	06.4	04.5	04.7	16.8
	120	00.0	05.1	03.1	03.2	22.3	12.7	06.9	08.7	08.4	29.6
	210	00.0	00.5	16.3	29.2	36.0	05.0	05.0	04.9	02.0	01.1
074345	50	00.0	00.0	08.0	08.5	22.4	08.9	18.1	07.2	06.-	20.4
	105	00.0	00.0	10.5	08.5	19.0	16.5	07.7	06.6	07.2	24.0
173358	150	01.1	01.8	03.4	03.7	11.8	16.2	10.0	10.1	09.2	32.7
205394	90	04.1	00.2	02.7	07.3	36.4	15.4	03.8	03.9	05.4	20.8
	110	02.6	02.3	04.8	04.4	09.9	10.9	21.9	13.2	12.1	17.9
	150	00.0	00.0	14.8	04.2	06.8	14.2	09.2	11.8	09.2	29.8
236363	90	00.0	00.0	00.1	00.4	03.1	04.8	15.2	20.5	15.9	40.0
244335	75	10.2	04.4	03.7	03.7	12.0	21.1	10.0	08.7	06.2	20.0
	135	00.8	01.9	03.6	03.2	13.9	20.6	10.6	11.5	11.0	22.9
	1	00.0	00.0	32.1	04.7	13.5	24.3	11.1	08.1	01.2	05.0
	2	00.0	00.0	10.0	39.0	36.7	11.6	02.7	00.0	00.0	00.0
	3	00.0	00.0	08.4	14.6	74.0	01.5	00.7	00.0	00.0	00.0
	4	00.0	00.0	01.1	01.9	46.2	43.0	03.7	02.5	01.1	00.0
	5	00.0	00.0	00.0	00.1	01.1	47.1	27.2	11.1	08.7	04.8
	6	02.4	17.6	31.0	16.2	19.2	02.9	00.3	00.4	00.0	00.0
	7	05.7	06.5	17.8	09.1	20.0	25.9	09.5	05.5	00.0	00.0
	8	00.0	12.0	06.3	27.1	41.0	07.2	03.2	02.3	00.3	00.0
808370	22	0.5	0.9	4.0	6.1	39.0	31.9	4.9	4.2	3.4	5.6
	30	5.2	4.4	8.6	7.8	29.3	23.9	5.1	3.5	4.0	8.2
	90	0.0	1.0	3.4	2.3	3.5	7.6	22.2	26.1	15.1	18.8
	180	1.6	2.6	4.9	4.3	26.4	33.6	8.2	5.9	5.1	7.4
825428	90	5.4	10.2	13.2	5.1	20.1	9.6	6.1	8.4	6.9	15.0
	110	9.4	12.7	9.2	4.7	35.2	12.5	3.3	2.8	3.8	6.4
	160	10.4	12.9	9.1	4.8	25.6	12.3	6.1	3.9	4.9	10.0
826413	45	13.4	12.9	12.9	4.4	8.4	8.7	4.7	7.7	10.5	16.4
	70	7.6	11.6	19.8	9.1	10.3	11.6	4.2	3.3	9.1	13.4
	225	0.8	2.9	10.2	8.2	12.1	11.8	10.7	14.4	12.9	16.0

GRID REFERENCE	DEPTH	LARGER THAN -3.0ϕ	-3.0/ -1.5ϕ	-1.5/ 0.0ϕ	0.0/ 1.5ϕ	1.5/ 3.0ϕ	3.0/ 4.5ϕ	4.5/ 6.0ϕ	6.0/ 7.5ϕ	7.5/ 9.0ϕ	SMALLER THAN 9.0ϕ
836419	22	5.8	16.5	15.1	4.3	5.8	30.5	20.2	0.4	1.0	0.4
	45	4.8	4.1	2.9	2.2	18.0	25.3	17.3	11.4	9.7	4.3
	60	2.7	1.6	1.9	1.9	8.9	9.2	19.7	17.2	11.3	25.6
840397	30	4.2	11.8	6.0	3.8	15.1	16.7	10.2	8.2	8.8	15.2
	60	8.7	5.9	6.1	4.5	13.9	19.5	18.7	9.6	7.1	16.0
	90	8.8	5.5	4.5	3.2	13.1	17.1	10.2	8.2	7.7	21.7
	450	4.9	2.7	1.4	2.2	6.5	10.7	16.8	20.4	18.5	20.9
852407	180	5.1	10.9	9.2	2.8	18.0	21.1	10.9	5.5	6.2	10.3
	150	6.0	8.1	7.7	3.7	15.5	17.2	15.1	8.7	7.0	11.0
	105	11.0	9.0	9.7	4.6	14.1	19.1	10.3	6.8	6.0	9.4
	90	2.6	6.7	12.3	6.1	9.9	7.6	13.9	13.6	10.3	17.0
	60	9.4	11.9	12.7	4.0	16.3	15.8	6.2	6.5	5.3	10.9
	30	3.8	7.3	7.3	11.8	27.6	29.2	8.3	3.3	1.0	0.4
865410	195	4.1	0.8	2.3	4.9	11.1	35.2	14.4	5.5	7.2	14.5
	120	12.3	15.5	19.2	8.9	8.9	9.8	6.1	8.2	5.9	5.2
	45	0.0	1.8	1.3	4.8	12.7	12.6	9.1	13.1	13.0	13.6
	22	1.4	1.2	7.7	6.2	13.4	16.1	9.8	12.2	11.5	20.5
862353	180	7.2	9.8	7.8	3.4	10.2	26.2	18.2	7.2	5.7	4.3
	120	5.0	9.9	9.3	5.3	7.8	17.2	24.1	6.9	8.9	5.6
	105	1.4	0.6	2.5	1.9	5.2	22.4	22.0	11.8	10.8	21.4
	75	0.0	0.0	10.4	7.8	12.4	27.3	18.1	8.7	8.7	6.6
869360	150	6.3	4.7	8.1	2.6	9.2	16.9	14.6	9.9	7.7	20.0
	75	11.4	26.6	18.7	7.1	5.1	8.1	7.1	4.1	1.2	4.6
	60	5.3	10.2	16.9	11.0	13.4	14.5	5.9	8.2	7.4	7.2
869394	90	31.8	17.8	8.6	3.8	9.7	5.1	4.6	5.3	4.1	9.2
	60	7.4	5.4	5.9	7.2	16.9	14.5	6.7	7.4	6.5	22.1
	30	4.2	4.8	10.7	7.1	22.4	10.8	8.1	9.7	10.1	12.1
873379	60	2.1	5.7	11.9	6.5	17.8	14.4	7.5	6.8	7.1	10.2
	180	7.0	4.6	3.4	2.1	16.9	15.7	7.5	7.1	8.1	27.0
883346	360	6.6	12.9	17.9	7.2	13.6	7.6	6.8	8.9	7.3	11.2
	90	1.4	5.7	12.1	7.2	14.3	13.3	12.0	4.2	13.5	16.3
	30	0.8	1.9	7.5	7.4	23.2	25.3	6.6	6.5	6.8	14.0

GRID REFERENCE	DEPTH	LARGER THAN -3.0ϕ	-3.0/ -1.5ϕ	-1.5/ 0.0ϕ	0.0/ 1.5ϕ	1.5/ 3.0ϕ	3.0/ 4.5ϕ	4.5/ 6.0ϕ	6.0/ 7.5ϕ	7.5/ 9.0ϕ	SMALLER THAN 9.0ϕ
888413	195	1.2	3.1	6.4	4.6	11.6	29.8	14.8	7.5	6.5	14.5
	165	4.4	11.9	11.9	7.6	14.2	15.7	9.3	6.5	5.5	14.0
	90	2.8	5.1	8.1	5.7	18.3	20.8	11.8	6.4	5.0	16.0
903331	105	5.4	7.4	13.2	12.7	30.9	8.3	3.8	2.8	6.8	8.7
	90	2.3	6.3	18.4	16.8	25.6	15.9	4.1	4.7	3.6	3.8
912348	90	7.8	7.2	7.6	4.6	35.8	34.6	5.4	2.8	2.3	1.9
	22	10.9	11.1	9.7	4.7	21.6	29.0	5.9	2.4	3.2	1.5
927440	45	8.6	33.2	32.2	7.4	5.4	5.2	2.0	0.7	0.4	3.9
	30	9.8	26.1	34.3	7.4	3.7	2.7	3.0	3.2	3.6	6.2
931373	180	15.6	22.9	14.3	3.2	14.8	14.3	3.6	4.2	2.8	4.3
	75	25.0	19.8	8.9	4.2	11.4	14.1	4.6	4.1	2.6	5.3
	60	8.4	6.8	10.9	7.7	15.1	17.3	12.4	7.5	6.2	7.7
947386	90	6.1	8.2	10.5	5.2	16.9	17.7	9.4	8.1	7.2	10.7
	60	4.4	7.8	7.6	7.1	19.3	20.9	11.5	5.7	3.9	12.0
	30	0.6	2.2	3.9	2.5	18.6	23.9	10.7	8.6	9.3	20.7
952440	300	24.8	15.2	11.8	5.6	16.9	10.1	5.1	2.3	2.5	5.7
	240	5.4	11.2	15.2	6.4	20.1	22.2	7.4	3.7	3.4	5.0
	150	11.0	29.3	18.5	5.7	12.9	10.4	4.4	2.5	2.1	3.7
	75	7.3	13.9	9.8	4.3	8.5	9.9	8.4	8.2	6.5	23.3
952449	75	0.0	1.5	7.9	9.9	32.8	21.7	4.2	5.6	5.9	10.5
	45	0.2	3.5	10.1	10.2	13.8	18.9	12.8	15.8	8.9	5.8
	35	0.0	0.0	3.9	5.2	2216	32.6	9.9	7.2	6.8	11.8
	30	0.3	0.2	5.3	6.6	14.8	17.4	9.7	10.7	13.3	21.7
962334	240	5.4	28.7	38.7	10.4	5.7	4.8	2.7	1.4	1.4	0.8
	75	12.6	26.9	21.3	6.4	7.5	5.3	4.9	3.8	3.4	6.9
	30	10.1	22.9	22.3	6.8	5.8	5.1	3.9	3.4	7.3	12.4
	15	4.3	5.7	12.9	11.2	21.5	8.2	8.1	8.3	8.9	10.9
962450	30	1.8	3.1	7.7	8.2	27.1	14.4	3.9	6.8	7.4	13.6
	60	3.5	4.1	3.9	10.5	54.4	13.1	4.3	1.8	2.2	2.2
992403	150	2.9	9.1	10.4	5.7	24.3	17.9	7.5	6.0	5.4	10.8
	120	5.3	5.4	6.5	6.2	11.7	12.7	10.1	7.9	9.6	24.6
	90	1.4	4.5	5.9	4.7	17.7	16.8	14.1	8.1	7.8	19.0

GRID REFERENCE	DEPTH	LARGER THAN -3.0ϕ	-3.0/ -1.5ϕ	-1.5/ 0.0ϕ	0.0/ 1.5ϕ	1.5/ 3.0ϕ	3.0/ 4.5ϕ	4.5/ 6.0ϕ	6.0/ 7.5ϕ	7.5/ 9.0ϕ	SMALLER THAN 9.0ϕ
997324	90	11.6	18.5	16.2	11.5	14.4	11.3	6.3	3.6	3.4	5.2
	45	2.6	1.8	7.7	11.1	27.1	15.7	6.6	7.2	5.6	14.6
	30	0.1	2.0	8.0	10.6	27.5	18.1	6.6	5.9	7.5	12.7
003348	120	18.7	19.6	16.4	7.3	10.4	12.5	5.1	3.8	2.7	3.5
	90	6.7	7.3	24.3	23.7	21.4	6.6	2.4	3.0	2.9	1.7
	15	17.4	21.2	19.5	9.7	18.3	4.6	2.1	2.5	3.4	1.3
010423	150	9.3	2.8	33.9	18.3	18.5	6.4	1.8	2.4	2.8	3.8
	60	2.7	11.8	20.7	18.6	33.0	4.9	1.5	0.7	1.4	4.7
	22	7.4	7.4	15.2	16.3	31.3	6.9	1.5	3.8	3.4	6.8
049341	120	9.2	5.7	6.7	4.6	21.1	28.3	4.3	4.9	4.4	10.8
	60	18.7	13.4	14.8	13.4	21.7	4.1	1.5	1.5	2.5	8.4
	45	10.2	14.8	21.1	15.6	27.1	3.2	2.9	1.9	2.3	0.9
	22	19.7	23.1	19.1	12.7	18.4	2.6	1.3	1.8	1.0	0.3
074345	270	11.3	10.6	12.9	11.2	16.3	14.2	5.3	5.5	5.8	7.4
080362	60	1.2	3.6	13.3	47.1	25.3	6.4	2.9	1.0	0.8	0.4
	38	0.0	2.1	29.8	25.9	20.3	6.6	1.4	2.9	2.8	8.2
	22	3.1	3.3	20.8	17.3	22.3	9.9	3.7	3.5	5.9	8.7
097408	45	8.9	10.2	9.1	9.7	14.7	12.7	8.2	6.9	5.9	13.7
	15	4.2	5.9	7.7	13.0	28.8	12.4	5.5	7.9	7.8	6.8
095353	45	10.1	6.1	9.9	8.9	7.2	10.7	1.3	8.5	6.9	10.4
	22	3.2	5.9	28.0	23.1	26.9	6.7	1.2	2.2	2.2	0.6
097493	60	9.6	11.1	16.6	10.7	18.4	14.8	7.0	3.8	4.6	3.4
	270	4.0	8.1	12.1	6.2	16.2	26.2	11.6	3.9	6.3	5.4

7.5 The Effect of Class Intervals on Factor Analysis Results

It was of interest to investigate what effect, if any, this regrouping had on the purposive sample data. Table 5.5 presents the loadings produced for a five factor solution to the data grouped in single phi unit categories. Table 7.3 presents the results of the factor analysis of the purposive sample data grouped by 1.5ɸ classes (i.e. the purposive sample data as contained in Table 7.2 Samples P1-P53). Abstracting dominant factors for each sample makes it possible as in Table 7.4 to compare the solutions.

At first it appears that there is no consistency between the two groups. However it must be emphasised that factor analysis is a data processing technique. It therefore analyses the data supplied to it and in the foregoing change of size classes the data supplied has been changed from a sand-size range of data with large terminal classes to a broader range of data from fine gravel to clay with very much reduced terminal classes (see Tables 5.1, 7.2). Consequently the data contained in Table 7.2 are more sensitive to gravel content and clay content than the data in Table 5.1.

The numbers of the factors (1-5 inclusive) are only convenient labels. It is obvious that factor 1 does not always have the same significance for every data set. If data from a beach environment are used the factors will all have a different significance from the factors produced from an analysis of a lacustrine environments. If the beach and lacustrine data were combined and a further factor analysis was undertaken the order in which the factors would emerge would depend on the dominant characteristics of the data. If beach materials were in the

TABLE 7.3

PURPOSIVE SAMPLE (1.5 phi unit categories) VARIMAX FACTOR MATRIX

COMMUNALITY AND LOADINGS FOR FIVE FACTORS

Sample No.	Field Classification	Communality	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
P1	S	0.9728	0.4510	0.6649	0.0604	0.5583	0.1094
P2	T	0.9596	0.9559	-0.0316	0.1271	0.1691	0.0076
P3	T	0.9056	0.9363	-0.0916	0.0994	0.1019	0.0182
P4	T	0.9539	0.7363	0.0958	0.4280	0.3867	0.2643
P5	R	0.9391	0.4860	0.2301	0.6580	0.2745	0.3764
P6	R	0.9909	0.0299	0.0467	0.2735	-0.0632	0.9534
P7	S	0.9940	0.4884	0.8530	0.1003	0.0982	0.0902
P8	R	0.9098	0.2642	0.3933	0.7762	0.1483	0.2467
P9	S	0.9845	0.4489	0.7226	0.1768	0.4699	0.0933
P10	T	0.9801	0.7176	0.4922	0.3046	0.1430	0.3313
P11	T	0.9878	0.7096	0.4887	0.1327	0.4294	0.2088
P12	T	0.9225	0.8564	0.0752	0.3410	0.2587	0.0124
P13	T	0.9479	0.6055	0.1052	0.6898	0.2383	0.1940
P14	T	0.9770	0.8513	0.1007	0.4144	0.2269	0.1376
P15	R	0.9758	0.5290	0.1741	0.6742	0.2370	0.3937
P16	R	0.9274	0.2932	0.1342	0.7655	0.1136	0.4738
P17	T	0.9838	0.8626	0.3469	0.2752	0.2074	0.0258
P18	T	0.9475	0.8283	0.3068	0.3790	0.1521	0.0225
P19	S	0.9792	0.8337	0.3025	0.0947	0.3405	0.2603
P20	T	0.9004	0.6536	0.2003	0.6552	0.0522	-0.0320
P21	R	0.9487	0.3935	0.1438	0.3138	0.3784	0.7290
P22	R	0.9543	0.5161	0.2913	0.4296	0.5948	0.2544
P23	S	0.9763	0.6488	0.4068	0.2570	0.3469	0.4510
P24	S	0.9748	0.8611	0.1578	0.3688	0.0185	0.2682
P25	R	0.9597	0.0835	0.1779	0.2669	0.1230	0.9136
P26	S	0.9703	0.8955	0.2873	0.2354	0.0670	0.1609

Sample No.	Field Classification	Communality	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
P27	S	0.9856	0.8898	0.2477	0.1309	0.2416	0.2389
P28	T	0.9794	0.6475	0.0719	0.1640	0.7244	0.0565
P29	S	0.9474	0.7703	0.2806	0.3579	0.3462	0.1654
P30	T	0.9563	0.8756	0.2433	0.1976	0.1789	0.2436
P31	T	0.9944	0.7327	0.4428	0.2614	0.2502	0.3613
P32	R	0.9514	0.2441	0.1488	0.7424	-0.1080	0.5540
P33	T	0.9977	0.8823	0.2974	0.1705	0.0946	0.3046
P34	R	0.9952	0.5812	0.6850	0.3106	0.1077	0.2831
P35	S	0.9650	0.8203	0.5079	0.0538	0.1363	0.1126
P36	R	0.9268	0.1486	0.8645	0.3956	0.0080	0.0287
P37	T	0.9484	0.7472	0.5494	0.2387	0.1762	0.0145
P38	T	0.9705	0.7469	0.5475	0.2172	0.2491	0.0598
P39	T	0.9732	0.9122	0.2869	0.0598	0.2192	0.0851
P40	S	0.9910	0.5442	0.7923	-0.0139	0.1923	0.1728
P41	T	0.9223	0.8494	0.1936	0.2627	0.3010	0.0607
P42	T	0.9354	0.8779	0.2062	0.2993	0.1789	0.0252
P43		0.9912	0.9953	-0.0014	0.0216	-0.0031	-0.0129
P44	T	0.9914	0.7440	0.3231	0.1241	0.4435	0.3482
P45	T	0.9844	0.8225	0.3526	0.1130	0.4043	0.0860
P46		0.8932	0.3127	0.3680	0.6538	0.4814	0.0280
P47		0.8478	0.0732	0.8697	0.2778	0.0857	0.0385
P48		0.9242	0.0683	0.9539	0.0668	-0.0164	0.0692
P49		0.9737	0.1491	0.7369	-0.0128	0.6294	0.1102
P50		0.9811	0.4222	0.0212	0.1364	0.8852	0.0157
P51		0.9850	0.0322	0.5536	0.7883	-0.0664	0.2273
P52		0.9929	0.2141	0.5573	0.4988	0.5750	0.2388
P53		0.9125	0.0940	0.8971	0.2797	0.0423	0.1375

TABLE 7.4

Sample No.	Dominant Factor (1 phi unit categories)	Dominant Factor (15 phi unit categories)
P1	3	2
P2	1	1
P3	1	1
P4	2*	1
P5	2	3
P6	2	5
P7	3	2
P8	2	3
P9	3	2
P10	2*	1
P11	1	1
P12	1	1
P13	2	3
P14	1	1
P15	2	3
P16	2	3
P17	1	1
P18	1	1
P19	1	1
P20	2	3
P21	2	5
P22	2	4
P23	2*	1
P24	1	1
P25	2	5
P26	1	1
P27	1	1
P28	4	4
P29	1	1

Sample No.	Dominant Factor (1 phi unit categories)	Dominant Factor (15 phi unit categories)
P30	1	1
P31	2*	1
P32	2	3
P33	1	1
P34	2	2
P35	1	1
P36	2	2
P37	1	1
P38	1	1
P39	1	1
P40	1*	2
P41	1	1
P42	1	1
P43	1	1
P44	1	1
P45	1	1
P46	2	3
P47	2	2
P48	5	2
P49	3	4
P50	4	4
P51	2	3
P52	2	4
P53	3	2

majority one might reasonably expect factor 1 to be associated with them. Consequently every factor analysis solution is unique and the factors have to be assessed for significance in each individual analysis.

It therefore seems pertinent to compare the classification of the purposive samples by both their field classification and their factor analysis explanation when used as data with 1.5ϕ unit class intervals.

TABLE 7.5

Number of Samples with Dominant Loading on Each Factor

	Total	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Till	18	16	0	2	0	0
Solifluction	6	2	4	0	0	0
Regolith	11	0	2	5	1	3
Solifluction??	4	4	0	0	0	0
Till??	5	4	0	0	1	0
	44	26	6	7	2	3

Comparing Table 5.4 and Table 7.5 indicates clearly that the use of the 1.5 phi units class interval considerably affects the factor loadings of the samples, [illegible] ~~of regolith~~. Instead of having their highest loadings all on a single factor (as for factor 2 in Table 5.4) they are now considerably dispersed amongst factors 2-5 inclusive. Four samples of regolith which loaded on factor 2 in the initial analysis (see Table 7.4) are here (Table 7.5) loaded on factor 1 and one sample loading on factor 1 in the initial analysis now loads on factor 2. This "reclassification" of dominant influence is amongst samples classified in the field as till. It appears from these results that the wider the size-range covered the more sensitive are the results, hence the use of a slightly larger class interval for the data analysis provides a more useful interpretation of the data.

7.6 Establishing the Characteristics of the Factors

It is pertinent to consider the factor score matrix for each case because this provides insight into the typical composition of the factors. In Q-mode analysis of grain-size data, the factor score matrix gives the relationship between the factor and each of the class intervals of the grain size data. In Q-mode analysis with arbitrary selection of variables (see Vincent, 1969) the factor score matrix indicates which variables are of significance in the composition of each factor.

Table 7.6 presents the factor score information for the 1 and 1.5 phi unit categories used with the purposive sample data. The indications it gives are as follows.

Factor 1 in both analyses has its greatest score on the clay-size category therefore indicating that the factor 1 is a measure of the clay content of the deposit. In the case of the single phi unit categories there is only this major score, although the 5.00ϕ category (4.99ϕ to 5.99ϕ) appears slightly more important than the others. In the terminology suggested by King (1966, p. 277) these categories are medium silt (5.0-6.0ϕ) and clay content (> 8ϕ). When the larger class interval is adopted Factor 1 has three categories of significant scores. Again the clay size category is the most important but in two cases it is medium and fine clay sizes (> 9ϕ) which dominate rather than the

TABLE 7.6

VARIMAX FACTOR SCORE MATRICES FOR PURPOSIVE SAMPLE DATA

(i) For data using single phi unit categories

Size Categories	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
<1ϕ	0.2525	3.1397	0.0520	-0.2622	-0.1090
1	0.1022	0.0752	0.4047	-0.0957	2.9346
2	0.0689	-0.0816	2.2692	-0.4125	0.4587
3	0.0407	0.0212	1.9827	1.0441	-0.7929
4	0.5781	0.1499	0.2157	2.1586	-0.1195
5	0.8065	0.0347	-0.6099	1.4286	0.4897
6	0.7739	0.0211	-0.4861	0.7698	0.3669
7	0.7191	0.0332	-0.2070	0.2280	0.2184
8	0.5748	-0.0270	-0.1087	0.0026	0.0932
>8ϕ	2.7350	-0.3380	0.2448	-1.1249	-0.3918

(ii) For data using 1.5 phi unit categories

Size Categories	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
< - 3.0ϕ	0.0704	-0.2450	-0.3010	-0.0750	2.8286
-3.0 - 1.5ϕ	-0.0572	-0.1993	1.2252	-0.2235	1.2504
-1.5 - 0ϕ	0.0142	0.2170	2.5746	-0.1894	-0.0325
0 - 1.5ϕ	-0.0294	1.1168	0.7588	-0.4754	-0.1167
1.5 - 3.0ϕ	0.2150	2.8482	-0.2482	-0.0024	0.2434
3.0 - 4.5ϕ	0.2962	0.3812	-0.0043	2.8771	0.2824
4.5 - 6.0ϕ	1.0782	-0.5164	0.7706	0.9291	-0.3657
6.0 - 7.5ϕ	1.0568	-0.3013	0.5211	0.114	-0.2055
7.5 - 9.0ϕ	0.9055	-0.0983	0.0788	-0.0374	-0.0092
> 9.0ϕ	2.6098	0.0958	-0.5031	-0.7491	0.1499

whole clay-size range. Very fine silt and coarse clay are not as important as coarse, medium, and fine silt. It is however clear that Factor 1 relates samples with a high silt-clay content.

Factor 2 differs considerably between the two analyses. In the case of the single phi categories for the original data, sand, granules and pebbles form a single category (see King, 1966, p. 277) and this has considerable significance (factor score 3.1397), no other size categories having any comparable score. Factor 2 for the 1.5ϕ class interval has a negative score on the pebble size category and its high scores are on the sand size categories (0-3.0ϕ). Negative scores appear for the silt size categories. Thus Factor 2 in the first analysis is a response to sand and gravel content of the sample, in the second analysis it is a response to sand content and low silt values.

Factor 3 of the first analysis has its high scores on the medium sand and fine sand content (2ϕ and 3ϕ) and negative scores on silt content. Factor 3 of the second analysis scores high values on pebbles and granules and coarse sand and negative values for silt categories. It thus appears that factors 2 and 3 in analysis of single phi unit categories correspond to factors 3 and 2 respectively of the 1.5ϕ unit category analysis. That this is so is apparent from Table 7.4 where Factor 3 and Factor 2 of the single phi unit category analysis frequently correspond to Factors 2 and 3 in the 1.5ϕ category analysis.

Factors 4 and 5 of the first analysis seem to reflect high content of fine sand and silt, and medium sand content respectively. In the second analysis Factor 4 also reflects fine sand and silt content and Factor 5 seems to reflect high content of pebbles and granules.

Attempting to summarise this in a table gives a clearer statement of the properties of the two sets of factors.

TABLE 7.7

	First Analysis (1ϕ categories)	Second Analysis (1.5ϕ categories)
Factor 1	High clay content with high content of silt also important.	High clay content and medium silt content.
Factor 2	Sand granules and pebbles content of major importance.	High sand content and low silt content.
Factor 3	High content of medium/fine sand and low silt.	Sand and granules content of major importance.
Factor 4	High content of fine sand and silt.	High content of fine sand and silt.
Factor 5	High content of medium sand.	High content of pebbles and granules.

It is immediately apparent that four similar sets of characteristics emerge in both analyses and in the second analysis the extra categories clearly delimit the content of the largest size of particle whereas in the first analysis the smaller categories emphasise smaller ranges of size and medium sand is seen as the fifth influence on the composition, whereas the pebbles and granules are the fifth influence in the second analysis. That this consistency should emerge is considered to be a further endorsement of the applicability of this technique. In the analysis of this suite of deposits the use of the 1.5ϕ unit category for the raw data appears to be of value as it does not give undue emphasis to the sand size material and it does sub-divide the categories of larger particles so that their influence may be more easily assessed. Consequently this size of category was adopted for the subsequent analysis of the random sample data.

7.7 Analysis of the Random Sample

Table 7.8 lists the random samples by number, grid reference and depth. The grid references thus listed were obtained as described in Chapter 5.63 and the individual samples collected from various depths as shown were also obtained by the procedure described above in Chapter 5. Figure 6.1 shows the distribution of both purposive and random sampling sites in Upper Weardale.

Table 7.9 gives the cumulative explanation of variance table for the 10 factor analysis of the random sample data which were grouped in 1.5 phi unit categories.

TABLE 7.9

	Cumulative % explanation of total variance.
Factor 1	75.92
Factor 2	86.02
Factor 3	91.73
Factor 4	95.21
Factor 5	97.39
Factor 6	98.34
Factor 7	99.16
Factor 8	99.58
Factor 9	99.89
Factor 10	100.01

Klovan (personal communication) suggests that the 5 factor solution should be examined as a significant explanation of the total system.

TABLE 7.8

RANDOM SAMPLE

LISTED BY SAMPLE NUMBER, GRID REFERENCE AND DEPTH

SAMPLE NO.	GRID REF.	DEPTH CMS.	SAMPLE NO.	GRID REF.	DEPTH CMS.	SAMPLE NO.	GRID REF.	DEPTH CMS.
R1	808370	22	R33	869360	75	R65	952440	75
R2		30	R34		150	R66	962334	15
R3		90	R35	86394	30	R67		30
R4		180	R36		60	R68		75
R5	825428	90	R37		90	R69		240
R6		110	R38	873379	60	R70	962450	30
R7		160	R39		180	R71		60
R8	826413	45	R40	883346	30	R72	992403	90
R9		70	R41		360	R73		120
R10		225	R42		90	R74		150
R11	836419	22	R43	888413	90	R75	997324	30
R12		45	R44		165	R76		45
R13		60	R45		195	R77		90
R14	840397	30	R46	903331	90	R78	3348	15
R15		60	R47		105	R79		90
R16		90	R48	912348	22	R80		120
R17		450	R49		90	R81	10423	22
R18	852407	30	R50	927440	30	R82		60
R19		60	R51		45	R83		150
R20		90	R52	931373	60	R84	49341	22
R21		105	R53		75	R85		45
R22		150	R54		180	R86		60
R23		180	R55	947386	30	R87		120
R24	862353	75	R56		60	R88	80362	22
R25		105	R57		90	R89		38
R26		120	R58	952440	75	R90		60
R27		180	R59		150	R91	95353	22
R28	865410	22	R60		240	R92		45
R29		45	R61	952440	300	R93	97408	45
R30		120	R62		30	R94		15
R31		195	R63		35	R95	97493	60
R32	869360	60	R64		45	R96		270

Table 7.10 presents the factor loadings. The nature of these five factors is given by the factor score matrix produced as Table 7.11.

Factor 1 again emerges as the reflection of the silt and clay content of the material. Factor 2 is a reflection of the gravel and coarse sand content, Factor 3 reflects the sand content and Factors 4 and 5 the fine sand/coarse silt content and the gravel and fine sand content. In this case no field categorisation has been used so far and it appears that there are five main influences on the deposits. The true nature of these factors must be investigated in detail. It is, however appropriate to comment that these categories correspond closely with those established in the two previous analyses of the purposive sample.

Whilst the solution to a factor analysis produces a series of factors which are, statistically, as independent as possible, relationships can and do exist between the factors. The easiest approach to this is to plot the loadings of pairs of factors on simple graphs. Figure 7.2 the plot of Factor 1 and Factor 2 loadings (Random sample only) shows that, whilst there is some recognisable grouping of the samples loading predominantly on these two factors there is no discernable pattern for the Factor 1 and Factor 2 loadings of the samples which load predominantly on Factors 3 and 4. Considering all these samples plotted on pairs of factor axes for all combinations of 4 factors reveals that there are no completely distinct groups. This is to be expected.

In a system such as Upper Weardale where the same bedrock sequence provides the basic material for the genesis of the superficial deposits it would be surprising indeed if some samples of each group

TABLE 7.10

VARIMAX FACTOR MATRIX
(RANDOM SAMPLE DATA)

Sample No.	Field Classification of Sample	Communality	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
R1	R	0.9902	0.3323	0.0502	0.5459	0.7343	0.2000
R2	R	0.9956	0.4063	0.2454	0.5580	0.6532	0.1796
R3	T	0.8871	0.9196	0.962	0.0232	0.0855	-0.1557
R4	R	0.9893	0.4528	0.1146	0.3871	0.7838	0.0843
R5	T	0.9776	0.6292	0.4864	0.4923	0.2801	0.1558
R6	S	0.9690	0.2868	0.4139	0.5880	0.4802	0.3729
R7	S	0.9865	0.4380	0.5074	0.4818	0.4536	0.3151
R8	S	0.9786	0.6586	0.6766	0.2081	0.1499	0.1458
R9	S	0.9548	0.5333	0.6673	0.4113	0.2262	-0.0685
R10	R	0.9817	0.8349	0.2606	0.3879	0.2376	-0.0989
R11	R	0.9803	0.3173	0.5288	0.0342	0.7235	-0.2747
R12	R	0.9489	0.5901	0.1834	0.2131	0.7222	-0.0010
R13	S/T	0.9718	0.9640	0.1135	0.0925	0.1413	0.0346
R14	S	0.9766	0.7208	0.4026	0.2651	0.4613	0.1096
R15	T/S	0.9731	0.7601	0.3237	0.1874	0.5037	0.0424
R16	T	0.9854	0.8164	0.3050	0.1991	0.3866	0.1920
R17	T	0.9524	0.9464	0.1588	0.0458	0.1707	0.0167
R18	T	0.9884	0.5723	0.4205	0.3077	0.6201	0.0698
R19	S	0.9807	0.6831	0.3851	0.2711	0.5396	0.0315
R20	S/T	0.9920	0.5795	0.5062	0.2647	0.5688	0.0804
R21	T	0.9819	0.8359	0.3987	0.3033	0.1468	-0.1029
R22	S	0.9916	0.5395	0.5828	0.3549	0.4677	0.1276
R23	T	0.9909	0.2742	0.2560	0.5023	0.7718	0.0471
R24	R	0.9608	0.6441	0.1062	0.1157	0.7204	-0.0481
R25	R	0.9831	0.3900	0.8088	0.3211	0.2605	-0.0765
R26	R	0.9763	0.9377	0.0683	0.2324	0.1345	0.1421
R27	S	0.9915	0.8624	0.1795	0.3398	0.3163	0.0017
R28	R	0.9858	0.5279	0.4007	0.0908	0.7233	-0.1227
R29	T	0.9012	0.6130	0.4269	0.1015	0.5295	-0.2291
R30	T	0.9893	0.8866	0.0890	0.0015	0.4262	-0.1173

Sample No.	Field Classification of Sample	Communality	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
R31	S	0.9890	0.6088	0.1714	0.2827	0.6635	-0.2623
R32	T	0.9875	0.8503	0.3204	0.1459	0.3749	0.0063
R33	S	0.9741	0.2373	0.9193	0.1407	0.2188	-0.0705
R34	T	0.9867	0.4968	0.5825	0.4856	0.3867	-0.1234
R35	S	0.9152	0.3101	0.7901	0.0500	0.1651	0.4062
R36	T	0.9752	0.7643	0.3088	0.3760	0.3228	0.2240
R37	T	0.9776	0.6441	0.3305	0.5646	0.3478	0.1177
R38	S	0.9707	0.5660	0.4913	0.4353	0.4448	0.1467
R39	T	0.9668	0.8209	0.2216	0.2579	0.3092	0.2860
R40	T	0.9868	0.5578	0.6656	0.4375	0.2018	-0.0225
R41	T	0.9529	0.7467	0.3444	0.4090	0.3251	-0.0608
R42	S	0.9811	0.5948	0.1524	0.4798	0.6068	0.0755
R43	T	0.9857	0.6891	0.1742	0.1787	0.6612	-0.1066
R44	T	0.9840	0.6366	0.5133	0.3706	0.4219	0.0007
R45	T	0.9847	0.6869	0.2662	0.3741	0.5473	0.0500
R46	R	0.9883	0.3655	0.3822	0.7484	0.3276	0.2028
R47	R	0.9981	0.2983	0.4077	0.7334	0.4498	-0.0526
R48	R	0.9937	0.2642	0.2354	0.4528	0.7898	0.1991
R49	R	0.9925	0.2844	0.4356	0.3279	0.7749	0.1175
R50	R	0.9444	0.0862	0.9252	0.2222	0.0865	-0.1551
R51	R	0.9658	0.1773	0.9116	0.2511	0.0010	-0.2008
R52	S	0.9911	0.2565	0.8086	0.2218	0.4351	0.1817
R53	S	0.9656	0.2737	0.7875	0.0892	0.4118	0.3047
R54	T/S	0.9813	0.5796	0.4596	0.3700	0.5449	-0.0174
R55	S	0.9968	0.6232	0.4322	0.3794	0.5245	0.0510
R56	R	0.9889	0.5942	0.3360	0.3927	0.6035	0.0669
R57	R/S	0.9886	0.7658	0.1673	0.2651	0.5257	0.1656
R58	R	0.9518	0.2645	0.7524	0.2671	0.3606	0.3382
R59	R	0.9907	0.3754	0.4961	0.4433	0.6381	-0.0071
R60	R	0.9533	0.1879	0.8727	0.2347	0.3135	0.0552
R61	S	0.9647	0.7792	0.5392	0.1728	0.1523	0.1171
R62	R	0.9921	0.4521	0.1255	0.6522	0.5662	0.1612
R63	R	0.9380	0.6399	0.2574	0.4010	0.5062	-0.2126
R64	S/T	0.9881	0.5716	0.0556	0.3552	0.7285	0.0375

Sample No.	Field Classification of Sample	Communality	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
R65	S	0.9861	0.8606	0.1068	0.3455	0.3369	0.0341
R66	R	0.9567	0.0611	0.8740	0.3198	0.0687	-0.2865
R67	S	0.9828	0.2544	0.9270	0.2024	0.1329	-0.0064
R68	S	0.9706	0.3916	0.8709	0.2322	0.0519	-0.0461
R69	S	0.9864	0.5831	0.3982	0.6381	0.2788	0.0555
R70	S/T	0.9903	0.6022	0.1999	0.6017	0.4465	0.1619
R71	R	0.9510	0.1775	0.1044	0.7326	0.4857	0.3687
R72	R	0.9805	0.5258	0.3618	0.5126	0.5426	0.1260
R73	T	0.9774	0.8678	0.2971	0.2686	0.2255	0.1142
R74	T	0.9833	0.7927	0.2076	0.3412	0.4367	0.0684
R75	R	0.9898	0.3111	0.7749	0.4064	0.3559	0.0273
R76	S	0.9976	0.5827	0.1868	0.6350	0.4390	0.1651
R77	R	0.9959	0.5547	0.1594	0.6343	0.4973	0.1151
R78	R	0.9876	0.2483	0.8569	0.2210	0.3662	0.0932
R79	R	0.9798	0.1679	0.5433	0.7759	0.1971	-0.1246
R80	S	0.9905	0.1282	0.8433	0.4329	0.2223	0.1616
R81	R	0.9160	0.1814	0.5763	0.7069	0.1343	-0.1822
R82	R	0.9820	0.1645	0.4682	0.8197	0.2390	0.0821
R83	R	0.9966	0.2747	0.4223	0.7913	0.2838	0.1900
R84	B	0.9670	0.4858	0.2989	0.3460	0.6986	0.1841
R85	R	0.9736	0.2543	0.6924	0.5542	0.1887	0.2945
R86	R	0.9838	0.1223	0.6429	0.7034	0.2255	0.0994
R87	R	0.9845	0.0602	0.8536	0.4330	0.1780	0.1818
R88	S	0.9839	0.4423	0.6009	0.4826	0.4322	0.0871
R89	R	0.7720	0.0973	0.2554	0.8067	0.1418	-0.1624
R90	R	0.9709	0.2543	0.4208	0.8142	0.0989	-0.2378
R91	R	0.9904	0.3798	0.4255	0.7690	0.2613	-0.0738
R92	T	0.9861	0.6379	0.5230	0.4000	0.3641	0.1145
R93	S	0.9723	0.4424	0.1854	0.6897	0.4347	0.1744
R94	R	0.8920	0.6119	0.5705	0.3541	0.2521	0.0550
R95	R	0.9946	0.1227	0.4738	0.8334	0.2113	-0.1256
R96	S/T	0.9945	0.3350	0.6169	0.5183	0.4828	-0.0023
R97	R	0.9962	0.4704	0.3856	0.3342	0.7106	-0.0977

TABLE 7.11

VARIMAX FACTOR SCORE MATRIX (RANDOM SAMPLE DATA)

Size Categories in phi units	FACTOR 1	FACTOR 2	FACTOR 3	FACTOR 4	FACTOR 5
<-3.0	-0.0100	1.5094	-0.5646	0.1587	1.5578
-3.0/-1.5	-0.1462	2.1772	-0.5495	0.2046	0.3281
-1.5/0	0.0210	1.6815	1.0889	-0.2958	-1.4982
0.0/1.5	0.0514	0.2998	1.6861	-0.3133	-0.8740
1.5/3.0	0.1749	-0.1056	2.2449	1.0204	1.5673
3.0/4.5	0.6197	-0.0004	-0.3097	2.6947	-0.5173
4.5/6.0	1.1706	0.1247	-0.5191	0.7198	-0.9762
6.0/7.5	1.2764	0.0417	-0.0236	-0.2502	-0.2583
7.5/9.0	1.1189	0.0341	0.1102	-0.2483	-0.1587
79.0	2.3076	0.0196	0.0362	-0.8646	0.8076

were not very similar to samples in the adjacent group. That this is so is indicated in the accompanying graphs. Vincent's (1969) so called "binary system" (a system with two members) is not reflected here probably because of the interpretation of a 5 factor system giving a 97% explanation of the variance rather than Vincent's (1969) 3 factor system explaining only 81% of the variance.

Factor 5 is not the dominant factor in any single case and so it is not included in the series of graphs forming Figures 7.2-7.7. It is included in the consideration of the factor analysis solution because without it the four factor solution gives low communalities for 17 of the sample explanations and it is considered inappropriate to analyse a system in which 20% of the components are inadequately explained.

The indeterminate distribution of samples other than those forming the principal axes in each graph indicates that whilst a sample may be dominantly the product of one factor it may also have a high loading on any one or several of the remaining factors. Thus in terms of field classification a till may appear similar to a solifluction deposit. Either of these may closely resemble the regolith of the local bedrock. If the till has not been reworked it may resemble neither of the other two materials. Thus if samples are (conceptually) ordered by their till-like-ness or solifluction-type-appearances they may be distributed in an entirely different manner to an ordering based on similarity to bedrock and content of frost shattered stones.

That this system should be clearly revealed as a true continuum between four end-members with a suggestion of a fifth influence is not surprising. An attempt to relate the results of this statistical

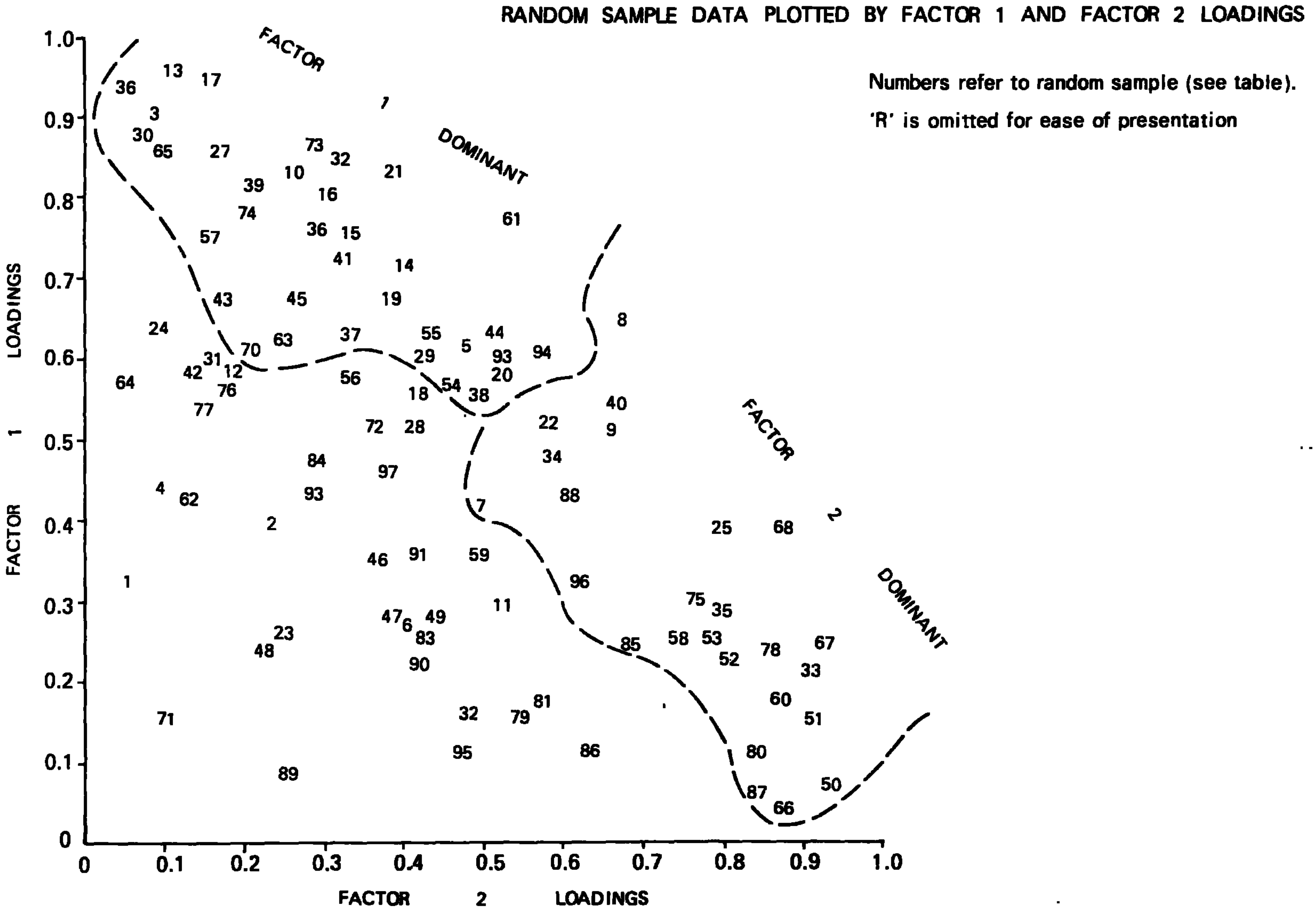
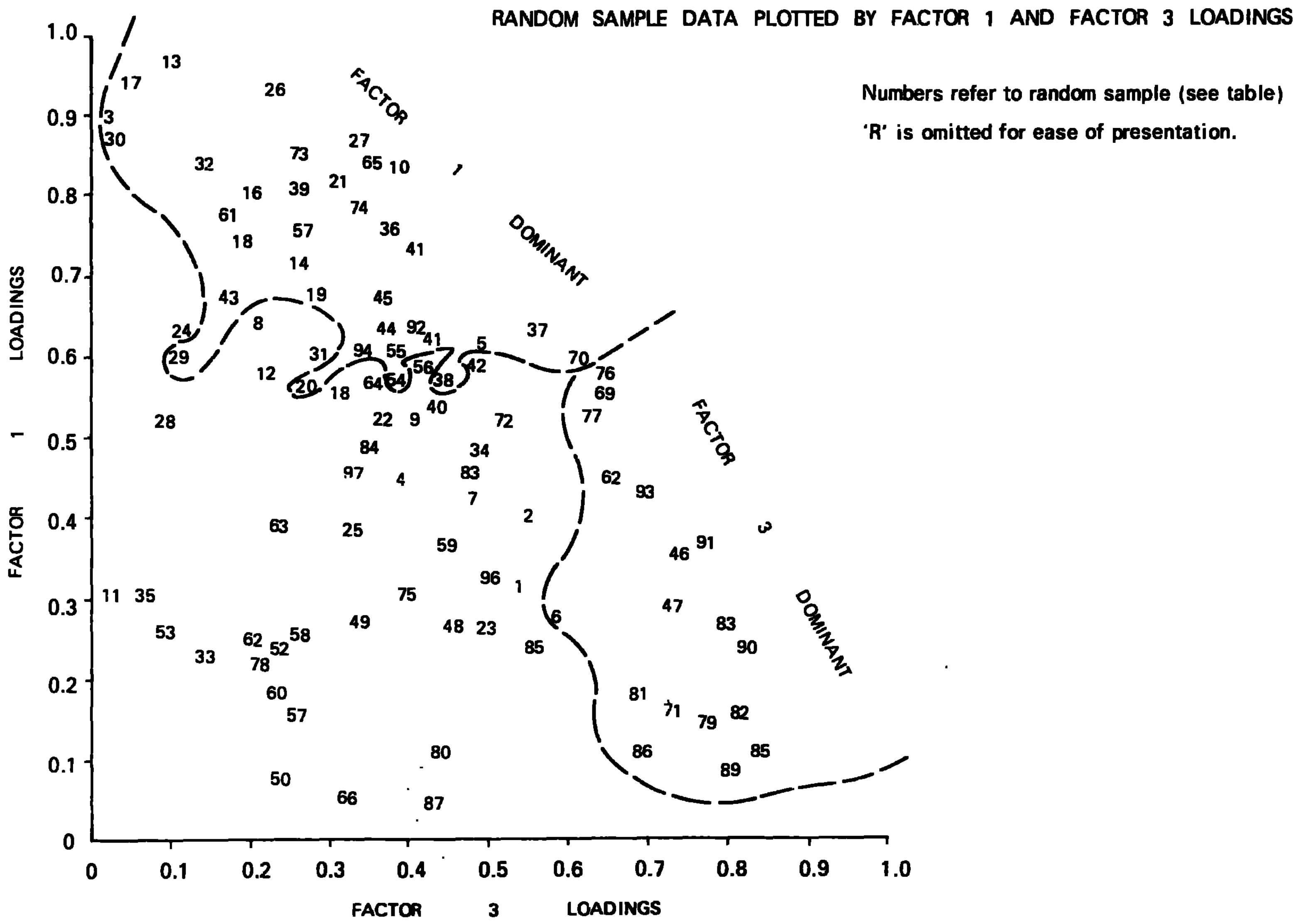

RANDOM SAMPLE DATA PLOTTED BY FACTOR 1 AND FACTOR 2 LOADINGS
Numbers refer to random sample (see table).
'R' is omitted for ease of presentation
FACTOR 1 DOMINANT
FACTOR 2 DOMINANT
FACTOR 1 LOADINGS
FACTOR 2 LOADINGS

Figure 7.2



RANDOM SAMPLE DATA PLOTTED BY FACTOR 1 AND FACTOR 3 LOADINGS
Numbers refer to random sample (see table)
'R' is omitted for ease of presentation.
FACTOR 1 DOMINANT
FACTOR 3 DOMINANT
FACTOR 1 LOADINGS
FACTOR 3 LOADINGS

Figure 7.3

RANDOM SAMPLE DATA PLOTTED BY FACTOR 1 AND FACTOR 4 LOADINGS

Numbers refer to random sample (see table).
'R' is omitted for ease of presentation.

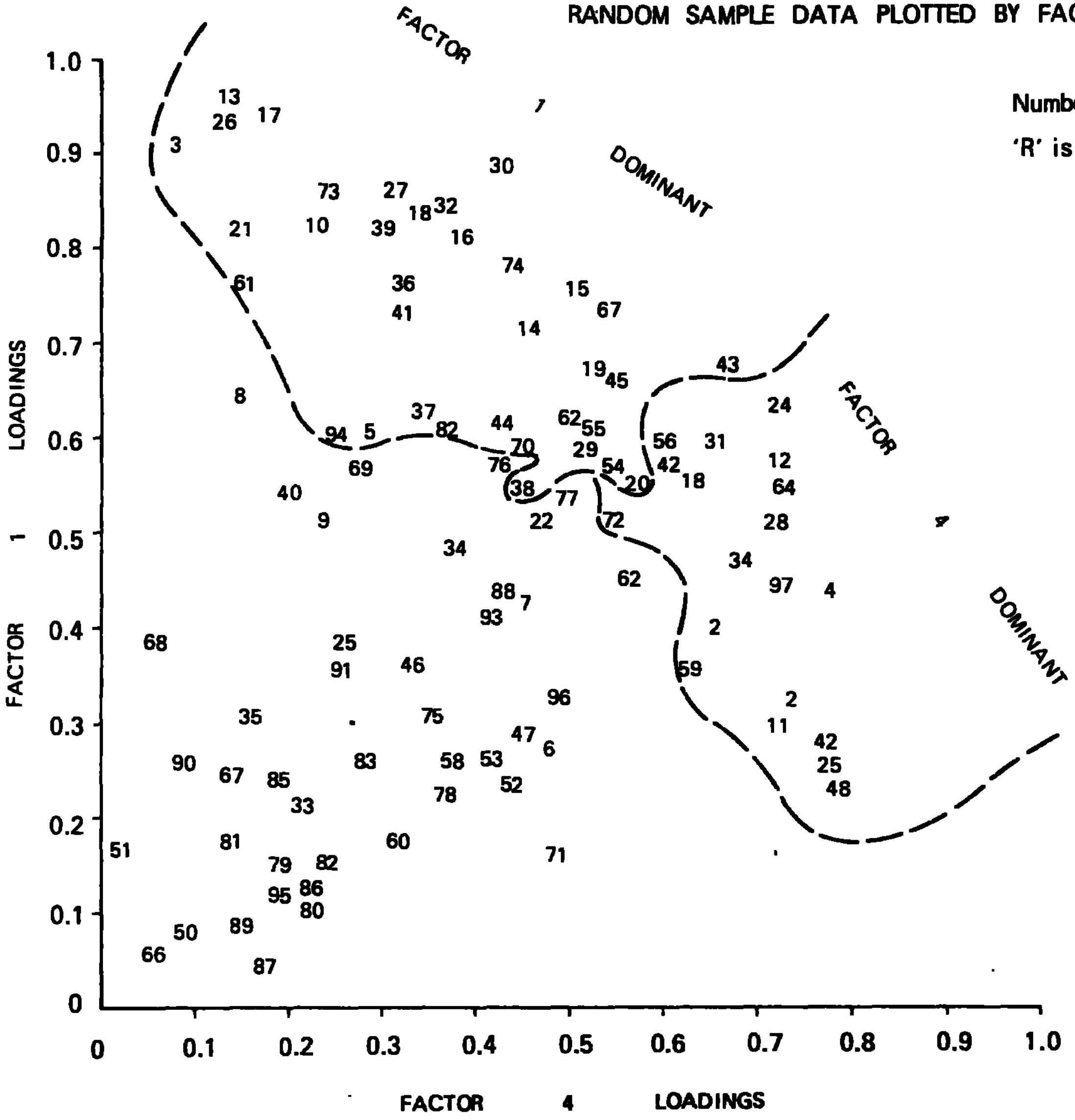


Figure 7.4

RANDOM SAMPLE DATA PLOTTED BY FACTOR 2 AND FACTOR 3 LOADINGS

Numbers refer to random sample (see table).
'R' is omitted for ease of presentation.

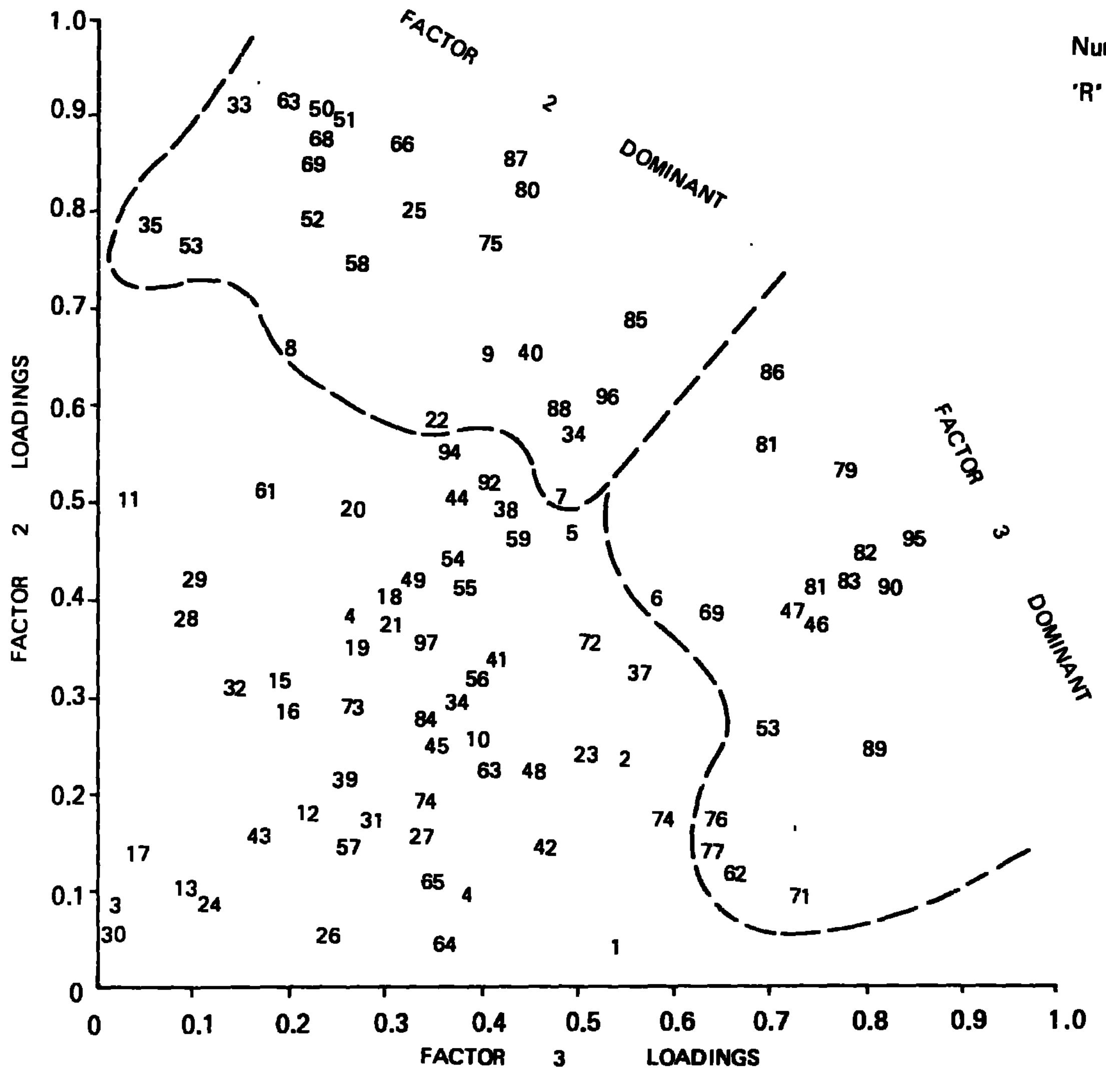


Figure 7.5

RANDOM SAMPLE DATA PLOTTED BY FACTOR 2 AND FACTOR 4 LOADINGS

Numbers refer to random sample (see table)
'R' is omitted for ease of presentation.

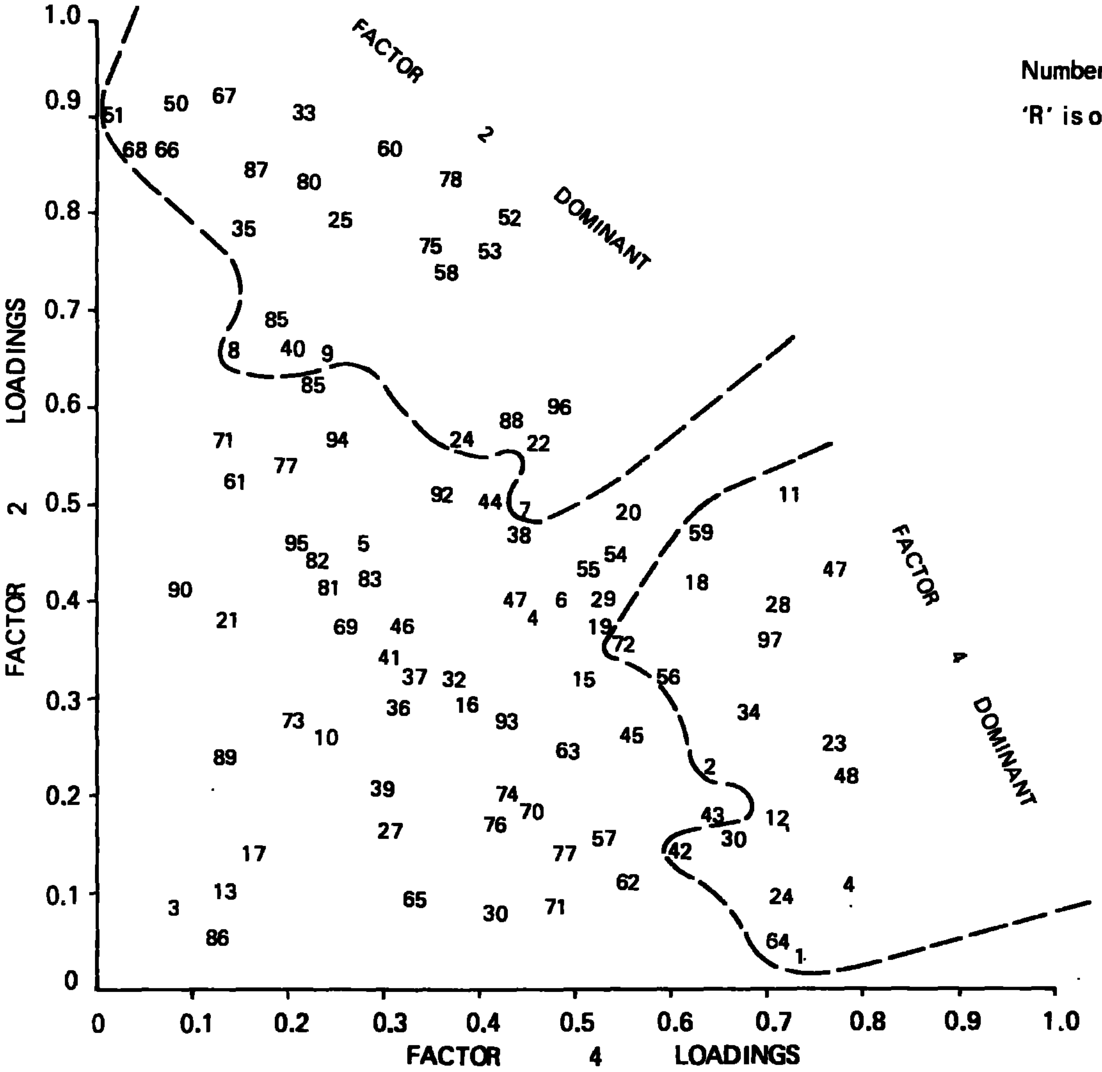


Figure 7.6

RANDOM SAMPLE DATA PLOTTED BY FACTOR 3 AND FACTOR 4 LOADINGS

Numbers refer to random sample (see table).
'R' is omitted for ease of presentation.

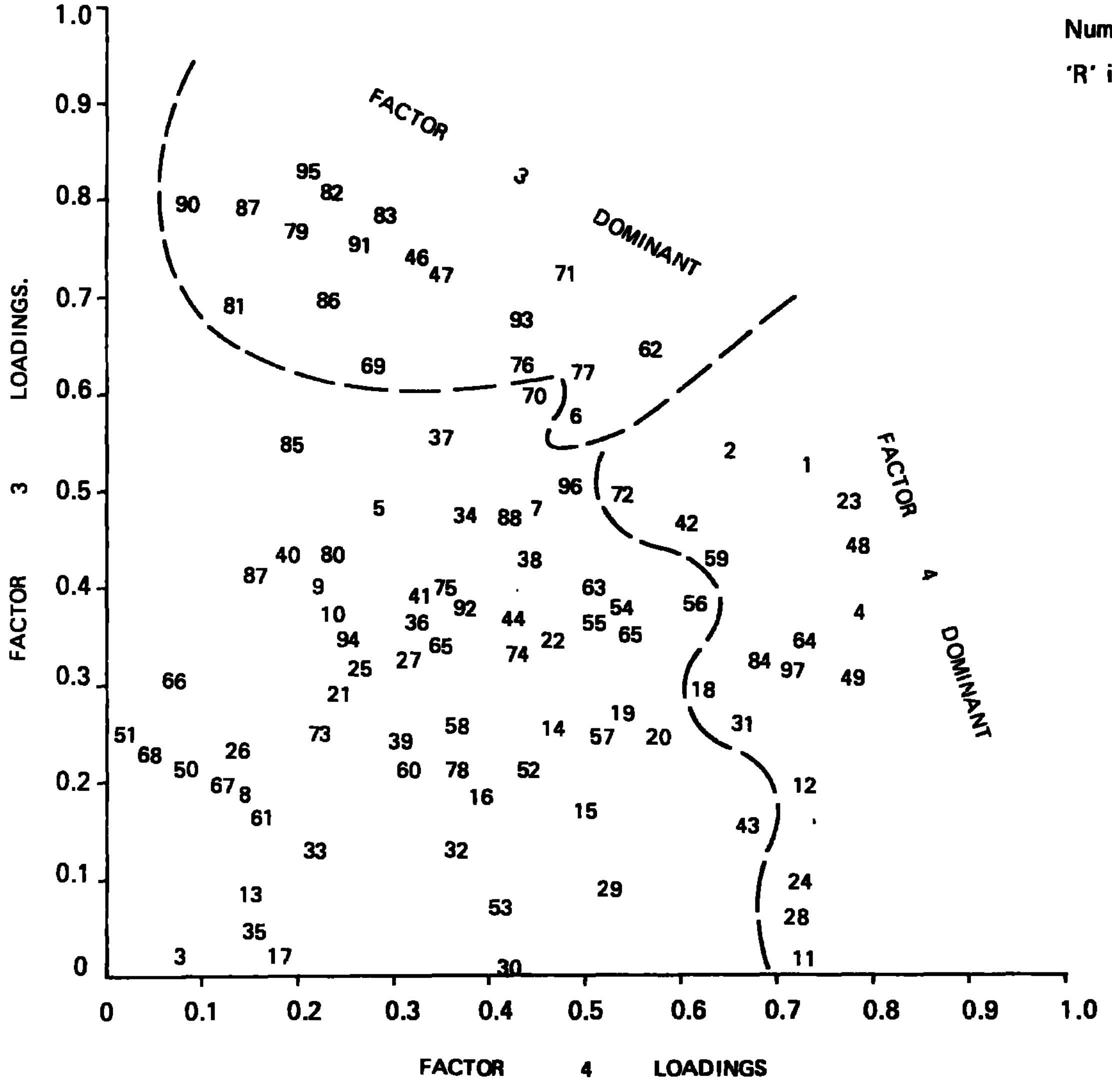


Figure 7.7

reasoning to field data is included in Figures 7.8-7.13 where the principal factor loadings are again plotted in pairs but the samples are indentified by their tentative field classification. It is immediately apparent that Factor 1 is effective in delimiting a group containing the "tills". Whilst it also includes samples given a field classification of regolith or solifluction it is, nonetheless a useful primary grouping (see Figures 7.8, 7.9, 7.10). The field classification of "regolith" and "solifluction" samples seems to be inadequate to meet the needs of a significant explanation of the total data and it is obviously necessary to establish the validity of the factors by other methods.

7.8 Conclusion

In concluding this presentation of the factor analysis results for the data of the random sample it is pertinent to consider the applicability of the field classification in interpreting the geomorphology of Weardale. The great variability of lithology in Upper Weardale means that rotted rock (regolith) may be rotted sandstone, rotted shales or limestones and the regolith may in each case be different in its particle-size characteristics. It would not be surprising therefore to find a sub-division of regolith into several classes as the result of an analysis of the particle-size data. Solifluction deposits, migrating down slope in such a region would necessarily be a mixture of the different types of regolith with, possibly, some admixture of till. It would be also surprising if solifluction did not demonstrate a considerable variability and hence sub-divisions into more categories as a result of analysis of particle-size data.

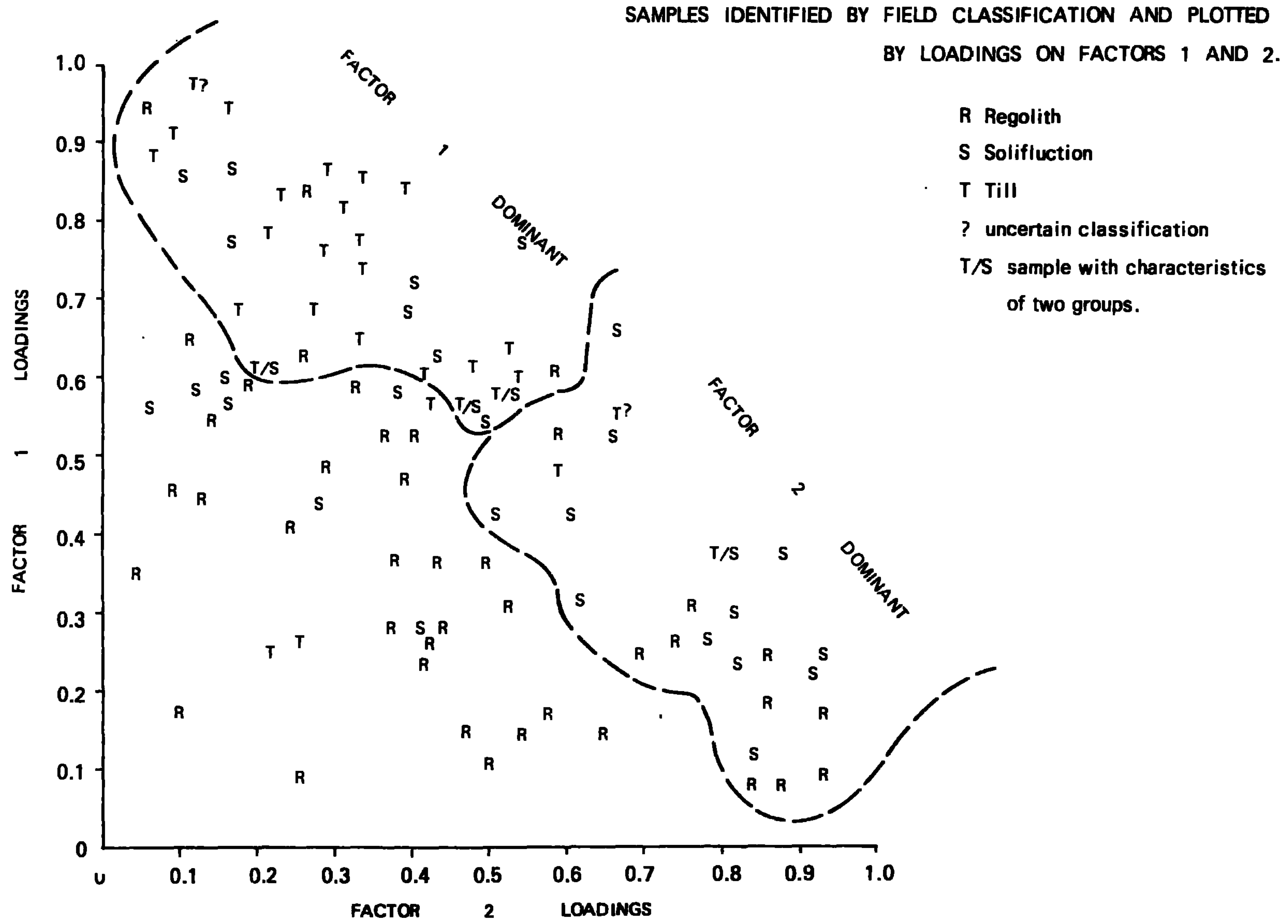
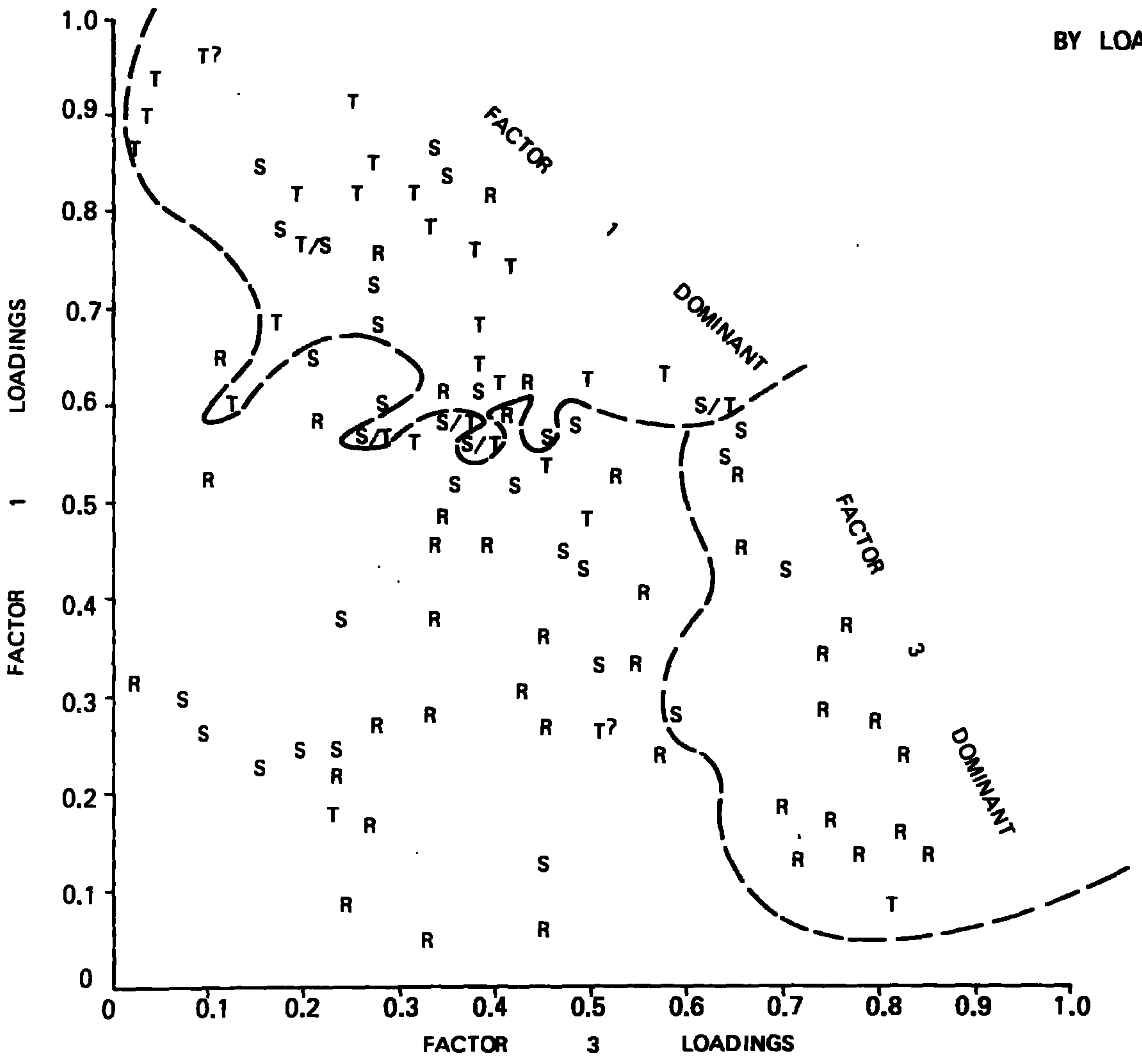

SAMPLES IDENTIFIED BY FIELD CLASSIFICATION AND PLOTTED
BY LOADINGS ON FACTORS 1 AND 2.
R Regolith
S Solifluction
T Till
? uncertain classification
T/S sample with characteristics of two groups.
FACTOR 1 DOMINANT
FACTOR 2 DOMINANT
FACTOR 1 LOADINGS
FACTOR 2 LOADINGS
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Figure 7.8

SAMPLES IDENTIFIED BY FIELD CLASSIFICATION AND PLOTTED

BY LOADINGS ON FACTORS 1 AND 3.



R Regolith

S Solifluction

T Till

? uncertain classification

T/S sample with characteristics of two groups

Figure 7.9

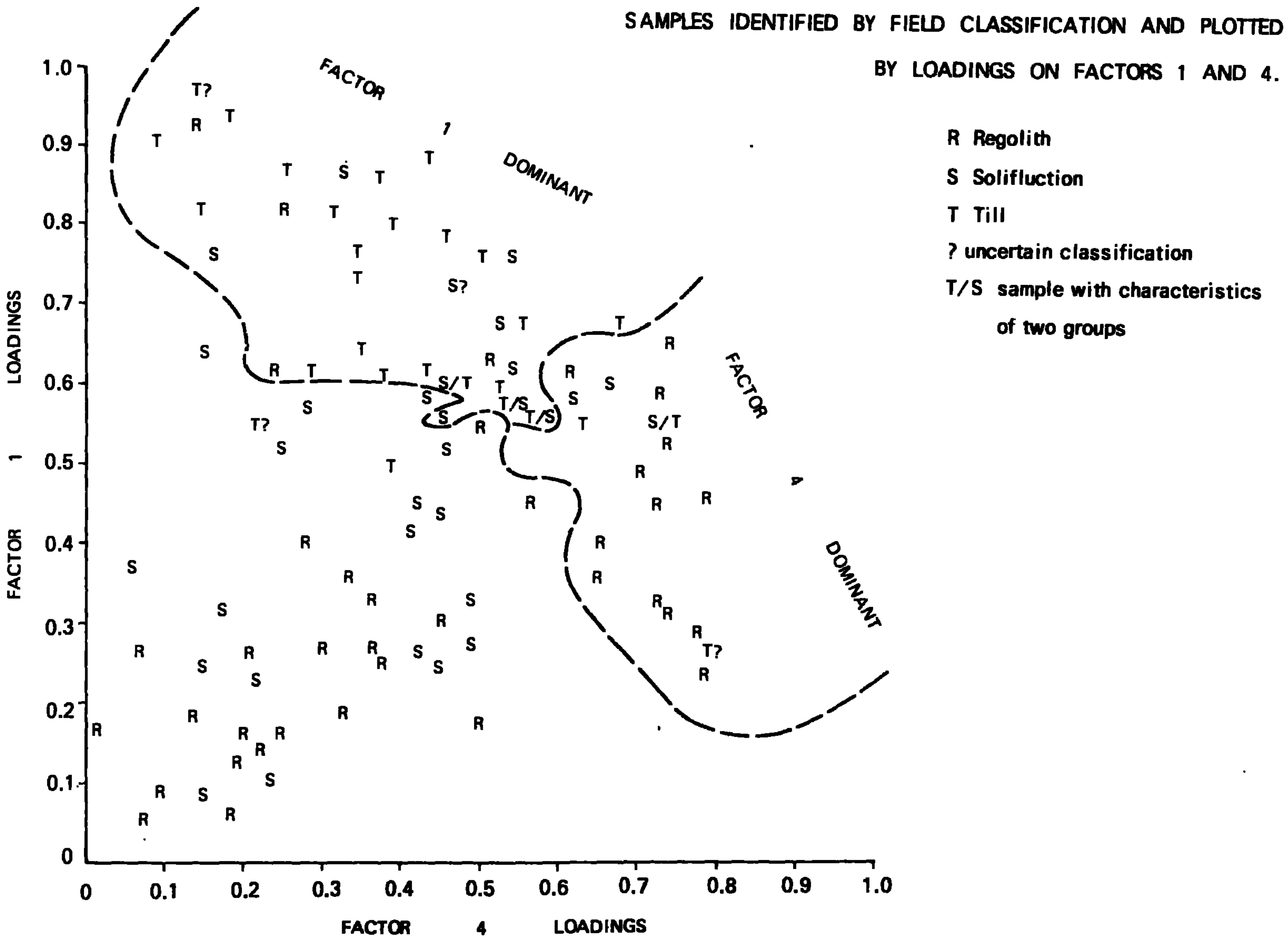
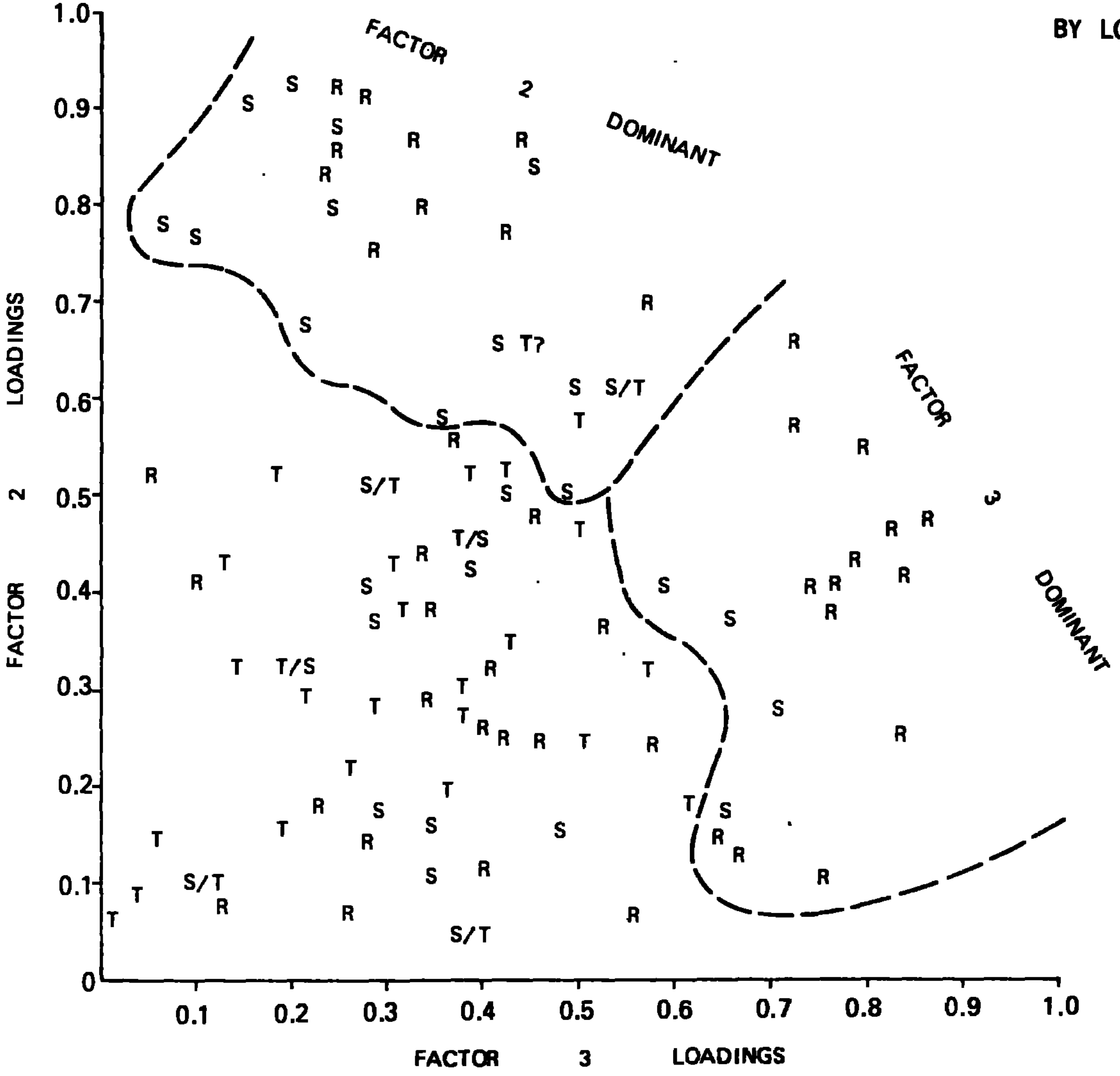

SAMPLES IDENTIFIED BY FIELD CLASSIFICATION AND PLOTTED BY LOADINGS ON FACTORS 1 AND 4.
R Regolith
S Solifluction
T Till
? uncertain classification
T/S sample with characteristics of two groups
FACTOR 1 DOMINANT
FACTOR 4 DOMINANT
FACTOR 1 LOADINGS
FACTOR 4 LOADINGS

Figure 7.10

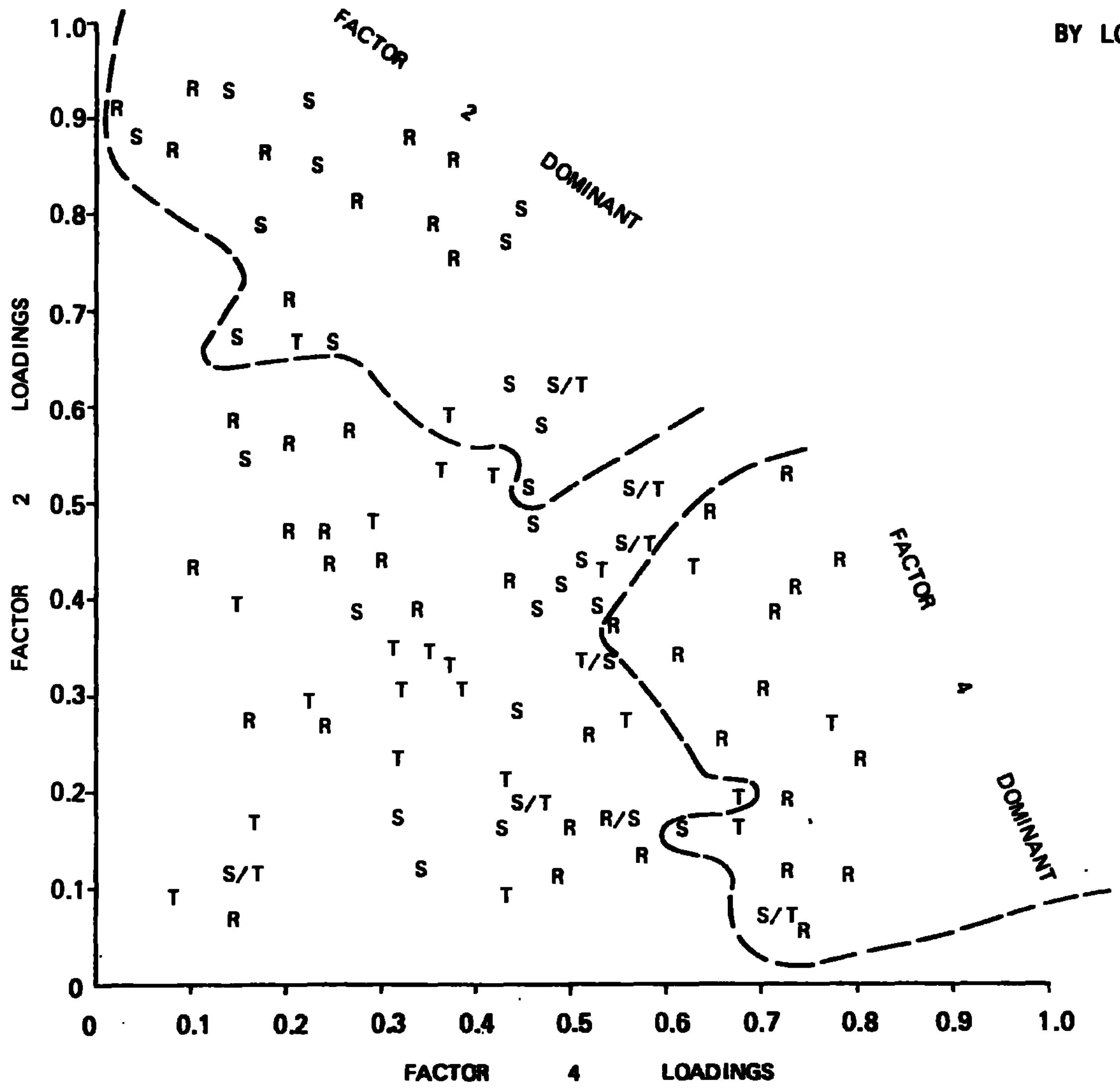
SAMPLES IDENTIFIED BY FIELD CLASSIFICATION AND PLOTTED BY LOADINGS ON FACTORS 2 AND 3.



R Regolith
S Solifluction
T Till
? uncertain classification
T/S sample with characteristics of two groups

Figure 7.11

SAMPLES IDENTIFIED BY FIELD CLASSIFICATION AND PLOTTED BY LOADINGS ON FACTORS 2 AND 4.



R Regolith

S Solifluction

T Till

? uncertain classification

T/S sample with characteristics of two groups.

Figure 7.12

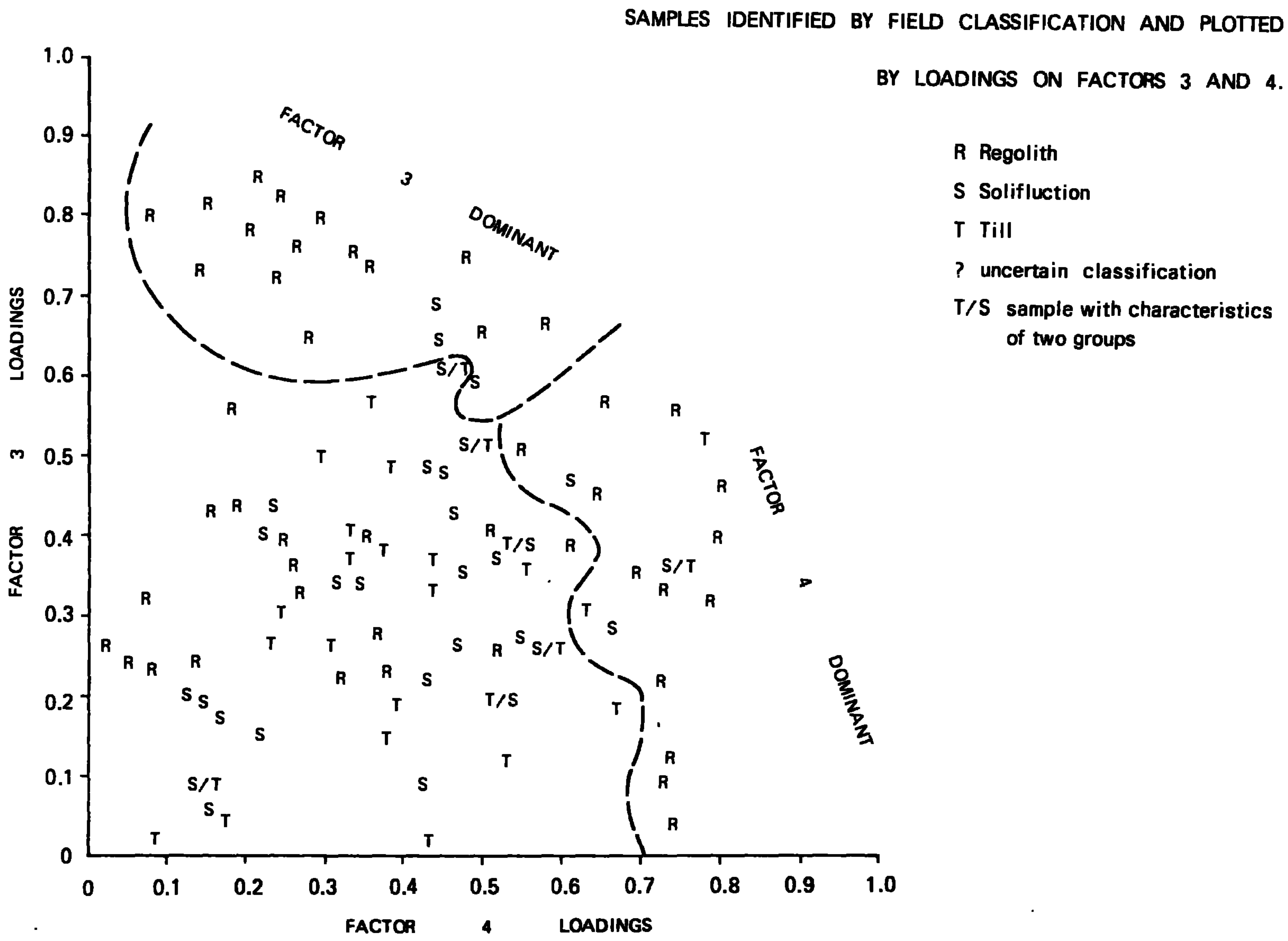

SAMPLES IDENTIFIED BY FIELD CLASSIFICATION AND PLOTTED
BY LOADINGS ON FACTORS 3 AND 4.
FACTOR 3 DOMINANT
FACTOR 4 DOMINANT
R Regolith
S Solifluction
T Till
? uncertain classification
T/S sample with characteristics of two groups
FACTOR 3 LOADINGS
FACTOR 4 LOADINGS
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Figure 7.13

The results of this data analysis describe the deposits of Upper Weardale in terms of objective factors reflecting their sedimentary characteristics. In this study size distribution has been used because the classification of till, solifluction and regolith is frequently based on texture. It is interesting to view the author's field classification in the light of a factor analysis solution of the particle size data. Figures 7.8, 7.9, 7.10, 7.11, 7.12 and 7.13 indicate that the simple field classification is not satisfactory in terms of the textural characteristics of the samples. It is therefore important to investigate the sediment characteristics of the groupings in the manner adopted by Klovan (1966). That the plots of pairs of factors here indicate that complete admixtures of sediment type are possible is a reflection of the difference in environment. Klovan (1966) considered a situation in which the grain size data were taken from differing environments of deposition, the differences existing contemporaneously. In Upper Weardale the sediments sampled have undergone a sequential history. From the earlier discussion (Chapters 1-4) it may be supposed that initially, as ice retreated there were two distinct deposit types - glacially deposited "tills" and other detritus either slightly processed by glacial action (after the model of Vincent, see Figure 4.1 above) or produced in 'nunatak' areas by frost action.

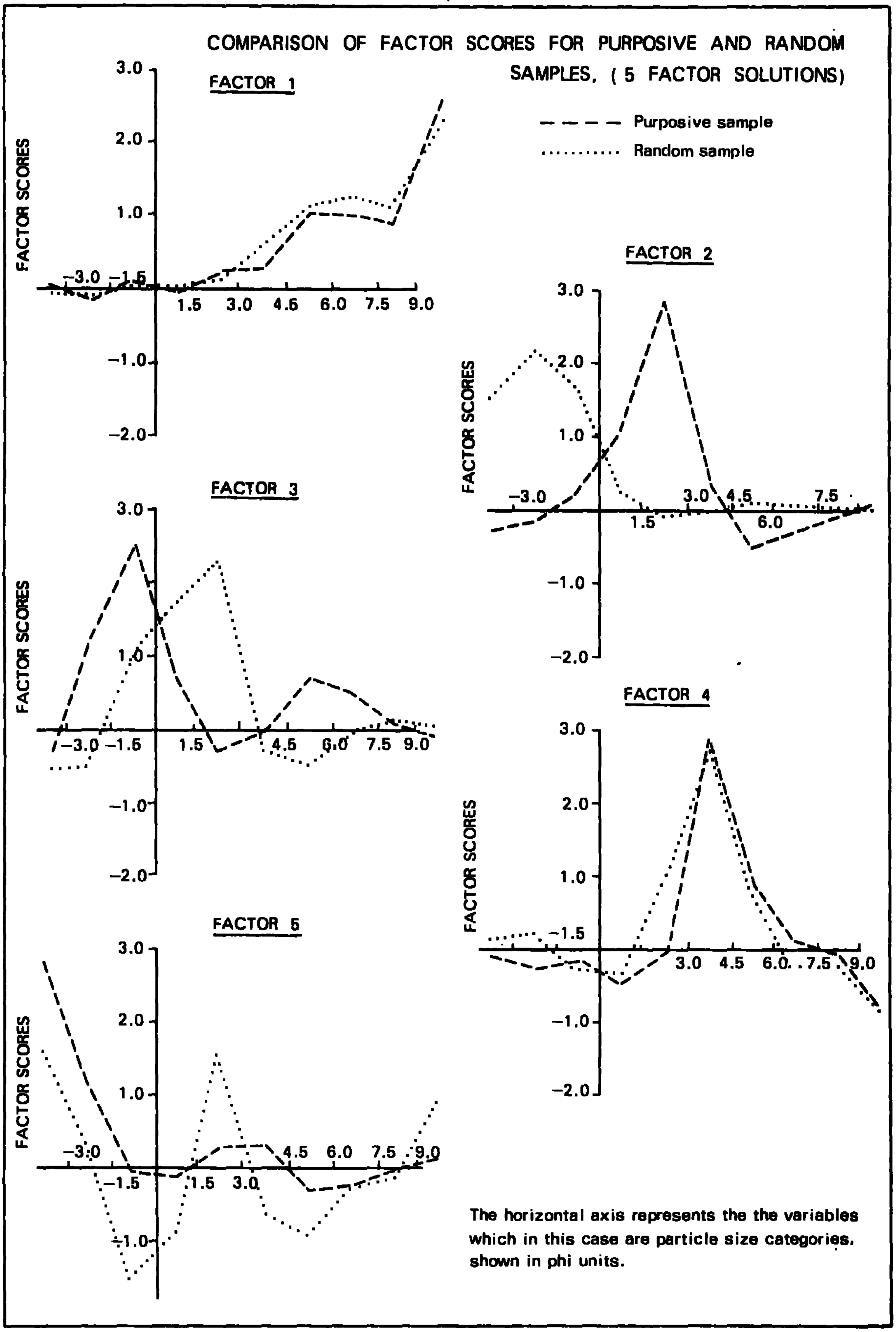
Subsequent periglacial climate and the initiation of solifluction and latterly hill wash processes, and the production of bedrock disintegration material (regolith) means that the environments of deposition are not necessarily distinct either areally or in terms of a simple single deposition process. This indicates that the deposits may be polygenetic and the plots of factor loadings attest to the utility of factor analysis - in that it permits an objective assessment of the influence of <u>each</u> factor on the characteristics of each deposit. It remains to establish the nature of the factors.

Chapter 8

The Nature of the Factors

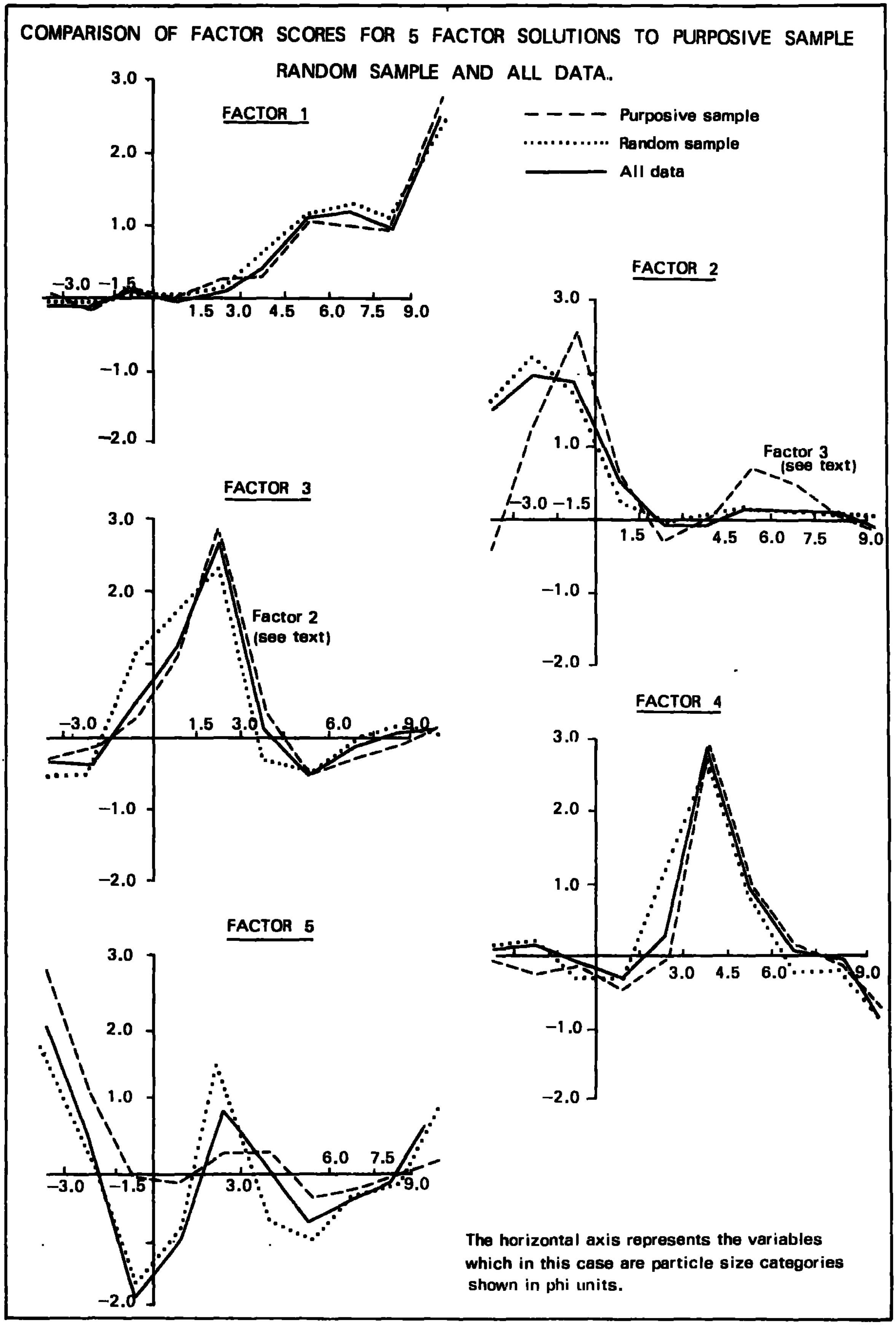
A comparison of the factor scores for the five factors identified in the purposive sample using 1.5 phi unit categories and the factors generated in the analysis of the random sample (also using 1.5 phi unit categories) is presented as Figure 8.1. The similarity noted above (Chapter 7) between Factor 2 of the purposive sample, using 1.5 phi unit categories, and Factor 3 of the random sample, using 1.5 phi unit categories, (and vice-versa) can be detected on the appropriate graphs (Figs. 8.1 and 8.2). A further test of the technique to determine the reproducibility of results using extended data from the same region was conducted. This consisted of the factor analysis of the data for all samples in both the purposive and random sample. The results provide a clear indication that the same five major influences are detected. The graphs produced as Figure 8.2 illustrate this, Factors 2 and 3 from the purposive sample data have been included with the diagrams for Factors 3 and 2 respectively to allow for the above mentioned interchange of these two between the purposive and random samples. It can be clearly seen that the same major influences are being recorded. If these factor scores were any more similar the results would be extremely suspect as <u>identical</u> factor scores from different data sets are most unlikely.

This processing of all data together introduces a fourth set of factor analysis results (see Table 8.1) and a fourth factor score matrix (see Table 8.2). The results of this are extremely useful in the



COMPARISON OF FACTOR SCORES FOR PURPOSIVE AND RANDOM SAMPLES. (5 FACTOR SOLUTIONS)
Purposive sample
Random sample
FACTOR 1
FACTOR 2
FACTOR 3
FACTOR 4
FACTOR 5
FACTOR SCORES
3.0
2.0
1.0
−1.0
−2.0
−3.0
−1.5
1.5
3.0
4.5
6.0
7.5
9.0
The horizontal axis represents the the variables which in this case are particle size categories, shown in phi units.

Figure 8.1



COMPARISON OF FACTOR SCORES FOR 5 FACTOR SOLUTIONS TO PURPOSIVE SAMPLE RANDOM SAMPLE AND ALL DATA.
Purposive sample
Random sample
All data
FACTOR 1
FACTOR 2
FACTOR 3
FACTOR 4
FACTOR 5
Factor 2 (see text)
Factor 3 (see text)
3.0
2.0
1.0
−1.0
−2.0
−3.0
−1.5
1.5
3.0
4.5
6.0
7.5
9.0
The horizontal axis represents the variables which in this case are particle size categories shown in phi units.

Figure 8.2

TABLE 8.1

Varimax Factor Matrix - All Data

Sample No.	Field Classification	Communality	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
P1	S	0.9628	0.4571	0.0638	0.6113	0.6008	0.1231
P2	T	0.9529	0.9612	0.0828	-0.0295	0.1407	0.0378
P3	T	0.9004	0.9389	0.0706	-0.0887	0.0767	0.0122
P4	T	0.9620	0.7476	0.4649	0.0654	0.4261	0.0342
P5	R	0.9510	0.4935	0.7248	0.2071	0.3630	0.0863
P6	R	0.9546	-0.0014	0.8219	-0.0008	0.0418	0.5266
P7	S	0.9900	0.4716	0.1248	0.8402	0.1715	0.1292
P8	R	0.9071	0.2699	0.7466	0.4020	0.2392	-0.2408
P9	S	0.9897	0.4579	0.1435	0.6843	0.5371	0.0515
P10	T	0.9920	0.7138	0.4295	0.4851	0.2085	0.1390
P11	T	0.9782	0.7108	0.1939	0.4505	0.4599	0.1442
P12	T ?	0.9302	0.8828	0.2220	0.0909	0.2575	-0.1643
P13	T	0.9381	0.6325	0.6079	0.1221	0.2921	-0.2613
P14	T	0.9743	0.8623	0.3930	0.1036	0.2354	-0.1002
P15	R	0.9872	0.5442	0.7434	0.1706	0.3144	-0.1017
P16	R	0.9445	0.3017	0.8834	0.1264	0.2229	-0.0859
P17	T	0.9793	0.8705	0.2040	0.3586	0.2107	-0.0831
P18	T	0.9419	0.8375	0.2850	0.3328	0.1520	-0.1595
P19	S?	0.9821	0.8397	0.1968	0.2775	0.3527	0.1923
P20	T	0.9125	0.6882	0.4391	0.2683	0.0688	-0.4114
P21	R	0.8716	0.3950	0.6471	0.1000	0.4378	0.3085
P22	R	0.9609	0.5363	0.4453	0.2489	0.6407	-0.0502
P23	S	0.9788	0.6517	0.4481	0.3718	0.4046	0.2268
P24	S	0.9826	0.8645	0.4491	0.1768	0.0427	0.0216
P25	R	0.8754	0.0646	0.7549	0.1305	0.2182	0.4867
P26	S?	0.9685	0.8874	0.2960	0.2888	0.0839	0.0540
P27	S?	0.9803	0.8853	0.2412	0.2277	0.2483	0.1574
P28	T?	0.9833	0.6826	0.0782	0.0281	0.7124	-0.0554
P29	S?	0.9579	0.7918	0.3292	0.2760	0.3789	-0.0528
P30	T	0.9563	0.8701	0.3079	0.2318	0.1884	0.1236

P31	T	0.9886	0.7273	0.4031	0.4174	0.3034	0.1754
P32	R	0.9651	0.2346	0.9379	0.1658	-0.0184	-0.0511
P33	T	0.9938	0.8716	0.3197	0.2897	0.1176	0.1846
P34	R	0.9908	0.5695	0.4044	0.6763	0.1862	0.1044
P35	S	0.9582	0.8057	0.1209	0.4866	0.1656	0.1739
P36	R	0.9475	0.1536	0.2903	0.8925	0.1039	-0.1794
P37	T	0.9402	0.7486	0.1615	0.5512	0.2178	-0.0495
P38	T	0.9652	0.7488	0.1827	0.5452	0.2715	-0.0164
P39	T	0.9634	0.9083	0.0950	0.2740	0.2103	0.0999
P40	S	0.9907	0.5268	0.0844	0.7581	0.2543	0.2582
P41	T	0.9336	0.8688	0.1939	0.1936	0.3138	-0.0733
P42	T?	0.9333	0.8877	0.2305	0.2279	1.1592	-0.1216
P43	Clay	0.9949	0.9954	0.0166	0.0179	-0.0451	0.0376
P44	T?	0.9807	0.7461	0.2770	0.2781	0.4679	0.2258
P45	T?	0.9858	0.8334	0.1085	0.3293	0.4088	0.0621
P46		0.8669	0.3502	0.4416	0.3827	0.5126	-0.3742
P47		0.8739	0.0760	0.2072	0.8821	0.1765	-0.1265
P48		0.9189	0.0501	0.0819	0.9382	0.0916	0.1450
P49		0.9792	0.1580	-0.0035	0.6641	0.6936	0.1794
P50		0.9877	0.4681	0.0166	-0.0356	0.8701	-0.1003
P51		0.9861	0.0339	0.7526	0.5825	0.0526	-0.2765
P52		0.9818	0.2388	0.4581	0.5251	0.6540	-0.1066
P53		0.9042	0.0849	0.2934	0.8846	0.1682	0.0123
R1	R	0.9898	0.2803	0.0641	0.7194	0.6081	0.1408
R2	R	0.9958	0.3619	0.2630	0.6965	0.5410	0.1336
R3	T	0.8684	0.8920	0.1108	0.0051	0.1900	-0.1562
R4	R	0.9909	0.3941	0.1217	0.5479	0.7154	0.0931
R5	T	0.9775	0.6142	0.5011	0.5466	0.2141	0.0677
R6	S	0.9549	0.2603	0.4223	0.7308	0.3214	0.2673
R7	S	0.9771	0.4132	0.5104	0.6063	0.3368	0.2545
R8	S	0.9774	0.6463	0.6762	0.2276	0.1510	0.1669
R9	S	0.9493	0.5179	0.6909	0.3880	0.2179	-0.0761

R10	R	0.9661	0.8017	0.2914	0.3861	0.2621	-0.1439
R11	R	0.9657	0.2695	0.5268	0.0966	0.7679	-0.1288
R12	R	0.9459	0.5238	0.1910	0.3439	0.7172	0.0496
R13	S/T	0.9698	0.9506	0.1132	0.1317	0.1885	0.0194
R14	S	0.9679	0.6869	0.3952	0.3688	0.4377	0.1109
R15	T/S	0.9763	0.7247	0.3255	0.2800	0.5089	0.0883
R16	T	0.9935	0.7939	0.2954	0.3053	0.3702	0.2141
R17	T	0.9339	0.9188	0.1604	0.0809	0.2377	0.0319
R18	T	0.9834	0.5308	0.4194	0.4259	0.5806	0.0853
R19	S	0.9789	0.6429	0.3910	0.3642	0.5270	0.0492
R20	S/T	0.9967	0.5372	0.5113	0.3597	0.5472	0.1340
R21	T	0.9827	0.8187	0.4219	0.2826	0.1836	-0.1440
R22	S	0.9895	0.5096	0.5879	0.4367	0.4208	0.1282
R23	T	0.9915	0.2159	0.2757	0.6368	0.6790	0.0478
R24	R	0.9652	0.5894	0.1017	0.2451	0.7374	0.0603
R25	R	0.9865	0.3643	0.8339	0.2924	0.2655	-0.0489
R26	R	0.9791	0.9278	0.0636	0.2955	0.1352	0.0931
R27	S	0.9859	0.8325	0.1958	0.3864	0.3233	-0.0275
R28	R	0.9853	0.4700	0.4012	0.1889	0.7535	-0.0065
R29	T	0.8973	0.5673	0.4378	0.1375	0.5870	-0.1429
R30	T	0.9898	0.8523	0.0845	0.0676	0.4998	-0.0430
R31	S	0.9830	0.5488	0.2000	0.3349	0.6984	-0.2046
R32	T	0.9949	0.8267	0.3199	0.2074	0.4053	0.0437
R33	S	0.9592	0.2277	0.9167	0.1238	0.2267	-0.0174
R34	T	0.9815	0.4589	0.6180	0.4811	0.3727	-0.1365
R35	S	0.9600	0.3021	0.7745	0.1191	0.1212	0.4899
R36	T	0.9841	0.7477	0.3105	0.4683	0.2690	0.1923
R37	T	0.9720	0.6125	0.3599	0.6227	0.2811	0.0229
R38	S	0.9743	0.5318	0.5128	0.5061	0.3909	0.1398
R39	T	0.9776	0.8097	0.2077	0.3766	0.2630	0.2605
R40	T	0.9884	0.5420	0.6910	0.4221	0.1830	-0.0741
R41	T	0.9513	0.7204	0.3646	0.4352	0.3179	-0.0948

R42	S	0.9836	0.5503	0.1681	0.5975	0.5419	0.0439
R43	T	0.9867	0.6402	0.1763	0.2799	0.6828	-0.0345
R44	T	0.9835	0.6100	0.5221	0.4252	0.3975	-0.0066
R45	T	0.9898	0.6537	0.2739	0.4768	0.5085	0.0391
R46	R	0.9895	0.3434	0.4184	0.8103	0.1891	0.0644
R47	R	0.9946	0.2616	0.4590	0.7538	0.3581	-0.1378
R48	R	0.9913	0.2092	0.2424	0.6282	0.6762	0.1920
R49	R	0.9955	0.2281	0.4380	0.4740	0.7045	0.1748
R50	R	0.9323	0.0912	0.9325	0.1548	0.0881	-0.1508
R51	R	0.9668	0.1848	0.9319	0.1468	0.0229	-0.2051
R52	S	0.9783	0.2303	0.7985	0.3041	0.3811	0.2236
R53	S	0.9904	0.2469	0.7701	0.1909	0.3652	0.4080
R54	T?/S	0.9826	0.5350	0.4819	0.4335	0.5254	0.0085
R55	S	0.9957	0.5827	0.4451	0.4627	0.4916	0.0480
R56	R	0.9897	0.5551	0.3438	0.5056	0.5508	0.0660
R57	R/S?	0.9926	0.7298	0.1635	0.3970	0.4946	0.1762
R58	R	0.9753	0.2453	0.7517	0.3548	0.2790	0.3824
R59	R	0.9900	0.3322	0.5129	0.5291	0.5802	-0.0054
R60	R	0.9300	0.1733	0.8651	0.2684	0.2728	0.0717
R61	S	0.9663	0.7789	0.5263	0.2116	0.1559	0.1166
R62	R	0.9942	0.4107	0.1518	0.7738	0.4468	0.0631
R63	R	0.9301	0.5808	0.2968	0.4223	0.5293	-0.2149
R64	S/T	0.9904	0.5156	0.0638	0.4995	0.6843	0.0516
R65	S	0.9801	0.8287	0.1196	0.4098	0.3334	0.0028
R66	R	0.9598	0.0628	0.9019	0.2102	0.0815	-0.3025
R67	S	0.9704	0.2520	0.9271	0.1781	0.1246	0.0122
R68	S	0.9609	0.3940	0.8755	0.1842	0.0599	-0.0412
R69	S	0.9826	0.5566	0.4385	0.6589	0.2096	-0.0491
R70	S/T	0.9922	0.5710	0.2240	0.7004	0.3491	0.0590
R71	R	0.9456	0.1473	0.1289	0.8836	0.2905	0.2051
R72	R	0.9805	0.4905	0.3749	0.6209	0.4579	0.0646
R73	T	0.9844	0.8561	0.2968	0.3249	0.2191	0.0988
R74	T	0.9890	0.7656	0.2127	0.4346	0.4093	0.0362

R75	R	0.9873	0.2867	0.7915	0.4280	0.3070	0.0358
R76	S	0.9990	0.5520	0.2147	0.7285	0.3364	0.0660
R77	R	0.9979	0.5170	0.1875	0.7318	0.3994	0.0215
R78	R	0.9969	0.2237	0.8608	0.2556	0.3372	0.1638
R79	R	0.9614	0.1477	0.6117	0.7098	0.1166	-0.2192
R80	S	0.9919	0.1146	0.8612	0.4465	0.1396	0.1350
R81	R	0.8965	0.1724	0.6486	0.6068	0.0833	-0.2665
R82	R	0.9911	0.1532	0.5158	0.8283	0.0963	-0.0791
R83	R	0.9960	0.2555	0.4668	0.8313	0.1390	0.0486
R84	R	0.9738	0.4371	0.2991	0.4996	0.6294	0.2182
R85	R	0.9833	0.2476	0.7156	0.5900	0.0699	0.2385
R86	R	0.9870	0.1085	0.6864	0.7022	0.1041	-0.0135
R87	R	0.9888	0.0510	0.8716	0.4407	0.0871	0.1571
R88	S	0.9855	0.4064	0.6252	0.5323	0.3725	0.0858
R89	R	0.7250	0.0719	0.3284	0.7391	0.0526	-0.2509
R90	R	0.9429	0.2456	0.4972	0.7087	0.0387	-0.3627
R91	R	0.9796	0.3588	0.4846	0.7411	0.1811	-0.1843
R92	T	0.9867	0.6117	0.5348	0.4599	0.3215	0.1078
R93	S	0.9689	0.4015	0.3203	0.7745	0.3177	0.0659
R94	R	0.8889	0.5804	0.5940	0.3602	0.2499	0.0845
R95	R	0.9839	0.1047	0.5449	0.7730	0.1142	-0.2558
R96	S/T	0.9954	0.2979	0.6486	0.5550	0.4217	-0.0127
R97	R	0.9949	0.4161	0.4000	0.4247	0.6921	-0.0485

TABLE 8.2

VARIMAX FACTOR SCORE MATRIX (TOTAL DATA)

Size Categories in phi units	FACTOR 1	FACTOR 2	FACTOR 3	FACTOR 4	FACTOR 5
<-3.0	-0.0204	1.4703	-0.3667	0.0604	2.0516
-3.01-1.5	-0.1386	1.9884	-0.3781	0.1647	0.4421
-1.5/0.0	0.0821	1.8751	0.4720	-0.1255	-1.6855
0.0/1.5	-0.0043	0.5036	1.2906	-0.3744	-0.9051
1.5/3.0	0.1354	-0.0481	2.7442	0.3108	0.8467
3.0/4.5	0.4026	-0.0533	0.1327	2.8174	0.0898
4.5/6.0	1.1492	0.1469	-0.5450	0.9792	-0.7709
6.0/7.5	1.1764	0.1238	-0.1755	0.0191	-0.3916
7.5/9.0	0.9756	0.0714	0.0089	-0.0560	-0.1217
79.0	2.4832	-0.0861	0.1152	-0.8915	0.6349

indications they give about consistency between data sets from the same area (see Fig. 8.2). No universal pronouncement can be made on the basis of this limited evidence but the consistency demonstrated here underlines the reliability of the technique in the Upper Weardale context. Because of the great bulk of the statistics used and their statement in extensive tables, the detailed diagnosis of the factors from the purposive sample, random sample and total data processing has been omitted. It is pertinent to note that in omitting the detailed diagnosis of factors from the purposive and random samples nothing is lost as the characteristics of the factors (including the interchange of Factors 2 and 3 as noted above) are consistent throughout. Consequently only the diagnosis of the factors for the whole body of data is presented here.

It is acknowledged that in so doing the rigorous stochastic reasoning developed from a random sample is forfeited. However, for the purposes of interpretation and presentation, the analysis of the total data is the more effective demonstration of the nature of the results. Appendix II including the profile descriptions of the random sample and the factor loadings gives the factor loadings for the analysis of the random sample alone. The nature of these factors does not differ from the exposition given below. In consequence the evidence presented here is in confirmation of the results obtained from the random sample, it is presented alone to avoid unnecessary repetition and it is preferred to a consideration of only the random sample because it is more comprehensive.

8.1 Textural Characteristics

It is customary to present the triangular graphs of sand, silt and clay content in works of this nature. In the present work a dilemma emerges between the presentation of data by field classification and its presentation by data analysis classification. The earlier demonstrations of the relationship between field classification and factor analysis grouping have shown that in a purposive sample, although the data gathered are not representative of the true nature of the suite of deposits in a region, there is a reasonably close correspondence between the field classification and the data grouping (see Table 5.4 and Table 7.5). Figures 7.8 to 7.13 demonstrate the lack of the field classification in the description of the random sample and hence the poor correspondence between the field classification and the data analysis grouping.

All the data presented in terms of both sand, silt and clay content and field classification are presented in Figure 6.5. Figure 6.9 presents the data by sand, silt and clay content identified by field classification and introducing the group "unclassified in the field" to include all samples elsewhere shown as e.g. "T??" or "S/T" or any classification recorded in the original field notes as even slightly doubtful. Figure 6.10 presents the zones of the graph in which each type is present and Figure 6.11 compares the tills described by Vincent (1969) and the Lower Till of Co. Durham described by Beaumont (1967) with the till identified in the field. It is apparent that this classification is "acceptable" in so far as it falls within the textural parameters used by workers in adjacent areas to describe "till".

It is evident that the field classification of "till" also overlaps the textures classified as "solifluction" and "regolith" (see Figure 6.10). Consequently there is a need to recognise that texture is not itself a suitable criterion for field determination of deposit type. Parameters established by other criteria e.g. the presence of striated stones do not allow a precise determination of polygenetic deposits. The value of "experience" and "investigator's decision" are called into question by the results displayed in Figures 7.8 to 7.13.

Having thus commented on the field classification it is necessary to consider the results of processing of particle size data. Figure 8.3 presents the distribution of samples by their dominant factor. The zone occupied by samples for which Factor 1 is dominant is, interestingly, coincident with much of the zone occupied by the samples classified as "till". To remove this gross subjectivity Figure 8.4 compares the zone of textures for which Factor 1 is dominant with the textures of the tills described by Vincent (1969) and Beaumont's (1967) Lower Till of Co. Durham. The author considers that the similarities of the textures constitute an initial indication that Factor 1 may be associated with deposits of till.

Similar indications are not so readily gained for the solifluction deposits as there are no published studies giving ranges of texture for solifluction deposits or colluvial or regolith materials in this area. However a series of studies in other regions have been published dealing with these topics. Washburn's work on mass wasting in areas of active solifluction provides excellent data for comparative purposes. A comparison of the textures of samples associated predominantly with

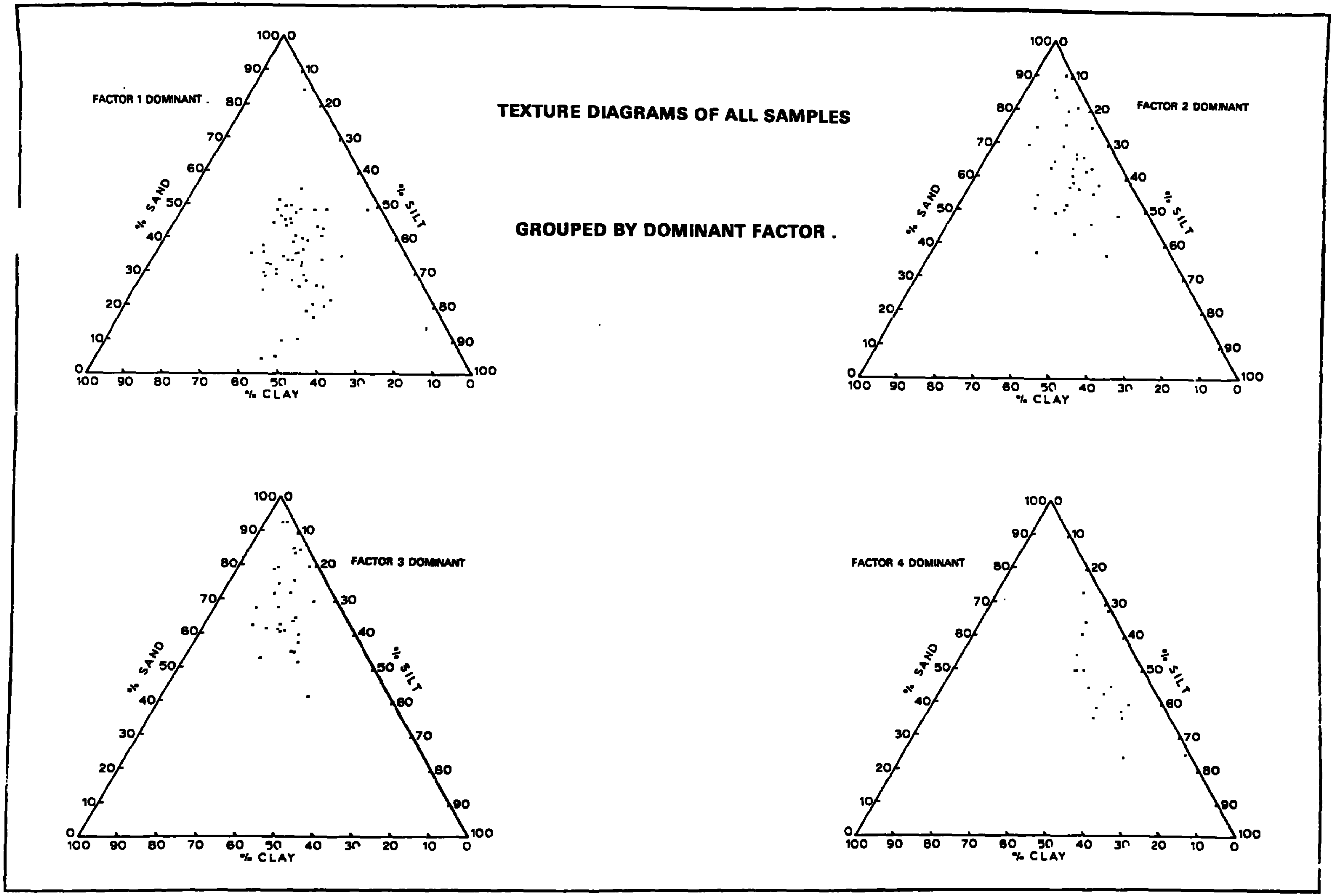

TEXTURE DIAGRAMS OF ALL SAMPLES
GROUPED BY DOMINANT FACTOR .
FACTOR 1 DOMINANT .
FACTOR 2 DOMINANT
FACTOR 3 DOMINANT
FACTOR 4 DOMINANT
% SAND
% SILT
% CLAY
100 0
10
20
30
40
50
60
70
80
90
100
0

Figure 8.3

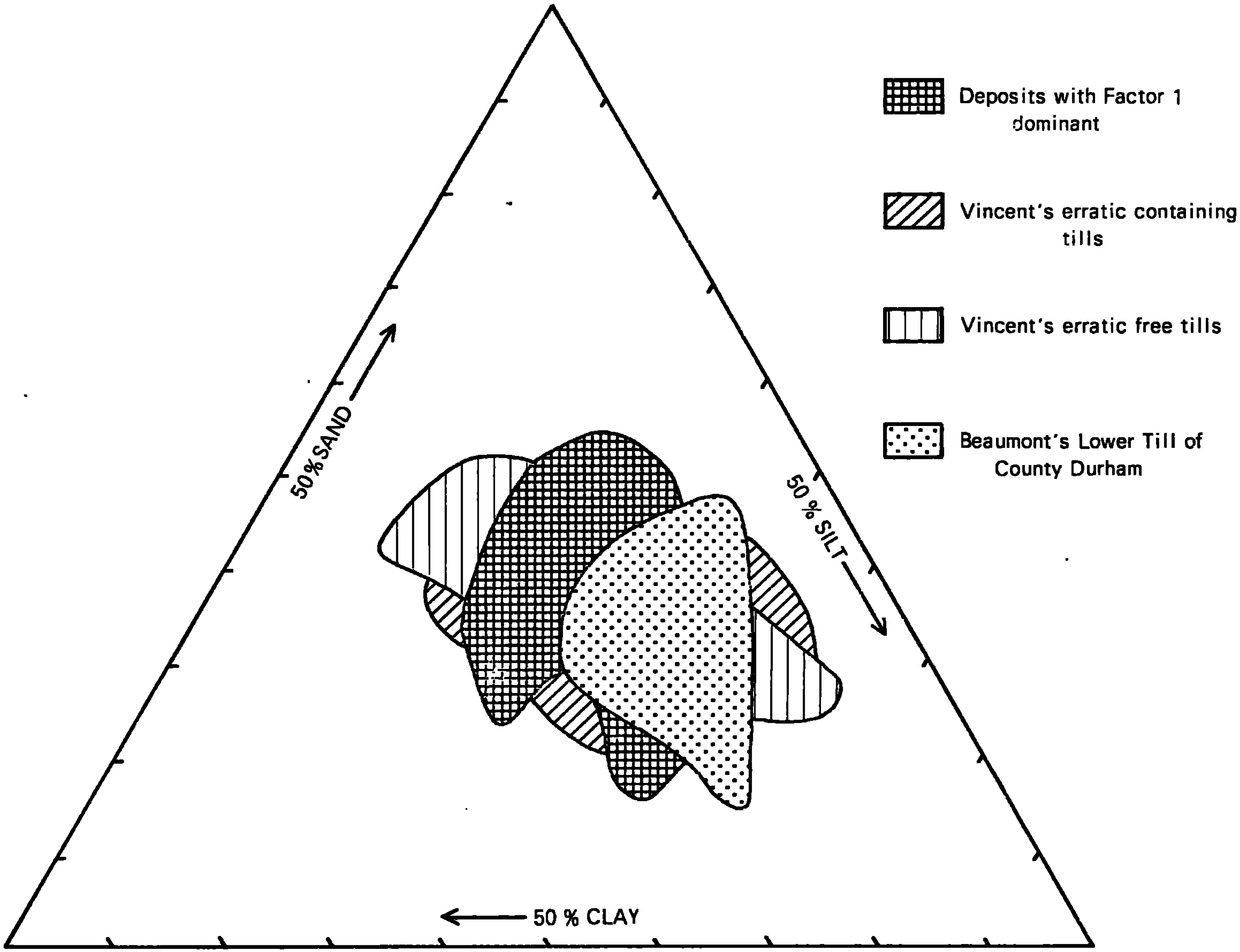


Fig. 8.4 Comparison of texture of Factor 1 samples with tills from adjacent areas .

Factor 4 and the textures from samples at Washburn's site 8 in his Greenland Study (Washburn, 1967) indicates again that Factor 4 may relate samples having definite response to "gelifluction". Washburn uses the term gelifluction to apply to movement of material in association with frozen ground adopting Baulig's definition of gelifluction as solifluction associated with frozen ground (Baulig, 1956, p. 50-51) and notes that this term is supported by the more recent publications of Hamelin and Clibbon (1962) and Hamelin (1963). There is some indication therefore that samples with high loadings on Factor 4 may reflect the action of gelifluction.

Factor 2 and Factor 3 both present problems of identification. They appear to dominate samples which have a similar texture range although the factor score matrices indicate that Factor 2 is more sensitive to high contents of gravel and Factor 3 to high contents of sand. The limitations of the sand, silt, clay triangular graph are clearly illustrated by its inability to demonstrate this difference. Consideration must therefore be given to the complete particle-size curves of the samples.

8.2 Particle Size Distribution Curves

Figure 8.5 presents the "family" of size-distribution curves for samples with Factor 1 dominant. They exhibit the typical characteristics of the till curve and correspond closely to the curve which may be constructed from the data given by Twenhofel (1932, p. 234) for a glacial till. The extent of the area occupied by this group of curves compares closely with that occupied by the group of clay tills reported by Flint (1957, p. 116).

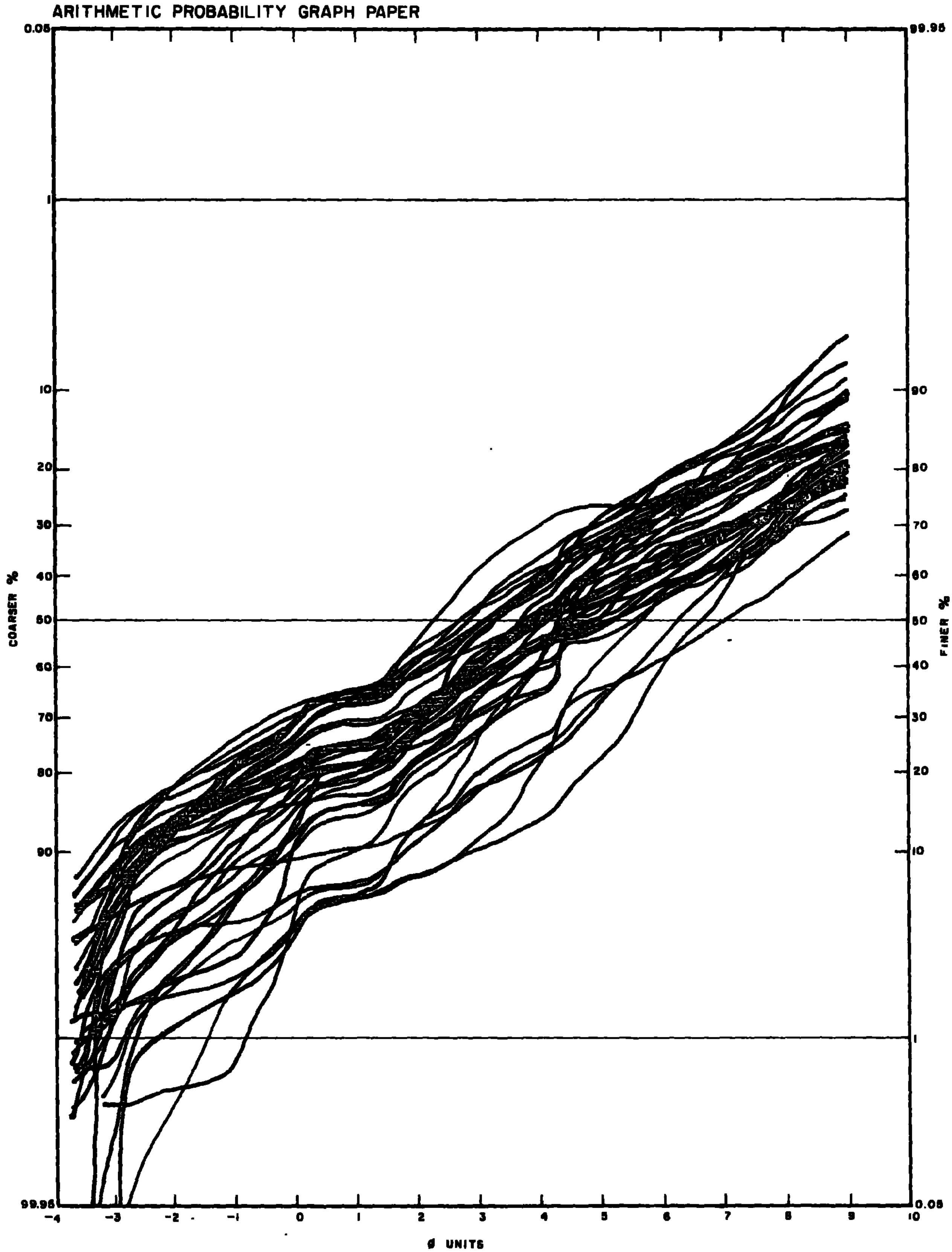


Figure 8.5 Particle-size Curves for Samples with Factor 1 Dominant

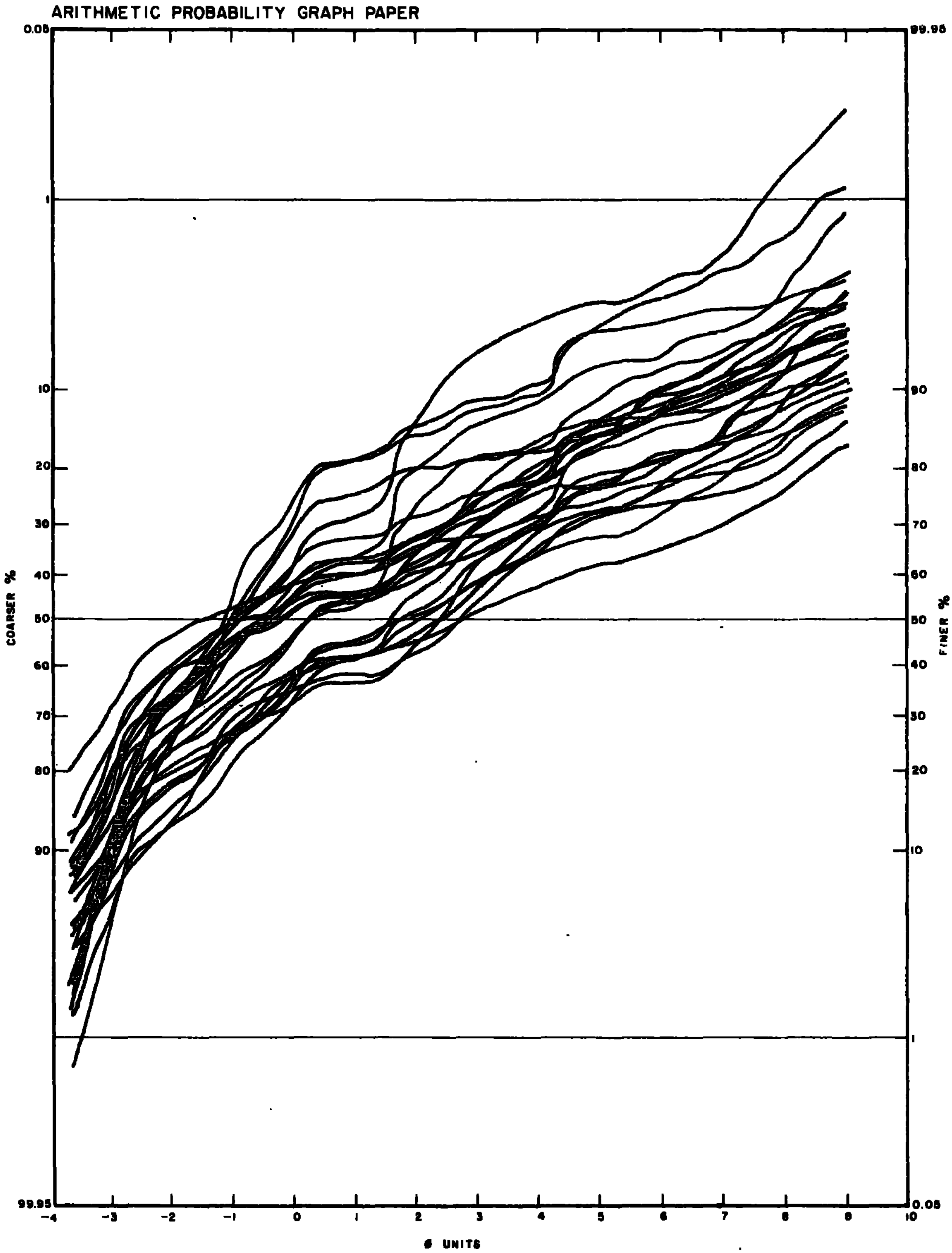


Figure 8.6 Particle-size Curves for Samples with Factor 2 Dominant

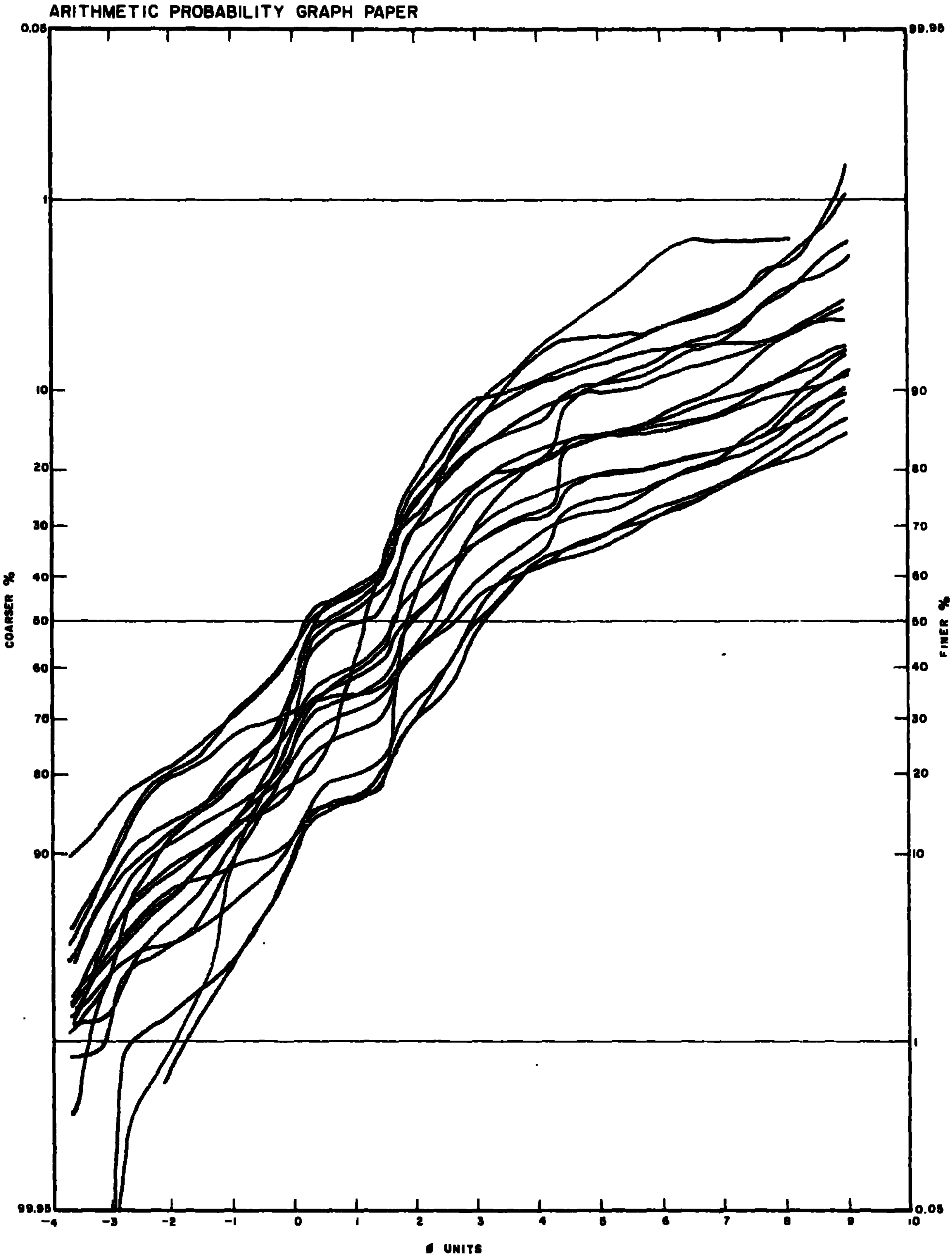


Figure 8.7 Particle-size Curves for Samples with Factor 3 Dominant

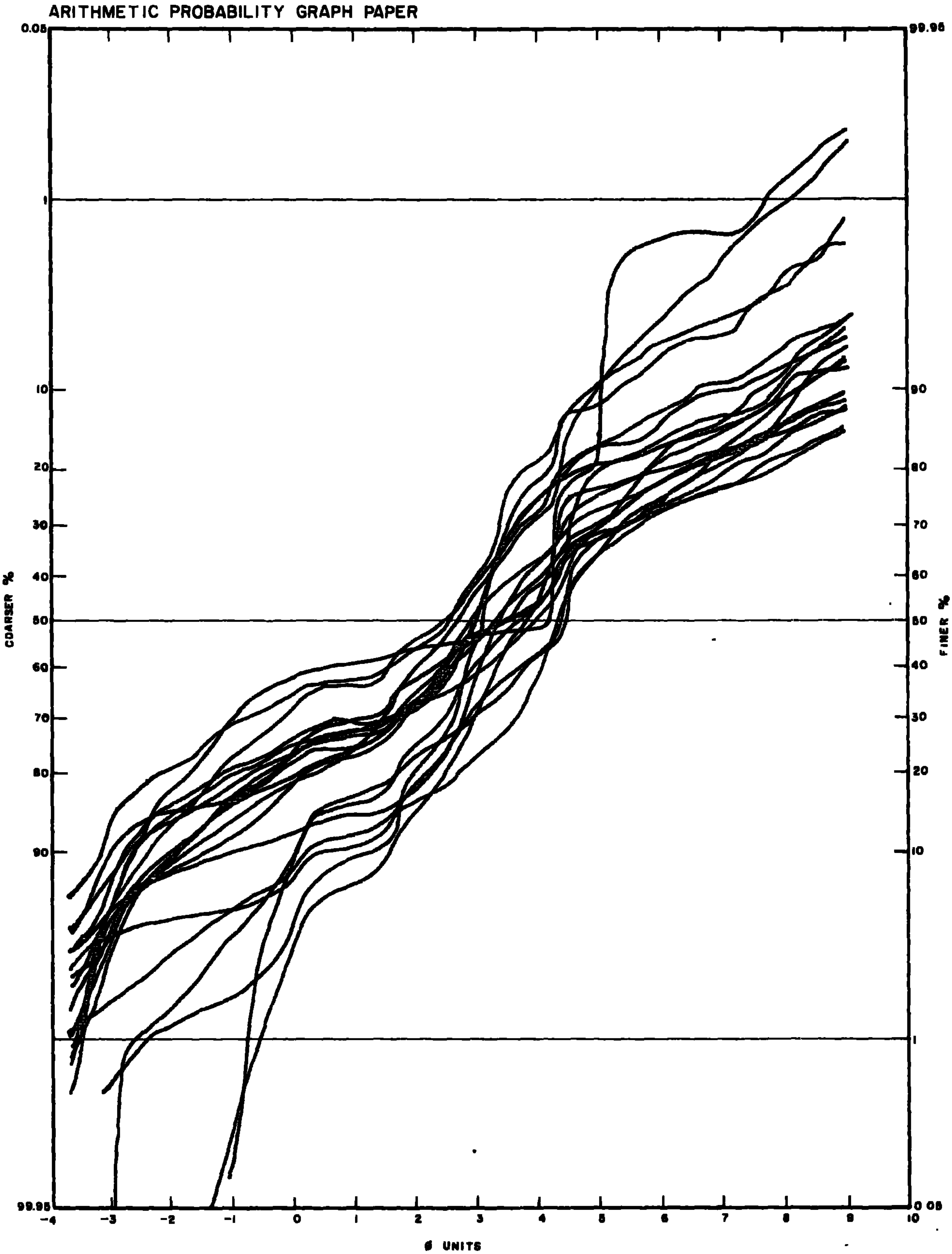


Figure 8.8 Particle-size Curves for Samples with Factor 4 Dominant

Factor 2 as yet uninterpreted has a family of curves (Figure 8.6) which are closely grouped about the curve constructed from Twenhofel's particle size data for rainwashed slope detritus (Twenhofel, 1932, p. 237) and this may be an indication that Factor 2 is associated with the coarser material of the hillslope deposit, similar to that described by Ragg and Bibby (1966). The sample of the finer material described by Ragg and Bibby is loaded most heavily on Factor 4, which appears to relate samples of silty gelifluction material, thus seeming to support their contention that periglacial processes have been important in creating the deposit.

Factor 3 remains to be identified. The curves (Figure 8.7) are those with the closest approximation to a log normal distribution (i.e. are apparently better sorted) and are low in clay content (10%) a characteristic they have in common with Factor 2. The loss of fines in the case of Factor 2 curves (see Figure 8.6) may be accounted for by the action of rain wash on the slope by analogy with Twenhofel. Factor 3 being responsive to sand content (see factor score matrix Table 8.2) seems to identify samples of disintegrating sandstone bedrock this being the only identifiable source of sand in the region. The close approximation to log normality indicates a better sorting of the deposit and suggests it is water lain or derived from water-lain deposits. These characteristics in the Upper Weardale environment can probably be considered as inherited from bedrock. However, the possibility that these are glacio-fluvial sands must also be considered. Thus the Factor 3 loading can be interpreted as the product of sandstone decomposition. This must however be evaluated in the context of the sample site to consider the possibility that these deposits are glacio-fluvial material deposited in the latter stages of ice retreat from Weardale.

Factor 5 having no group of samples for which it is the dominant influence appears, from its factor scores to be a response to a mixture of gravel, sand and clay. This is typical of the deposits of Upper Weardale (as demonstrated in Chapter 6) and so in this analysis Factor 5 probably represents a compensatory factor in the gravel, sand and clay categories for samples which exceed the appropriate content of these in their comparison with the other reference factors of the analysis routine.

8.3 Sediment-Size Parameters

The discussion of these parameters in Chapter 6 demonstrated the effect of purposive and random sampling on the characterisation of a suite of deposits by standard particle-size statistics. The formulation of groups according to their dominant factor loading provides subdivisions of the data obtained. The necessary next step is to establish the sediment size parameters for these groupings. In establishing the values for these descriptive parameters it is also of importance to evaluate the significance of any apparent differences between them. To avoid tedious repetition of the tabulated and calculated values in the difference of means test only the established significance levels are stated in the text unless there is a need to state the calculation more fully.

8.31 Median and Mean Values

The calculation of the mean of the median values (Md) for all samples in the Factor 1 grouping and for all the mean values of these curves also (M_z) gives some insight into the nature of the group of curves being considered. The scatter diagrams for the median and mean values of each curve of the groups shown in Figures 8.5 to 8.8 are presented as Figure 8.9. It is apparent that there is considerable overlap between the ranges of values particularly between Factors 3 and 4.

The Factor 1 group has a range of values for the median between 6.6 phi units and 2.2 phi units with a mean value for the median of 4.215 phi units and a standard deviation of 1.0804 phi units. It is instructive to compare this with the value for the median for glacial till given by Krumbein and Pettijohn (1938, p. 232). They indicate the value of the median for glacial till is 0.062 mm. which is 4.0 phi units. The mean of this factor grouping's median values from Upper Weardale is surprisingly close to this.

Mean of Median (Md) sizes for the Factor 1 group is 4.215, standard deviation 1.0804.

Mean of Median (Md) sizes for the Factor 2 group is 0.4033, standard deviation 1.455.

Mean of Median (Md) sizes for the Factor 3 group is 1.8875, standard deviation 1.015.

Mean of Median (Md) sizes for the Factor 4 group is 3.481, standard deviation .6642.

Mean of Mean sizes (M_z) for the Factor 1 group is 4.2851, standard deviation 1.056.

Mean of Mean sizes (M_z) for the Factor 2 group is 1.0387, standard deviation 1.2703.

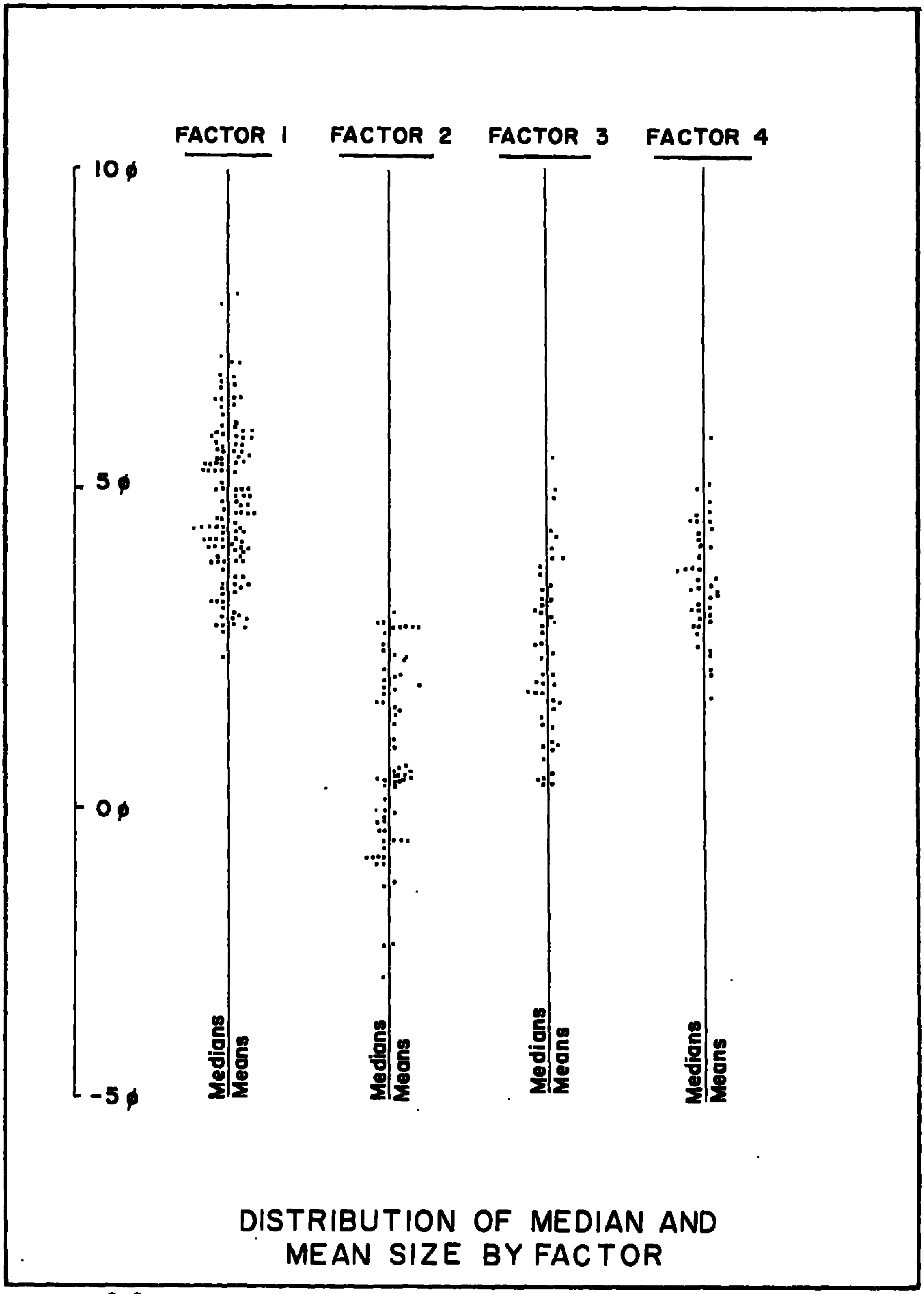

FACTOR 1
FACTOR 2
FACTOR 3
FACTOR 4
10 ϕ
5 ϕ
0 ϕ
-5 ϕ
Medians
Means
Medians
Means
Medians
Means
Medians
Means
DISTRIBUTION OF MEDIAN AND MEAN SIZE BY FACTOR

Figure 8.9

Mean of Mean sizes (M_z) for the Factor 3 group is 2.5379, standard deviation 1.5261.

Mean of Mean sizes ($\bar{M}_z$) for the Factor 4 group is 3.3143, standard deviation 1.0665.

Stating this in descriptive terms the Factor 1 group has a median and mean value in the coarse silt range. The Factor 2 group has a median value in the coarse sand range and a mean value in the medium sand range indicating that it has a skewed distribution. The Factor 3 group has a median in the medium sand range and a mean in the fine. The Factor 4 group has a mean and median in the very fine sand range (terminology as in King, 1966, p. 277).

8.32 Sorting

The scatter diagrams for the sorting values ($\sigma\phi$) for each of the curves in each factor grouping are presented as Figure 8.10. Factor 1 dominates in samples which have sorting values ranging from 2.65 to 5.65 phi units. Mean value of sorting for Factor 1 samples is 4.513 phi with a standard deviation of .7166. The samples therefore are mostly contained in the range 3.0798 to 5.9462 phi. This compares with the range of values observed by Vincent for tills of the N.W. Alston Block of 3.9 to 7.0 phi. He states that the sorting values "tend to concentrate" between 4.0 and 6.5 phi. Beaumont records sorting values ranging from 3.1 to 6.4 phi with the majority (80%) of the values in the interval 3.5 to 5.0 phi. 80% of the values for the Factor 1 grouping of the present study are contained in this same interval. It appears therefore that the Factor 1 group from Upper Weardale has sorting values comparable

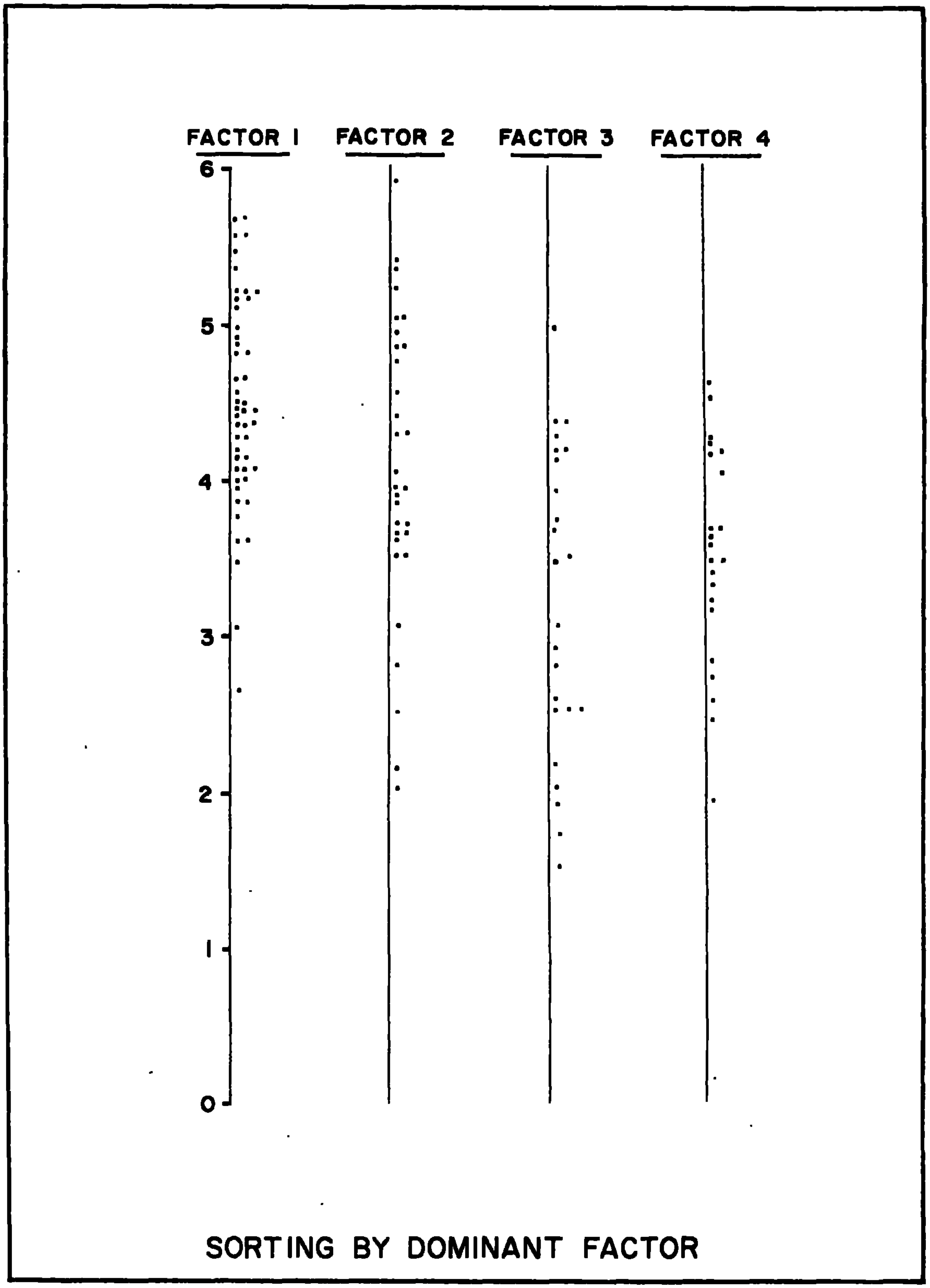

FACTOR 1
FACTOR 2
FACTOR 3
FACTOR 4
6
5
4
3
2
1
0
SORTING BY DOMINANT FACTOR

Figure 8.10

with those for the tills of Eastern Durham but is better sorted than the tills of the N.W. Alston Block.

Using Folk and Ward's (1957) terminology to describe these sorting values the Factor 1 group are very poorly sorted (values ranging from 2.0 to 4.0) and extremely poorly sorted (values larger than 4.0). This is also the case for the tills described by both Vincent (1969) and Beaumont (1967).

Factor 2 samples have sorting values ranging from 2.0 to 5.4ϕ. These values also are poorly sorted, the terms very poorly sorted and extremely poorly sorted also apply. The mean value of sorting for the Factor 2 group is 4.08 with a standard deviation of .9066.

Factor 3 samples have sorting values ranging from 1.5 to 4.95ϕ. Again these values are from poorly sorted to extremely poorly sorted although the mean value of 3.19 for these samples falls within the category "very poorly sorted". Standard deviation for this group is .9929.

Factor 4 samples have absolute values ranging from 1.9 to 4.55ϕ. The mean of these values is 3.45 with a standard deviation of .6896. The same verbal description as above applies to this range of sorting values.

8.33 Skewness

Values of skewness reflect the symmetry of the particle size curve, high values indicate departure from the normal curve, negative values indicating a skew to the coarser grain sizes and positive values to the earlier finer sizes. The absolute range of values for skewness is from -0.33 to +0.63. The values for each factor grouping are presented as scatter diagrams in Figure 8.11.

Factor 1 has skewness values ranging from -0.27 to + 0.33. Vincent (1969) reports skewness values ranging from -0.2209 to 0.2040 for the tills of the N.W. Alston Block. Beaumont records values ranging from -0.18 to 0.24. Clearly the Factor 1 grouping from Upper Weardale deposits exhibits a greater range of skewness than either of the other two studies records. The mean value for skewness in the Factor 1 group is 0.0191 with a standard deviation of 0.687. The majority of the Factor 1 skewness values are close to 0 with the majority exhibiting positive skewness.

Factor 2 samples exhibit a range of skewness from -0.05 to 0.38 almost all exhibiting positive skewness values. The mean of these values is 0.1643 with a standard deviation of 0.59.

Factor 3 samples exhibit a range of skewness from -0.23 to 0.63 with a mean value of 0.2104 and a standard deviation of .2012. Factor 4 is the only grouping of samples which has a negative mean value for skewness. The mean value is -0.0443 with a standard deviation of 0.2133 the absolute range being from -0.52 to 0.30.

8.4 Product Moment Correlations

It was indicated above (Chapter 6.6) that observed relationships between pairs of variables are of value in indicating the nature of sediments. Many published papers deal with such relationships (Folk and Ward, 1957, Passega, 1964, Bull, 1962, Folk and Ward cited in King, 1966, p. 282). The results of the total data body obtained from Upper Weardale also indicated that relationships recorded by Folk and Ward

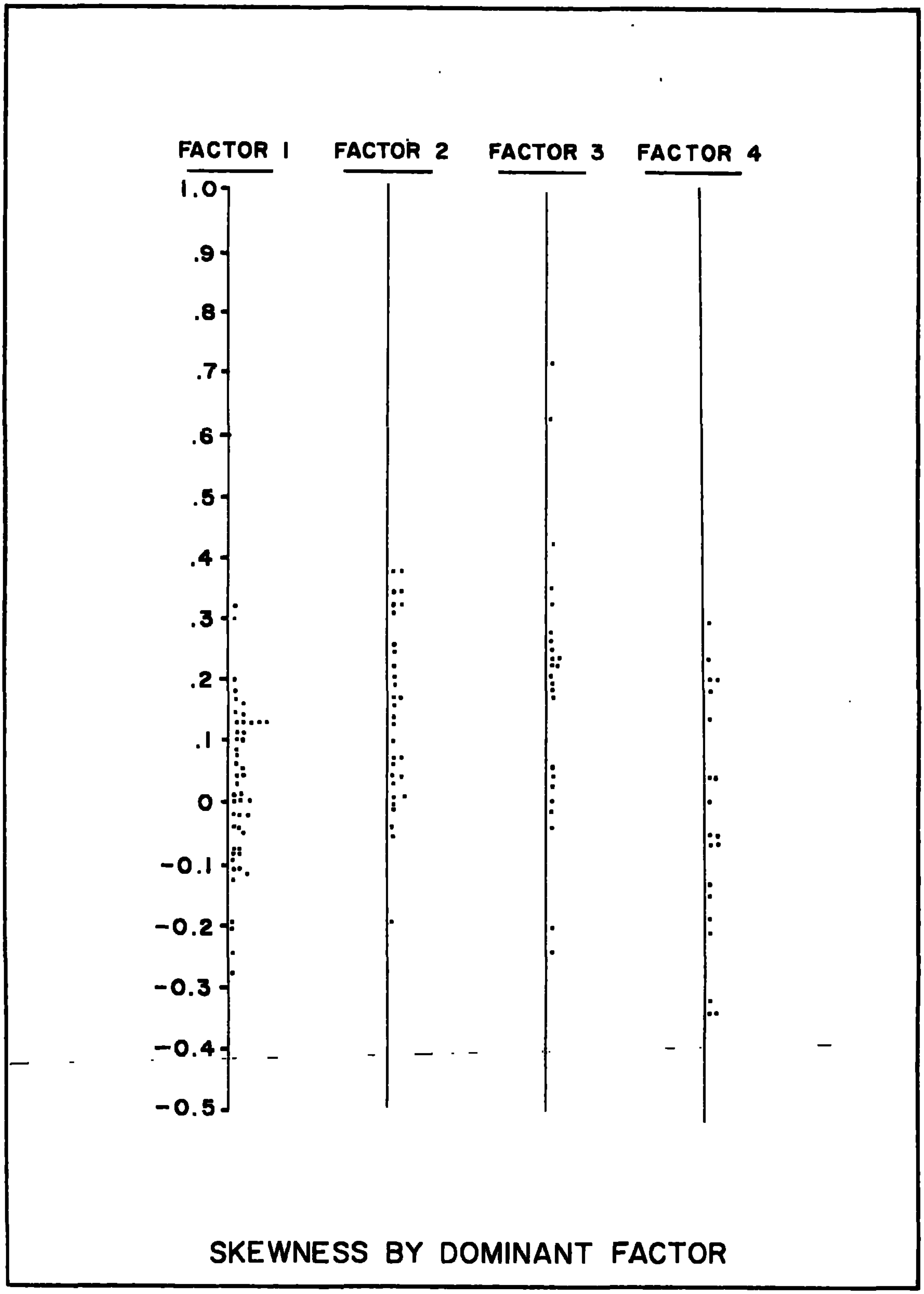

FACTOR 1
FACTOR 2
FACTOR 3
FACTOR 4
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
SKEWNESS BY DOMINANT FACTOR

Figure 8.11

(cited in King, 1966, p. 282) for marine sediments and by Beaumont (1967) and Vincent (1969) for till did not hold true for the whole suite of sediments in Upper Weardale. Consequently all measured properties for each sample were processed to calculate the correlation coefficient between every pair of variables. This was done for all data to indicate any relationships which were generally true for sediments in Upper Weardale. The factor groupings were also processed separately to establish which correlations existed between the variables in each grouping.

8.41 General Correlations in Upper Weardale Deposits

The result of the calculation of the correlation coefficients is given in Figure 8.12. Shading indicates correlation coefficients which are significant at the .05 level (based on Fisher and Yates tables of significant values of 'r'). Results of this indicate the close positive correlation of Factor 1 loadings with Median and Mean values while Factor 2 loadings have a close negative correlation with these two values. Factor 1 correlates with silt and clay content and has a negative correlation coefficient with both Kurtosis and sand content. Throughout Upper Weardale Factor 1 therefore reflects the sand, silt and clay content of the material and the Median and Mean particle size of each sample and the peakedness of the distribution. (Kurtosis for this work was based on projections of the particle-size curve to give estimated 5 and 95 percentiles for calculation. It is included for completeness but not recognised as important because of the uncertain nature of the projections of the particle size curve).

Factor 2 correlates with median and mean values and silt and

CORRELATION MATRIX

for all measured variables

of all samples

shading indicates values significant at the .05 level

FACTOR LOADINGS

1	2	3	4	5	Depths	Elevation	Median	Mean	Sorting	Skewness	Kurtosis	Sand	Silt	Clay	Organic Content	pH	Carbonate Content
1.000																	
-.436	1.000																
-.375	-.161	1.000															
.029	-.327	.046	1.000														
-.017	-.016	-.034	.131	1.000													
.086	.081	-.300	.014	.007	1.000												
-.130	.075	-.045	.211	-.127	.040	1.000											
.903	**-.824**	-.209	.228	-.137	.022	-.089	1.000										
.848	**-.794**	-.070	.203	-.067	-.024	-.147	**.877**	1.000									
-.014	.212	.100	.260	.032	-.105	.113	-.116	-.010	1.000								
-.174	.066	.245	-.237	.036	-.135	.036	-.344	-.057	.089	1.000							
-.507	.080	**.425**	.248	-.215	-.097	.381	-.318	-.259	.224	.208	1.000						
-.524	-.027	.866	.083	-.137	-.255	-.016	-.354	-.211	.100	.313	.499	1.000					
.725	**-.597**	-.486	.453	-.179	.134	.034	**.807**	**.675**	-.017	-.355	-.225	**-.537**	1.000				
.928	**-.634**	-.337	-.189	.045	.042	-.173	**.814**	**.783**	-.181	-.022	**-.527**	-.496	**.538**	1.000			
.226	-.301	.807	.022	-.014	-.170	.009	.284	.268	-.095	.008	-.085	-.060	.131	.248	1.000		
.349	-.243	-.010	-.108	.015	.182	-.543	.280	.326	-.029	.038	-.236	-.048	.144	.349	.008	1.000	
-.101	-.035	.201	.075	-.019	-.144	-.091	-.071	.015	.118	.141	.204	.175	-.062	-.077	-.228	.058	1000

Figure 8.12

FACTOR LOADINGS

CORRELATION MATRIX

for all measured variables

of samples with Factor 1 dominant

shading indicates values significant

at the .05 level

1	2	3	4	5	Depths	Elevation	Median	Mean	Sorting	Skewness	Kurtosis	Sand	Silt	Clay	Organic Content	pH	Carbonate Content
1.000																	
-.634	1.000																
-.577	.278	1.000															
-.495	-.065	.011	1.000														
-.153	.232	.307	-.020	1000													
.334	-.160	-.458	-.052	-.163	1.000												
.300	-.300	-.444	-.068	-.552	.105	1.000											
.848	-.740	-.682	-.186	.451	.378	.423	1.000										
.876	-.885	-.522	-.265	-.262	.276	-.349	.879	1.000									
-.120	.664	.271	-.287	.491	-.162	-.247	-.462	-.534	1.000								
.097	-.388	.250	-.098	.363	-.225	-.162	-.116	.337	-.288	1.000							
.401	-.550	-.505	.016	-.092	.566	.223	.523	.568	-.550	.182	1.000						
.704	.417	.850	.192	.266	-.432	-.462	-.795	.660	.257	.195	-.543	1.000					
.400	-.684	-.590	.314	-.575	.335	.447	.753	.624	-.718	-.159	.509	-.671	1.000				
.902	-.603	-.473	-.604	-.065	.159	.303	.733	.858	-.181	.311	.441	-.657	.259	1.000			
.301	-.225	-.124	-.194	-.305	-.216	.188	.377	.291	-.154	-.171	-.252	-.080	.192	.232	1.000		
.216	-.090	.065	-.162	.372	.315	-.537	.103	.117	.100	.007	.158	-.040	-.094	.128	-.157	1.000	
.246	-.056	-.019	-.314	-.108	.214	.021	.139	.210	.033	.164	.053	.102	-.044	.243	.062	.004	1.000

Figure 8.13

clay content and Factor 3 with sand content. Correlations between the median and mean values and the median and mean and silt and clay content are also significant. The remaining calculations between sand and silt content and silt and clay content are of interest. The negative correlation between sand and silt content and the positive correlation between silt and clay content indicate that the content of fines is inversely related to the content of coarser material. The relationships demonstrated from this analysis of all data are those which would be expected from the nature of the factor analysis. Five factors generated from particle size curves are necessarily correlated with other properties of the particle size data e.g. mean, median, sand, silt and clay content. The relationships recorded here reinforce the earlier assessment of the nature of the factors from factor scores (Chapter 8).

8.42 <u>Correlation Between Variables: Factor 1 Grouping</u>

Figure 8.13 presents the correlation matrix for all measured variables for all samples loading most highly on Factor 1. The significant correlations are more numerous than in the matrix of correlation for all samples from Upper Weardale. Certain expected relationships appear again, the median being significantly correlated with the mean and with sand, silt and clay content of the Factor 1 group. The mean exhibits a negative correlation with the sorting coefficient a relationship also noted by Vincent (1969) and Beaumont (1967) in their study of tills. It is possible to produce regression equations in such circumstances and for comparative purposes the following equations are presented.

$$(i)\ y = 6.7174 - 0.3174X \text{ (Vincent)}$$

$$(ii)\ a = 5.666 - 0.224b \text{ (Beaumont)}$$

$$(iii)\ \sigma\phi = 6.7995 - 0.3624\ M\phi$$

The latter equation calculated for the Factor 1 group of the present study is very similar to the equations obtained by Vincent and Beaumont in their studies. It would seem advantageous to employ the actual names of the variables in these equations. A relationship between phi mean and skewness values is also recorded by Vincent (1969) and Beaumont (1967). The regression equations they obtain are

$$(i)\ y = 2.477 + 0.3939x \text{ (Vincent)}$$

$$(ii)\ a = 0.571b - 0.42 \text{ (Beaumont)}$$

The correlation coefficient obtained by Vincent was 0.300 and by Beaumont 0.785. Vincent's correlation coefficient is significant at the 95% level, Beaumont's at the 99.99% level. In the present study the correlation coefficient is significant at the 95% level giving a regression equation

$$\alpha\phi = 0.5180M\phi - 2.2005$$

Comparing these with Vincent's equation, x is the notation for the mean value and y for the skewness, Vincent's equation is

$$\alpha\phi = 0.3939M\phi + 2.477$$

and Beaumont's equation where $a = \alpha\phi$ and b = the mean value

$$\alpha\phi = 0.571M\phi - 0.42$$

It is apparent that this is a very variable relationship, probably of only local significance whereas the consistency of the observed relationship between mean size and sorting appears to indicate a property of the deposit.

The correlations between the loadings on Factors 1, 2 and 3 and the mean and median size are not of particular note. As indicated above they are a reflection of the data from which the factor loadings were generated. It is interesting to note that Factor 2 correlates with the sorting of the deposit, giving higher Factor 2 loadings for higher values of sorting. The higher values of sorting are more poorly sorted deposits.

Correlations between Factor 1 loadings and clay content and the negative correlation between sand content and Factor 1 loadings further emphasise the characteristics of Factor 1 noted above in the discussion of the factor scores. Similar correlations exist between Factors 2 and 3 and the sand, silt, clay contents.

Of particular interest is the negative correlation between the Factor 5 loading and the elevation of the sample site. That Factor 5 loadings should be inversely related to elevation is difficult to account for. The author tentatively suggests that the nature of Factor 5 as a "catch-all" for the discrepancies between samples and the reference factors means that, at lower elevations the samples fit the reference factors less well. As the factors are developed for Upper Weardale, samples from the Lower part of the dale (necessarily at lower elevations) are less likely to be well 'explained' by these reference factors.

Relationship between mean and median and sand, silt and clay content are again to be expected. The inverse relationship between silt content and sorting values is of interest. When using a restricted size range (-3ϕ to 10ϕ) there is, of necessity a central group of classes, around 3.5ϕ which should contain the median, mean and mode of a normal distribution curve. This size group is in the fine sand and silt categories and consequently high sorting values indicating displacement of the curve from this zone are necessarily indications of reduction in the silt content. Other significant correlations between sand and silt and sand and clay are predictable from the factor analysis results mentioned above.

8.43 Correlation Between Variables: Factor 2 Grouping

The correlation matrix for the Factor 2 group, presented as Figure 8.14 indicates the expected relationships between factor loadings and median and mean values, also between factor loadings and silt and clay content and between media and mean and silt and clay content.

Relationships worthy of comment are those between Factor 1 loadings and sorting values, between Factor 2 loadings and skewness values. Inverse relationships between Factor 2 and sorting values and Factor 3 and skewness are also of interest. Factor 2 is shown to be a reflection of coarse sand and gravel content of samples from a consideration of the factor scores. However, sorting values increase as the clay content increases (i.e. ϕ 84 values are larger for clay rich sediments) and Factor 2 loadings therefore are inversely related to them. As Factor 1 appears to be sensitive to clay content the positive correlation between sorting and Factor 1 loadings is expected.

Positive correlation between Factor 2 loadings and skewness is similarly a re-statement of this relationship. Factor 2 loadings, sensitive to gravel and coarse sand content will increase as values of skewness

CORRELATION MATRIX

for all measured variables

of all samples with Factor 2 dominant

shading indicates values significant

at the .05 level

FACTOR LOADINGS																	
1	2	3	4	5	Depths	Elevation	Median	Mean	Sorting	Skewness	Kurtosis	Sand	Silt	Clay	Organic Content	pH	Carbonate Content
1.000																	
-.732	1.000																
.216	-.673	1.000															
.304	-.588	.388	1.000														
.015	-.231	.042	.234	1.000													
.118	-.202	.136	.226	.018	1.000												
.189	.226	-.339	-.376	-.445	.228	1.000											
.847	-.868	.576	.474	-.127	.128	-.014	1.000										
.973	-.760	.315	.368	-.125	.098	.168	.899	1.000									
.893	-.545	-.014	.215	.245	.043	.136	.564	.825	1.000								
-.190	.637	-.793	-.396	-.074	-.073	.415	-.632	-.245	.123	1.000							
-.480	.406	-.290	-.547	-.348	-.047	.120	-.443	-.471	-4.69	.238	1.000						
-.086	-.336	.847	.207	-.308	.043	-.194	.335	.067	-.341	-.645	-.070	1.000					
.719	-.606	.204	.729	-.014	.291	-.018	.688	.745	.629	-.210	-.542	-.013	1.000				
.914	-.571	.049	-.008	.042	-.035	.224	.672	.853	.873	-.022	-.281	-.254	.419	1.000			
.162	-.263	.448	-.177	.113	.117	-.105	.252	.148	.078	-.336	-.012	.292	-.194	.274	1.000		
.078	-.188	-.216	.132	.542	.067	-.291	-.124	.004	.301	.204	-.059	-.342	-.001	.129	-.116	1.000	
-.050	-.059	-.099	.086	.231	.232	-.105	-.196	-.058	.129	.258	.026	-.130	.110	-.089	-.205	.669	1.000

Figure 8.14

increase, positive skewness indicating that the curve is skewed to the coarser grain sizes. Because this group is the one in which Factor 2 loadings dominate there is an inverse relationship between the median size and skewness. Negative values of skewness give higher ϕ values for the mean and median, positive values of skewness indicating a dominance of coarser grain size are therefore associated with negative or low phi value for the median grain-size.

Correlation between pH and carbonate values appears for the first time. This has been noted by previous workers (notably Young, 1966, Beaumont, 1967 and Vincent, 1969) in analysis of superficial deposits. The positive correlation between Factor 5 loadings and pH values is considered to be the indication of higher pH values being associated with deposits lower in the valleys where the acid environment of the peat moors is not dominant. There were indications (above) that Factor 5 had an inverse relationship with elevation which could account for this. Also, Factor 2 is the dominant factor in a group consisting of coarse detritus through which water has relatively easy movement. This would aid in the assimilation of carbonate rocks into the ground-water solution and thus increase the pH. It is interesting that the Factor 1 group does not demonstrate this relationship between carbonate content and pH - possibly because in the clay rich deposits the movement of water is inhibited and thus the carbonates are not so readily taken into the ground water body.

8.44 Correlation Between Variables: Factor 3 Grouping

Samples for which Factor 3 dominates exhibit a large number of significant correlations between factor loadings (see Fig. 8.15). Factors 1 and 2 are inversely related in this group and Factor 4 has a direct correlation with Factor 1 and an inverse relationship with Factor 2. Factor 5 correlates with Factor 3 and inversely with Factor 2. Relationships also exist between factor loadings and mean and median values, and between the mean and median values themselves, also between sand, silt, clay and factor loadings and between sand, silt, and clay themselves.

High positive correlations between Factor 1 loadings, Factor 4 loadings and Factor 5 loadings and mean ~~sorting~~ values indicate that all three factors have loadings in this group which increase as the sediment tends to become finer, although Factor 4 and 5 loadings are comparatively low for this group. As all these factors are sensitive to particle size ranges below the 3.0ϕ group indicated as the major influence for Factor 3 by the factor score matrix, any tendency for the sediment to be finer grained (i.e. an increase in sorting value) will be reflected in the increase in the loadings on Factors 1, 4 and 5.

Correlation between elevation and Factor 4 and 5 loadings in this group is at first confusing. Factor 3, considered to be associated with disintegrating sandstone could dominate a group of samples from all elevations, loadings on Factors 4 and 5 appear to be sensitive to the content of finer particles. At higher elevations in Upper Weardale are the broad flat interfluves described by Maling (1956) and Atkinson (1968). It is considered possible that these flatter areas enable disintegrating sandstone to conserve the finer particles whereas on the slopes at lower elevations, hill wash will tend to remove them.

CORRELATION MATRIX

for all measured variables

of samples with Factor 3 dominant

shading indicates values significant at the .05 level

FACTOR LOADINGS (1–5)

	1	2	3	4	5	Depths	Elevation	Median	Mean	Sorting	Skewness	Kurtosis	Sand	Silt	Clay	Organic Content	pH	Carbonate Content
1	1.000																	
2	-.506	1.000																
3	-.158	-.450	1.000															
4	.667	-.746	.227	1.000														
5	.419	-.622	.563	.653	1.000													
Depths	-.316	.218	-.227	-.094	-.168	1.000												
Elevation	.360	-.251	.193	.503	.588	.357	1.000											
Median	.857	-.825	.247	.837	.649	-.325	.465	1.000										
Mean	.905	-.785	.142	.807	.554	-.333	.318	.954	1.000									
Sorting	.903	-.417	-.117	.614	.517	-.145	.409	.749	.831	1.000								
Skewness	.323	-.213	-.151	.099	-.195	-.222	-.364	.132	.371	.288	1.000							
Kurtosis	-.606	-.160	.570	-.078	.136	.129	-.137	-.322	-.361	-.512	.002	1.000						
Sand	-.212	-.184	-.014	-.030	-.223	-.003	-.399	-.137	-.018	-.210	.441	.288	1.000					
Silt	.786	-.629	.003	.880	.520	-.182	.408	.817	.837	.725	.277	-.371	-.030	1.000				
Clay	.961	-.449	-.149	.542	.314	-.304	.266	.788	.865	.891	.401	-.583	-.212	.638	1.000			
Organic Content	.581	-.403	.110	.477	.339	-.595	.176	.597	.581	.457	.139	-.276	-.030	.491	.493	1.000		
pH	-.252	.053	-.018	-.321	-.370	-.091	-.582	-.231	-.120	-.179	.254	.200	.256	-.193	-.122	-.505	1.000	
Carbonate Content	-.215	.013	-.001	-.298	-.443	-.047	-.475	-.237	-.065	-.213	.457	.129	.456	-.394	-.046	-.126	.468	1.000

Figure 8.15

The low pH values of the moorland on the Weardale watershed and the increasing values at lower elevations in regions of greater thickness of superficial material would seem also to support the above hypothesis. The water which removes the fines from Factor 3 deposits at lower elevations also, presumably releases the carbonates from adjacent material on the hillslope - reflected in the higher pH values in these deposits. The correlation between silt and clay content for this group is possibly a further reflection of this, the occurrence of these together representing "fines".

Organic content, noted for the first time in significant correlations is directly correlated with median, mean and Factor 1 loadings. As values of the median and mean increase the particle size is becoming smaller - thus the deposit is richer in fine material. Factor 1 is particularly sensitive to content of fine silt and clay sizes and so the loadings on Factor 1 increase also. Increase in organic content therefore indicates the more suitable conditions for plant growth in the finer deposits of this group. The inverse relationship between organic content and pH indicates only that the organic content is probably the cause of the acidic conditions. To complete the above hypothesis, the finer grained materials with high organic content at higher elevations probably are the decomposing sandstones of the watershed area which underly the extensive peat forming areas.

The inter-relationship of organic content and pH and Factor 1 and fines and organic material content is reflected in the correlation of Factor 1 loadings and pH values for this group of deposits.

8.45 Correlation Between Variables: Factor 4 Grouping

The relationships between variables in the group of samples dominated by Factor 4 loadings are presented in the correlation matrix produced as Figure 8.16. Predictable relationships exist between the factor loadings and the various particle size parameters. The peculiar inverse relationship between pH and carbonate content for this group is difficult to explain, it may result from the high value for soluble carbonates created by silt-size particles of Carboniferous Limestone in Factor 4 deposits which are not readily decomposed by ground-water. It is also possible that the carbonates were removed in solution when gelifluction process was most active. Negative correlation between Factor 4 loadings and pH indicates again a tendency for the high silt content samples to be acidic. The tentative establishment of Factor 4 as a gelifluction deposit of the type described by Washburn (1967) and Ragg and Bibby (1966) could provide something of an answer. Ragg and Bibby describe a deposit typical of Upland Britain. Throughout the area they describe and in many parts of Upper Weardale the vegetation is *Calluna vulgaris* an acid loving species. It can only be assumed that the conditions under which this plant flourishes are productive of the acidic conditions associated with the gelifluction deposit tentatively identified here.

8.5 The Definition of the Factors

On the basis of the accumulated evidence it is possible to define the nature of the factors with some accuracy. The flow diagram presented as Figure 5.2 gives a sequence of 4 steps before subjective

CORRELATION MATRIX

for all measured variables

of samples with Factor 4 dominant

shading indicates values significant

at the .05 level

FACTOR LOADINGS

	1	2	3	4	5	Depths	Elevation	Median	Mean	Sorting	Skewness	Kurtosis	Sand	Silt	Clay	Organic Content	pH	Carbonate Content
1	1.000																	
2	-.409	1.000																
3	-.233	-.217	1.000															
4	-.218	-.125	-.678	1.000														
5	-.226	-.160	.565	-.280	1.000													
Depths	.194	-.222	-.144	-.001	-.098	1.000												
Elevation	-.099	-.364	.012	.235	-.009	-.230	1.000											
Median	.634	-.382	-.729	.486	-.494	-.068	.051	1.000										
Mean	.821	-.787	-.180	.068	-.178	-.003	.162	.718	1.000									
Sorting	.459	.125	-.107	-.300	-.120	.320	-.061	.162	.215	1.000								
Skewness	.673	-.759	.315	-.320	.142	.074	.173	.202	.824	.200	1.000							
Kurtosis	.105	-.554	.421	-.112	.524	.003	.193	-.049	.308	-.020	.468	1.000						
Sand	-.348	-.340	.900	-.391	.523	-.173	.315	-.696	-.176	-.181	.285	.437	1.000					
Silt	.373	-.052	-.863	.609	-.683	.032	-.102	.874	.435	.005	.003	-.308	-.858	1.000				
Clay	.927	-.550	.027	-.353	.006	.176	-.031	.454	.832	.471	.827	.281	-.077	.107	1.000			
Organic Content	.190	-.505	-.022	.172	-.409	-.584	.358	.370	.444	-.119	.297	-.152	.130	.249	.148	1.000		
pH	-.045	.304	.353	-.557	.110	.167	-.446	-.474	-.251	.265	.028	-.204	.190	-.356	-.042	-.149	1.000	
Carbonate Content	-.012	.115	-.131	.039	-.056	-.204	.142	.134	-.010	.059	-.099	.018	-.170	.099	.027	.043	-.620	1.000

Figure 8.16

analysis of the results and the compilation of geomorphological history are undertaken. Data analysis, the third of the items in the progression leads to 'Models of sediment type'. The lack of rigorously stated theory precludes the construction of precise mathematical models of sediment type from existing knowledge in this case. In the summary given below the 'model' of the sediment type varies from a conceptual grouping of properties to a demonstrated mathematical relationship. Further work in this area should lead to the more precise statement of the conceptual models permitting more accurate assessment of similarity between deposits of the same genetic type.

This chapter represents the balance, frequently formed in scientific studies, between empirically derived relationships (which may be accurately stated for a specific case study) and concepts of the effects of processes not yet fully investigated. The definition of the factors developed below demonstrates this balance. Wherever possible existing relationships and published measurements are the basis for definition of the deposit type. Observations of the associations existing in this study are presented only in the nature of comment and hypothesis for general cases, and as a summary of the significant properties described above.

8.51 Factor 1

There can be little doubt that this factor represents the action of glaciation. Measurements of the particle-size curves of glacially produced till from North America and North England produce parameters of sorting, mean and median size which are directly comparable to the measured parameters of the group of deposits dominated by Factor 1 in the present study. Texture ratios commonly used to define deposits of various types demonstrate the coincidence of the Factor 1 grouping with the textures of tills in adjacent regions (see Fig. 8.4).

The calculated relationship between mean size and sorting values demonstrated by both Vincent (1969) and Beaumont (1967) for tills in adjacent regions is very closely duplicated by the regression equation obtained from the analysis of the Factor 1 group in this study. Factor scores indicate that this group of deposits are silt and clay rich and here again comparison with published data is of value.

Beaumont (1967) presents sand, silt and clay analyses for samples of till from other parts of Northern England. These together with the "typical stony clay of East Durham" (tills of various origins) are presented below.

Deposit	% Sand	% Silt	% Clay
Leeds Till	33	46	21
Hessle Till	23	51	26
Purple Till	20	50	30
Drab Till	35	40	25
East Durham stony clay	30/35	40/45	25/30
Factor 1 Group (Upper Weardale)	38	37	25

Thus it is concluded that the Factor 1 group is composed primarily of till - i.e. a glacially processed deposit.

8.52 Factor 2

The lack of studies of hillslope material in the area of Upper

Weardale means that there are no data vailable on which comparisons of these deposits may be based. The similarity between Twenhofel's rain washed slope deposit and the curves for which Factor 2 dominates in the present study indicate that Factor 2 may reflect a similar environment. The nature of the factor scores indicates that these deposits load most heavily on a factor which represents coarse material, of the type one would expect in a hillslope environment where water movement will remove the fines. This is further supported by the average clay content of this group which is less than 10% and total fines (silt and clay) are less than 25%. Particle size curves for this group (Fig. 8.6) demonstrate a high content of coarser material and an absence of fines.

Evidence suggests therefore that the Factor 2 group is composed of samples of water-washed slope detritus. This may result either in a hillslope or a peri-glacial environment. In the latter case the water-washing may be by snowmelt or dead ice dispersion.

8.53 Factor 3

The discussion of the nature of this factor in 8.44 above leaves to the formulation of the hypothesis that Factor 3 samples consist predominantly of decomposing sandstone. Correlations from the matrix presented as Figure 8.16 seem to support the hypothesis and, in the absence of evidence to the contrary the Factor 3 group is considered to be primarily decomposing sandstones. As sandstones form the dominant rock type in terms of area of outcrop Factor 3 may be considered to be the major "regolith".

8.54 Factor 4

The available evidence indicates that both the texture of these samples and their particle size curves are typical of gelifluction deposits. Factor scores indicate that this factor is a reflection of fine sand and silt-sized particles. Washburn comments that

> "The difference in grain size ... between silt and clay is particularly significant for frost action effects and flow." (Washburn, 1967, p. 102)

and also states,

> "... solifluction is primarily associated with flowing soil ... having a grain size ranging from 0.05 mm. to .0006 mm."

and

> "Because mechanical weathering tends to outstrip chemical weathering in cold climates (Ramann, 1915, p. 280-281, Blanck, 1919, p. 422-423, Blanck, Rieser and Martensen, 1928, p. 689-698), silt commonly predominates over clay minerals and clay-size particles, and when associated with frost action this predominance may be one of the important reasons for the significance of frost creep and gelifluction in such climates."
> (Washburn, 1967, p. 103)

The grain sizes stated above are, approximately 1.0 phi to 10.0 phi, the range being from medium sand to medium clay with the range centred on the silt-size category 4.0 phi to 7.0 phi. Loadings on the sample of the "subjacent layer" of Ragg and Bibby's (1966) work taken from Broad Law and analysed by the present author clearly indicate it is a 'factor 4 deposit'.

It appears to be clearly established that the Factor 4 group contains samples of gelifluction material (defined after Washburn, 1969, pp. 11-13).

8.6 Conclusion

The models of sediment type included above are, with the exception of the till model, mainly conceptual models inferred from descriptive fieldwork. It is significant that the data processing technique applied to the particle size data has demonstrated a subdivision of "solifluction" as generally applied in the introductory section of this work. The nature of this subdivision is particularly interesting as it clearly illustrates a difference in deposit genesis. That such a difference should be produced from Q-mode factor analysis is not only clear demonstration of the wide applicability of the technique but of its value in regional studies which consider the nature of superficial deposits. Objective data analysis in this study has proved its value to be greater than field classification not only in its sensitivity to different influences on the genesis of the deposit but in its clear identification of these influences.

Having thus deduced a genetic significance for each factor it is necessary to consider the areal distribution of the influence of each factor also.

Chapter 9

Trend Surface Analysis

There is no doubt that Chorley and Haggett in their paper expounding the use of Trend-surface mapping in Geographical Research (1965) provided geographers with a very powerful technique for analyses of spatial distribution. In their paper it is gratifying to note that the majority of the examples are of applications of the technique to physical geography. This is not surprising in view of the development of the trend surface technique primarily in the field of geological and sedimentological research. It is particularly valuable to the present study in that it permits the extension of objective techniques into the mapping of the various patterns of the sediment parameters measured in Upper Weardale.

King (1969) in her paper describing Pennine erosion surfaces states that

> "Trend-surface analysis is being increasingly used to study a wide variety of spatial problems in geography and geology (R.J. Chorley and P. Haggett, 1965; W.C. Krumbein and F.A. Graybill, 1965). The method can be used for a number of purposes, such as the reconstruction of a distribution that is no longer complete, the description of an areal pattern of any given variable, the testing of hypotheses, and as a search procedure."

In this study trend surfaces were adopted to fulfil several of these roles. They were used as a search procedure to establish which, if any of the bodies of data were distributed in clearly distinguishable patterns over the region. If such distributions were significant the trend-surface provides a concise description of them. A by-product of this also establishes the validity of conceptual patterns of distribution for deposit-type e.g. the contention that Factor 3 dominates on the upland areas may be tested.

The difficulty encountered in the present study was one of an excess of both hypotheses and data with which to test them. In order to reduce this situation to reasonably comprehensible proportions several possible data combinations were omitted. Of the data combinations used, the result of each investigation is provided in Appendix III together with the tests of significance as appropriate in each case.

9.1 The Nature of Trend Surface Analysis

There seems to be a growing reluctance to accept the nature of trend surfaces. The technique itself is mathematically sound. A computerized programme attempts to simulate a data distribution as closely as possible using standard mathematical surfaces. The nature of these surfaces was very clearly described by Chorley and Haggett (1965, p. 52) and their illustration is the basis for Figure 9.1 which exemplifies the types of surface which are used in an attempt to describe data distributions. These standard surfaces have precise mathematical expression in three dimentional space, the coefficients in each equation being those which give the "best-fit" of the surface to the data. Best-fit is defined, as the surface which has the least deviation from the data values supplied.

Vincent illustrates this for the linear surface and the illustrations for the higher order surfaces are similar. Figure 9.1 illustrates the concept of "best-fit" in two dimensional cases for the linear,

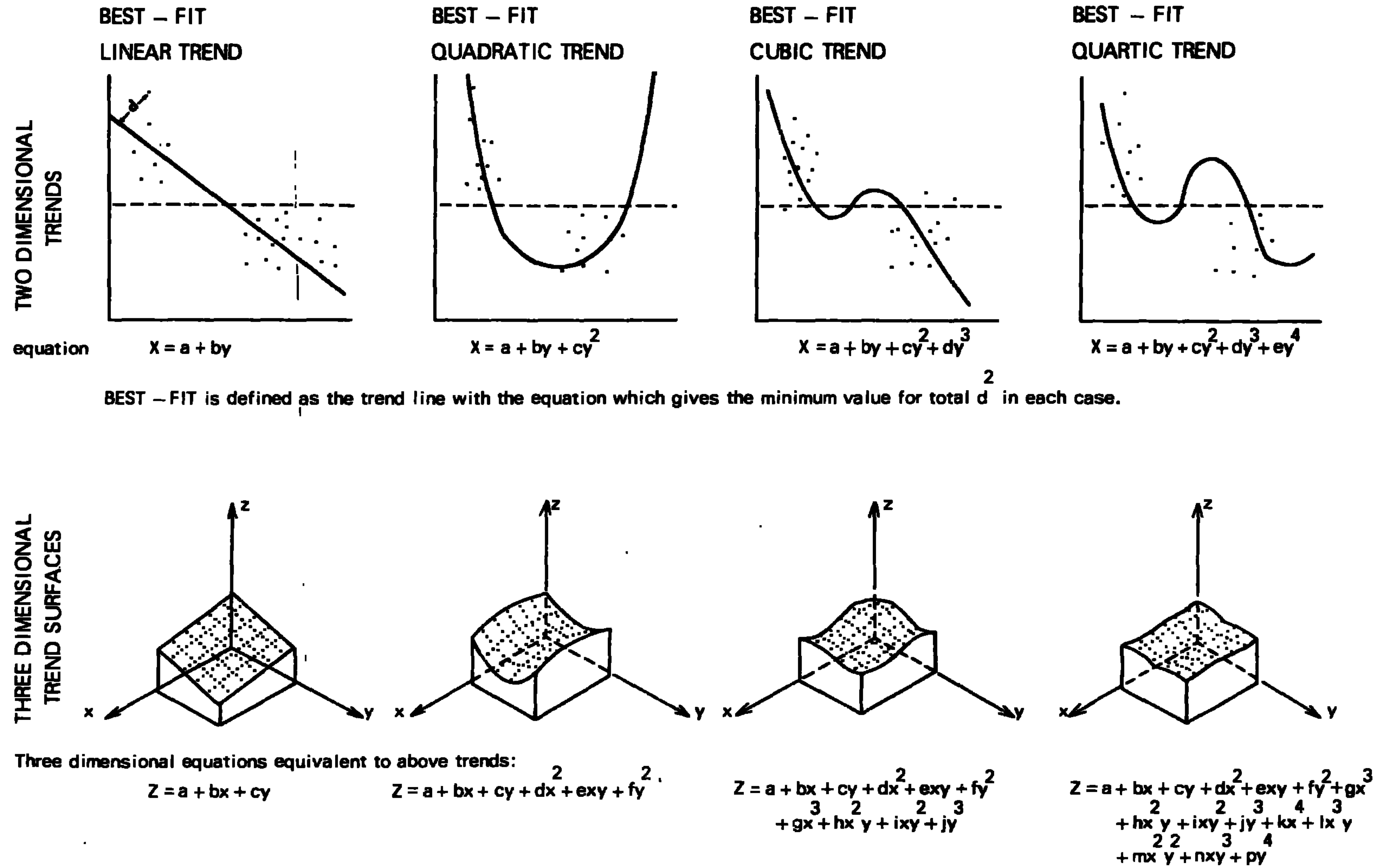


FIG. 9.1. THE NATURE OF POLYNOMIAL TREND SURFACES (based on Chorley and Haggett 1965)

quadratic, cubic and quartic surfaces. The extension of this into three dimensions can be visualised by reference to the three-dimensional diagrams in Figure 9.1. For "best-fit", d^2 (see Fig. 9.1) for the whole area is reduced to a minimum. The type equations for each surface are stated on the diagram (see Fig. 9.1).

Trend-surfaces therefore are the "best-fit" mathematical surfaces calculated for a given set of data. The trend-surface concept in geography applies this definition to three dimensional space, the x and y co-ordinates defining the geographical location with respect to some established origin and the z coordinate representing the value of the variable which is being studied. Thus for an individual point "a", the values X_a, Y_a, Z_a represent the value of variable 'Z' at the precisely defined location X_a, Y_a. Trend surface analysis provides alternate values for 'Z' at the point X_a, Y_a based on an estimate of the areal trend. If the trend is linear then

$$Za = A + BX_a + CY_a$$

It is more usually the case that the value from the regional data is not such an exact value. The computer programme, supplied with the regional data calculates a precise surface which has an equation of the form—

$$Z = A + BX + CY$$

This equation then supplies the calculated value for 'Z' based on the assumption that Z is distributed according to the linear model and dependant upon X and Y. Thus X_aY_a has the real data value for Z (i.e. Z_a) and a calculated value (Z_c). A perfectly linear distribution of Z would occur if the values Z_a precisely equalled the values Z_c. In cases where this is not true, there is a 'residual' value (the difference between Z_c and Z_a at the point X_a, Y_a). These "residuals" are the error term of the linear model.

$$Z = A + BX + CY + e$$

where A is a constant

B and C are coefficients

e is the error term

commonly used in regression analysis

Similar definition holds true for the quadratic, cubic, quartic and higher order models. No matter what the origin of the data supplied, the trend-surface calculated satisfies the criteria stated above. The only exceptions being the result of erroneous calculation or computer malfunction. Consequently it is possible to calculate a trend for <u>any</u> body of a data. That trend is precisely defined and, using the same data body, it will always result from the use of the same best-fit polynomial trend surface analysis procedure.

Trend surfaces thus supplied by trend-surface analysis may fail to be of any value whatsoever. It is obviously necessary to guard against the fitting of a trend to data in which no trends exist. However, the latter type of data exists only as a concept. As stated above, it is possible to calculate a precise trend-surface for any data body. What is required is a test of the significance or value of a trend-surface. Consequently the quest is not for "trend-surfaces" and the definition of "random trends" but, simply the quest for <u>significant</u>

trend surfaces.

9.2 Significance of Trend Surfaces

If, as stated above, the trend-surface model is considered as a regression model of the type $Z_{ij} = A + Bx_i + CY_j + e_{ij}$. Then there exist several tests of significance of the results, all based on the F test utilising the sums of squares of the total data body and the reduction in sums of squares achieved by the use of the regression equation. If each term of the trend surface equation is regarded as a variable in the explanation of the total variance it is possible, and conventional to use the 'F' test (see Freund, 1967, King, 1969, etc.). Krumbein and Graybill (1965) partition the 'F' value applying the test to each additional increment of the higher order equations.

To clarify these methods it is necessary to make some statement of the nature of the 'F' test. This test assumes that repeated measurements at the same point will yield a normal distribution of values of the dependent variable. In the trend-surface model it implies that the repeated measurements of Z_a at the point X_aY_a will give a normal distribution and that the repeated trend surfaces based on the use of the different values Z_a will also give a normal distribution about some mean. The variance of these distributions is called the error variance. This is assumed to be the same for all points on the surface and the F test measures the probability of any given surface being within this error variance or outside it and specifies the level of probability.

In the trend-surface situation the number of data points influences the total variance of the distribution and so the F test, taking this into account may be simply stated as :-

$$'F' = \frac{R.S.S./d.f.}{S.S.\ unexplained/N{-}{-}d.f.{-}1}$$

where R.S.S. is the reduction of sum of squares resulting from the use of the given surface

d.f. is the number of degrees of freedom for that surface

S.S. (unexplained) is the Total sum of squares - R.S.S.

N is the number of data points

This is the 'F' test as it is commonly applied to the "explained" and "unexplained" portions of the variance in any multivariate regression analysis. To view the trend-surface model in this way is statistically valid as the terms of the trend-surface equation, although related, do not vary together, (e.g. x^2 does not vary directly with X or X^3 etc....)

A transposition of this basic 'F' test may be made to give the equation developed by Norcliffe (1969) cited in Vincent (1969). It would seem useful to adopt this criterion for evaluation of the significance of a surface as the typical use of 'F' test is indeed repetitive - as noted by Norcliffe (1969). In this context the tabulation of minimum explanation levels given by Norcliffe is particularly valuable.

Thus the 'F' test applied to the whole trend-surface equation may be used to give the measure of significance of the surface obtained.

Figure 9.2 presents an example from the present work. The table presents the analysis of variance using the F test (total significance of each surface considered as a multivariate explanation of the variance) as described above. The upper portion of the table applies

MAPS OF % SILT CONTENT OF SURFACE LAYER

TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT
OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

source	sum of squares	degrees of freedom	mean square	F	%confidence
linear surface deviations from above	632 5270	2 42	210.66 125.47	1.67	75+
quadratic surface deviations from quadratic	821 4449	3 39	273.66 114.07	2.39	90+
cubic surface deviations from cubic	561 3888	4 35	140.25 111.08	1.26	50+
quartic surface deviations from quartic	229 3659	5 30	45.80 121.96	0.37	10+
quintic surface deviations from quintic	795 2864	6 24	132.50 119.33	1.11	50+

TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

source	sum of squares	degrees of freedom	mean square	F	%confidence
first order surface deviations from first order	632 5270	2 42	210.66 125.47	1.67	75+
second order surface deviations from second order	1453 4449	5 39	290.60 114.07	2.54	95+
third order surface deviations from third order	2014 3888	9 35	223.77 111.08	2.01	90+
fourth order surface deviations from fourth order	2243 3659	14 30	160.21 121.96	1.31	50+
fifth order surface deviations from fifth order	3038 2864	20 24	151.90 119.33	1.27	50+
source	sum of squares	degrees of freedom	mean square	F	%confidence

Figure 9.2

the 'F' test as suggested by Krumbein and Graybill.

The difference between the two methods can be demonstrated as follows. In this analysis of the trends of the silt content of the surface layer the linear surface has the equation

$$Z = 19.57 - 3.53X + 3.25Y$$

The total sum of squares from the data (total variation) is 0.5902×10^4

The sum of squares not explained by the above surface is 0.5269×10^4

The sum of squares explained by the above surface is therefore 0.6323×10^3

'F' is therefore calculated as follows.

The degrees of freedom for a three dimensional linear surface are $3 - 1 = \underline{2}$

The degrees of freedom for the data recorded at 45 sites are therefore 45-1. However the sum of squares not explained by the above surface is a residual amount being the total sum of squares (with 45-1 = 44 degrees of freedom) minus the amount explained by the above surface (which has 2 degrees of freedom). Therefore, two degrees of freedom being taken up by the surface, leaves the unexplained sums of squares with 45-1-2 degrees of freedom i.e. 42.

the 'F' value therefore is $\dfrac{0.6322 \times 10^3/2}{0.5270 \times 10^4/42}$

$$= \frac{210.66}{125.47} = 1.67$$

The tabulated F value for 2 and 42 degrees of freedom reveals that this value is significant only in the 75% - 90% range, it is therefore not a significant trend-surface.

Applying the 'F' test in the same manner for the quadratic (second degree) surface gives a value (test of the overall significance of the surface) of 95%. Hence this surface is a significant description of the distribution of silt content in the surface layer. Krumbein and Graybill (1965) argue, however, that the quadratic or second degree surface which in this case has the equation

$$Z = -160.64 - 26.65X + 104.76Y - 3.26X^2 + 8.42XY - 14.29Y^2$$

is in reality a compound of a linear and a quadratic equation. They claim that the linear part of the equation (in this case; -160.64 - 26.65 + 104.76Y) has been evaluated above in the consideration of the linear surface. Consequently they subtract the explanation due to the linear surface from the total explanation given by the quadratic to give a measure of the additional explanation of variance brought about by increasing the order of the polynomial equation. They then apply the 'F' test as before but only for the increase in explanation brought about by using a second degree equation and not the total explanation which that second degree equation gives.

It is difficult to see the justification for the use of the 'F' test in this way. Krumbein and Graybill (1965, p. 337) state:

> "Note that the assumptions necessary to interpret the 'F' values in this and similar examples may not be satisfied, in that the residuals may contain systematic effects. Hence, we examine the 'F' values simply as indices or cutoff points for deciding whether to fit the next higher degree polynomial."

The present author finds that, as in Figure 9.2 there is not necessarily a continuing decrease in the significance levels. If the F values were used as Krumbein and Graybill suggest, the low significance of the first-order equation should indicate a cut-off point for fitting the next higher degree surface. It is obvious that the second degree surface is of much greater significance. This same change of significance is seen between the third, fourth and fifth order surfaces. It is difficult to see why either the linear or the quartic surfaces should preclude the evaluation of higher order trends by determining cut-off points as proposed above.

Finally the F test assumes that the deviations from the surface (the 'residuals') are uncorrelated. If they are correlated then the result is to overstate the significance levels. Merriam and Harbaugh consider this and conclude that

> "The failure to satisfy basic probability assumption does not invalidate the use of analysis of variance and confidence surfaces when applied to trend-surfaces. These methods however must be applied with caution, and users should be aware of the assumptions that underlie their application to trend analysis."
> (Merriam and Harbaugh, 1968, p. 72)

The 'F' test both as advised by Merriam and Harbaugh and as proposed in Krumbein and Graybill (1965, p. 336) are used to assess the significance of the surfaces obtained for this work. All these values are tabulated together with the appropriate maps in Appendices III and IV.

9.3 Random Data and Trend-Surfaces

Using the 'F' test in the way it is commonly applied to assess the value of an explanation provided by some multivariate analysis technique (as in the lower part of Figure 9.2) effectively eliminates the consideration of attempts to demonstrate the random trends of data. The present author however, investigated the effect of random data used with the control points for the maps of Weardale.

Vincent discusses this at length, and the literature on this topic is growing (see Howarth, R.J. 1967, Tinkler, 1969, Unwin, 1970). For the pattern of observations obtained by using both random sample sites and purposive sample sites the present author generated 50 sets of random numbers using each set as a z value in 50 sets of trend-surface mapping to the sixth order. It is interesting to note that the mean value for percent reduction in the sum of squares was close to that cited by Unwin (1970). The mean value obtained was 5.79%. This compares with 4.03% for Unwin's analysis. The maximum value obtained in the present study was 18.4%. Unwin obtained a maximum value of 15.63.

Using the F test on this 18.4% figure a significance level of 25% is obtained, which indicates the trend is of no significance. Using Norcliffe's published tables a value of 13.0% gives a significance of 5%. It is obvious that this is an important area for further research and Norcliffe's (1969) paper represents the first major attempt to draw attention to the limitation on the reliability of trend-surfaces. It is particularly important because it

> "makes use of the fact that the trend-surface models ... are variants of the multiple regression model and can be readily tested for significance using 'F' tables. A random trend-surface is simply defined as one where a non-significant F value is obtained." (Norcliffe, 1969)

The use of the 'F' test as noted above (Chapter 9.2) is therefore considered to be fully supported by current work. (The author wishes to indicate that the 'F' calculations for the present work were complete before the appearance of Norcliffe's paper).

9.4 Data for Trend-Surface Analysis

Merriam and Harbaugh provide a most important cautionary statement of the effect of clustering of data points within an area which is to be subjected to trend surface analysis. This is cited by Norcliffe (1969, p. 342).

> "In fitting trend-surfaces, it is desirable that the data points be more or less evenly distributed within the map area. They should not be clustered in some places and spread far apart elsewhere, because clustered data points give undue influence to the areas containing them relative to areas in which the points are far apart."
>
> (Merriam and Harbaugh cited in Norcliffe, 1969)

In their work on the use of computer in stratigraphic analysis they also amplify this,

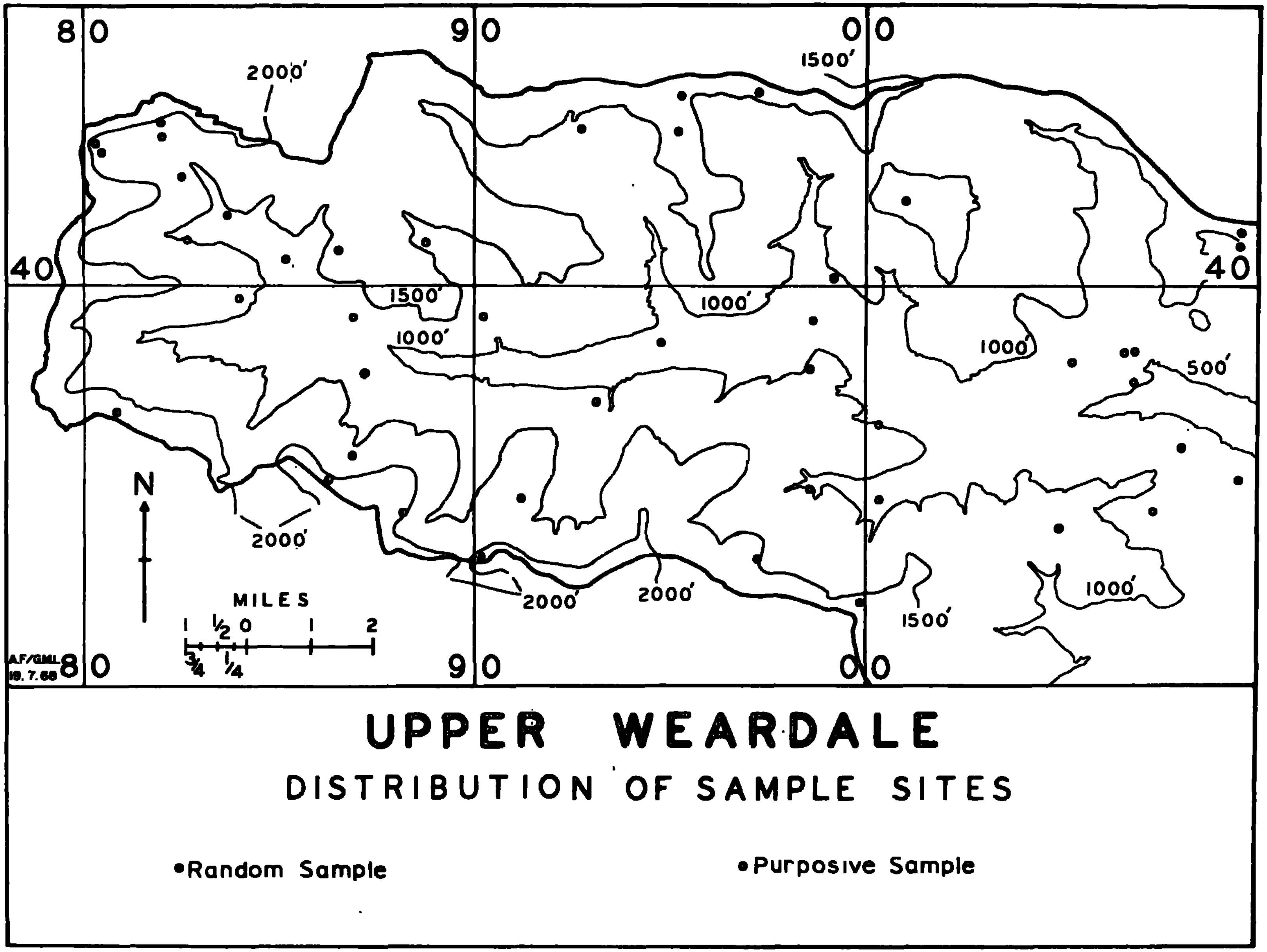
> "Ideally, points should be more or less equally distributed geographically but need not be regularly spaced. The reason for equable distribution is that when the least squares criterion is satisfied, closely spaced points exert undue influence on configuration of the trend-surface as compared with widely spaced points."
>
> (Merriam and Harbaugh, 1968, p. 72)

Norcliffe (1969) indicates that data with regularly and randomly spaced points are acceptable. In this study the generation of sample sites from random number tables means that the data points are randomly distributed. It was indicated however (Proudfoot personal communication) that larger numbers of data points are advantageous to the computing of meaningful surfaces, thus the purposive sample points were added to the random data points to give a total point pattern as illustrated by Figure 9.3. The test of the effect of these additional points was conducted as described by Vincent (1969) and the test proved that there was no significant orientation resulting from grouping of the sample points. Consequently purposive and random sample data were used together for all maps.

Having identified five factors, four of which have been established as representing genetic influences on the nature of the deposit it seemed necessary to examine the distribution of these influences. The maps therefore were constructed to show the spatial variation of the factor. To achieve this it was decided that the maximum loading of each factor at each site should be used as the Z coordinate. This establishes variation in the influence of each factor and is not dependent upon the local stratigraphy. To take the factor loadings of the surface layer would have ignored the influence of factors at depth and this would not have provided the best description of the distribution of the influence of the factor. To do this analysis for each layer would have multiplied the task beyond the resources of the author.

For comparative purposes the gravel, sand, silt and clay content of the surface layer were analysed to see what similarity existed between these trends and those of the factors. This procedure of trend-surface mapping has also been used by Chorley, Stoddart, Haggett and Slaymaker (1966) in an evaluation of the surface sands of the Breckland.

Thus trend surface maps were prepared for the following



80
90
00
40
2000′
1500′
1000′
500′
N
MILES
1 ½ 0 1 2
¾ ¼
AF/GML 19.7.68
UPPER WEARDALE
DISTRIBUTION OF SAMPLE SITES
•Random Sample
•Purposive Sample

Figure 9.3

variables.

1. Gravel content of the surface layer (% of total sediment below 20 mm.)

2. % Sand content of the surface layer) (% of sand, silt and
3. % Silt content of the surface layer) clay fraction only)
4. % Clay content of the surface layer)

5. Maximum Factor 1 loading at each site

6. Maximum Factor 2 loading at each site

7. Maximum Factor 3 loading at each site

8. Maximum Factor 4 loading at each site

9. Maximum Factor 5 loading at each site

Maps of all the equations of first to sixth degree were produced but the difficulties of interpreting the maps of fifth and sixth degree equations led to these being omitted from the appendix. All other maps are presented in Appendix III. The computer programme used for this work is the trend surface programme developed by O'Leary, Lippert and Spitz (1966).

9.5 Results of Trend-Surface Analysis (Maps)

As indicated above the purpose of trend-surface analysis in this study was primarily to establish which, if any, of the variables identified were areally distributed according to some defined pattern. The results, frequently negative, are presented as Appendix III. Residuals are not mapped because of the essentially subjective nature of their assessed value. (Vincent, p. 288).

9.51 Trend-Surface Maps of the Gravel Content of the Surface Layer

None of the maps of the gravel content of the surface layer are statistically significant using the 'F' test, nor do they have the minimum explanation level required by Norcliffe's published table (1969).

9.52 Trend-Surface Maps of % Sand Content of the Surface Layer

Of these maps the quadratic surface is particularly significant at the 2.5% level the third order surface is significant at the 10% level. Both of these surfaces define an area of high sand content on the southern watershed of the River Wear and an area of lower sand content in the region of the valley floor from easting 88 to easting 01 and north of this area. The reason for this is not clear although the superficial deposits in the area will be influenced by the lower elevation of the valley floor and the probability that fines, washed downslope will tend to accumulate here. The high sand values recorded on the watershed area seem to reflect the loss of fines from the surface layer by water action, and the sandy nature of the bedrock. The residuals (not mapped) define the valleys where samples show values below those of the surface i.e. are richer in fines.

9.53 Trend Surface Maps of % Silt Content of the Surface Layer

These maps demonstrate again significant relationships with the mathematical trends only for the second and third order surfaces (95% and 90% confidence levels or .05 and .1 significance levels respectively). The high values of silt (30%+) are shown to occur in an area extending northeast - south-west across a zone centred around Westgate

(Grid ref. 910380) with low values on the watershed areas of the south-east and north-west (25% - 10%) and high values on the watershed areas in the south-west and north.

9.54 Trend-Surface Maps of % Clay Content of the Surface Layer

Only the quadratic surface is significant at the .05 level (95% level of confidence) and this demonstrates a zone of high values of clay content (25%+) in the area corresponding to low sand and high silt values. Thus there appears to be a zone in the north of the study area which has a surface mantle richer in fines than the rest of the area.

9.55 The Importance of the Surface Layer

It appears from this examination of the textural properties of the deposit at the surface that the geomorphological significance of this layer in Upper Weardale is not great. Processes of pedogenesis active in this layer and described by Atkinson (1968) are the probable cause of this result. The parent materials are least likely to maintain their characteristics in this layer and it is the layer most disturbed by many processes of slumping, hill creep and colluvial action. It is doubtful therefore that any significant geomorphological evidence of deposit genesis is contained in the surface layers.

9.6 Trend Surface Maps of Factor Influence

These maps were produced to investigate the trends of the influence of each factor within the region. Vincent's (1969) trend maps of the properties of the tills he investigated represent an important development in work of this type but these are concerned with the distribution of measured properties of the tills and not the distribution of "till-likeness" or Factor 1 loading as in the present study. Similar situations are encountered in the evaluation of the remaining factors although there is less published material for the purposes of comparison.

9.61 Trend Surface Maps of Factor 1 Loadings

Confidence levels on these surfaces were sufficiently high for the first, second and third order surfaces to merit consideration. The linear trend (significant at the .1 level) shows a decrease in Factor 1 loadings in a south-easterly direction. This alone is difficult to interpret, however it may represent the regional direction of ice movement. That the influence should decrease down valley is considered to be a reflection of the great variability of the deposits in this region. Progress down-valley leads into a region where solifluction processes have been more active because of the more rounded topography and the less extreme climate. Samples of till from the valley floor, more extensive in the lower part of the valley, are therefore likely to be more subject to other factor influences and hence give slightly lower loadings on Factor 1.

The second order surface (significant at the 0.025 level) provides a much more illuminating view of the trend. It demonstrates a zone of higher values of Factor 1 crossing the region in a west east direction with high values in the west. Low values occupy the watershed regions east of easting 85. The third order surface demonstrates the trend in a more easily comprehensible pattern as it shows the zone of higher values trending to the south-east in the eastern part of the map along a line almost coincident with the present river valley. This third degree surface is significant at the 0.1 level.

The conclusions to be drawn are that Factor 1 influence (i.e. glacial influence) is strongest on deposits in the valley floor and the influence is generally less important in watershed areas. It is slightly more important on the northern watershed than the southern, but in all cases the western watershed indicates high values of Factor 1. The extreme values are the result of the surface being generated in the absence of control data beyond the watershed area.

Residuals show negative values in the watershed areas and positive values in the valley floor region, this confirmation of the expected pattern reinforces the interpretation of Factor 1 as representing glacial influence. The total importance of the trend is that it suggests both that ice may have entered the region from the west and that there is an overall ice trend to the south-east.

9.62 Trend Surface Maps of Factor 2 Loadings

None of the maps produced was statistically significant. This is taken as being a further confirmation of the nature of Factor 2 as rain-washed hillslope material. The ubiquitous hillslopes of this area would presumably all contribute to high Factor 2 loadings and it would be surprising if there was a significant regional trend. A larger area in which climate and topography varied significantly could give such a regional trend, but Upper Weardale with its relief type and a climate which does not vary very widely within the region does not have the conditions which would yield this type of trend.

9.63 Trend Surface Maps of Factor 3 Loadings

The maps of Factor 3 distribution were not statistically significant. A consideration of the nature of this factor - sandstone regolith - reveals that this is not surprising. The geology map Figure 2.4 indicates the extent of the Upper Carboniferous strata. These strata are primarily the sandstones of Weardale and it can be readily appreciated that the qxtent of this rock type almost inevitably procludes the description of its regolith by comparatively simply mathematical surfaces of the trend surface type.

9.64 Trend Surface Maps of Factor 4 Loadings

The first and second order surfaces are significant in this case. The first order surface is significant at the .1 level and the second order at the .05 level. First order trneds show a decrease in Factor 4 loadings towards the north-east. The second order trend exhibits its high values on the south side of the valley and low values elsewhere. This distribution was at first perplexing, however the nature of this factor (gelifluction material) and the north-facing aspect of the southern side of the valley together indicate that it would be the southern side of the valley which would sustain permafrost for the greater length of time. If this were true then there would be a tendency for gelifluction layers to predominate here - a fact demonstrated by trend-surface analysis.

Thus the use of trend surface to reveal the tendency for Factor 4 loadings to increase in the north-facing areas of the valley appears as a confirmation of the sedimentological nature of the Factor 4 deposits.

9.65 Trend Surface Maps of Factor 5 Loadings

Factor 5 as considered above (Chapter 8) is of the general nature of Factors 2 and 3 in that it is unlikely to have any pronounced regional trend in its distribution. The nature of this factor as a general influence of an excess of certain particle-size ranges is such that it has not any true genetic nature which may be related to regional land-forming influences. It is therefore not surprising that none of the generated trend surfaces for this factor was significant.

9.7 Trend Surface Diagrams

Having established the use and validity of trend surface maps in this investigation it was the author's opinion that such surfaces could be of value in an assessment of the distribution of properties with depth. Consequently all the data gathered for the survey were plotted on the trend-surface diagrams using distance from the head of the valley as the x axis and depth as the y axis. This means that the diagrams are a projection of all samples onto a west-east vertical plane. This has been achieved by measuring depth from the surface, thus there is no compensation for topographic location of the sample sites. Data grouped in this way are also available for trend-surface analysis and any emergent trends should be of significance in interpreting the stratigraphy of the area. The author is not aware of any published use of such a technique in previous work although the idea is implicit in the hyper surfaces discussed by Merriam and Harbaugh (1968) even though they do not use vertical surfaces *per se* in that work. All the diagrams of trends in the vertical plane are grouped together as Appendix IV together with the appropriate 'F' tests for significance.

9.71 Vertical Trend Surfaces of Gravel Content

None of the surfaces of gravel content was statistically significant although the quadratic terms provide a significant increase in the explanation of variance. The second order surface therefore has some value in describing the distribution of gravel content and it indicates a zone of high gravel content (> 30%) between 2 and 4 metres extending east from the head of the valley to Stanhope. The significance of this is not certain, it may represent the larger fragments of bedrock found at depth immediately above solid rock in the upper part of the dale.

9.72 Vertical Trend Surfaces of Sand Content

Sand content data were processed using sand as a percentage of the total gravel, sand, silt and clay content, and as a percentage of the sand, silt and clay content of the deposit also. The results differ slightly because of the icnreased sensitivity of the contour interval (5%) in the latter cases.

Using the sand content of the gravel to clay calculation all surfaces are statistically significant although the major explanation is derived from the linear surface which is significant at the .001 level and demonstrates a down valley increase in sand content of the surface layer and also a decrease in sand content with depth. This is considered to reflect the effect of water washing on the deposits, the zone immediately below the surface being one from which fines are most readily removed. The down-valley increase in the amount of water available for this type of action could account for the down valley increase in the relative proportion of sand. Both the first order surfaces calculated for sand as a percentage gravel to clay size and sand to clay size indicate the same effect.

Second order surfaces demonstrate a similar pattern significant at the .001 level for the calculation based on gravel to clay size and at the .005 level for sand to clay size. The calculation based on gravel to clay size indicates a tendency for sand content to decrease below a depth of about 3.6 metres. The third and fourth order surfaces for these same data (significant at the .01 and .05 levels respectively) indicate a similar general trend but with a pronounced decrease in sand content below 4 metres. They also exhibit zones of low sand content at about 1.5 metres in the western part of the study area. This is considered to represent the deposits of till (lower sand content) typically found below the sandy and silty solifluction material and above the regolith (which is sand rich in areas of upper carboniferous gritstone strata). Similar trends exist for the data calculated from the sand to clay size ranges.

9.73 Vertical Trend Surfaces of Silt Content

All surfaces are significant at or above the 0.01 level. The linear trend shows a tendency for silt content to decrease in a down valley direction and to increase with depth. The second order surfaces indicate a general depth of 4 metres for which silt content is approximately 30% throughout the area. (This figure is 35% when the sand-clay size range is considered alone). The remaining variation above this level is the variation described above by the linear surface - a tendency for silt content to decrease in the down valley direction and to increase with depth.

Third and fourth order surfaces elaborate on these patterns giving some indication of a high silt content in the western part of the valley at depths of about 1 metre and low silt content from 2 to 3.5 metres. This is considered to represent the gelifluction layer and the siltier tills giving the high silt values at 1 metre and the sandstone regolith over bedrock giving the lower silt values at 3.0 metres. The general down valley trend of decrease in silt content is observed in the surface layer and is considered to be a reflection of the washing out of fines by water action being progressively more important in the down valley direction.

9.74 Vertical Trend Surfaces of Clay Content

Only the third and fourth order surfaces are significant (at the 0.1 level for the gravel to clay data) and they demonstrate low clay content at 3.0 metres in the west of the area and high clay content at 1.0 metres in the west of the area also. The clay content of the surface layer seems to be about 15% with a decline in the eastward direction to 5% or less visible on the fourth order surface. Very low values of clay content exist at about 3.0 metres in the west of the area but then increase rapidly to give values of 40% or more in the central and eastern parts of the area at this and greater depths. The same trends are demonstrated by the surfaces generated for the clay as a percentage of the sand to clay size data.

The high values of clay content found at about 1.0 metres probably reflect till either reworked and present in the solifluction layer or as beds relatively undisturbed in the layering of the superficial deposits. The low values at 3.0 metres in the west of the area reflect the shallowness of most deposits bedrock being encountered on the watershed areas well before this depth is reached. Consequently there are very few data in this zone of the diagram. The down valley decrease in clay content of the surface layer, clearly demonstrated by the fourth order surface, is compatible with the earlier opinion that the surface layer reflects increasing influence of water-washing and water action in the down-valley direction. The two clay rich zones identified by the fourth order surface, at 1.0 metres and below 4.0 metres, probably reflect reworked or re-deposited till, and undisturbed till deposits respectively.

9.8 Vertical Trend Surfaces of Factor Loadings

The loadings of each factor for each sample are considered in the use of vertical trend surfaces since the projection of all sample sites onto a common vertical plane does not create the need for the selectivity necessary in the mapping work where only one value of the factor loading could represent each site. In consequence these surfaces are expected to be of greater value in explaining observations in terms of overall trends.

9.81 Vertical Trend Surfaces of Factor 1 Loadings

Of these surfaces the first third and fourth order trends are significant at the 0.05 level or higher. The first order trend indicates highest values of Factor 1 at depth in the western part of the area with values decreasing with distance east of this and also decreasing as depth decreases. As a significant trend this is difficult to explain until the other significant trends are examined. The third order trend reveals high values at a depth of 1 metre in the western part of the area which extends throughout the area at this depth. The loadings of Factor 1 for the surface decrease down-valley and increase with depth to about 1 metre, decrease to a low value about 3.0 metres and increase with depth thereafter. The fourth-order surface demonstrates this pattern but reveals the existence of higher values in the eastern part of the area much more clearly than the third order surface and indicates that the low values at about 3.0 metres are much less significant in the eastern part of the region. This is also revealed by a consideration of the residuals from the third-order surfaces.

The nature of Factor 1 determined as glacial till from an investigation of the characteristics of the Factor 1 group is also reflected in the close similarity between the vertical trend surfaces of clay content and Factor 1 loadings. The further similarity between both of the fourth-order surfaces with the fourth order surface for silt content emphasises the silty-clay nature of the till of this area.

The surface for sand content is again similar although a reverse relationship is exhibited. Emerging from this evaluation of vertical trend-surfaces there is therefore a need to consider the apparent layering of the deposits of Upper Weardale with Factor 1 having high values at 1 metre depth and below 3.0 metres west of Westgate (Grid.ref.910385).

9.82 Vertical Trend-Surfaces of Factor 2 Loadings

None of the vertical trend-surfaces of Factor 2 loadings is statistically significant. As with maps of these values, this is considered to be a reflection of the great variability of water-washed hillslope material both in depth and areal occurrence. These attributes when considered as a part of a projection onto a common surface with all depths from the ground surface given the same datum are sufficient to create this "no trend" result.

9.82 Vertical Trend-Surfaces of Factor 3 Loadings

All of the vertical surfaces calculated are significant at the .05 level or better. This seems to reflect the very high significance of the linear component (.001 significance as the 'F' test on each successively higher order component (as per Krumbein and Allen) shows that quartic, cubic and quadratic components are of themselves not highly significant.

Factor 3, identified as decomposing sandstone (i.e. "regolith") has low values at depth in the western part of the region and highest values at the surface in the eastern part of the region as described by the linear trend. The second-degree trend aids in the explanation of this by revealing higher values at the surface with lower values in the zones 1.0 metres to 3.5 metres and higher values below this. The third and fourth order trend surfaces are of greater value in describing this distribution because of their inherently greater flexibility. They reveal a pattern of high values at the surface in the western part of the area decreasing with depth. The surface values then decrease with distance down valley to a point about easting 90 and then increase with distance down valley to a high in the eastern part of the region. A general low value exists at about 1.0 to 2.0 metres with increasing values with depth in the east. At easting 90 there appears to be a local group of high values at about 3.0 metres.

These trends seem to represent the shallow regolith of the upland areas giving high values at the surface in the west and east of the region and passing into bedrock at about 1.0 metres thus giving low values at and below this depth. The local group of higher values at easting 910 probably represents sandstone regolith buried by solifluction deposits in the valley floor area. The trend to increasing values with depth in the eastern part of the area probably reflects a similar influence with an accumulation of sandstone regolith from down-slope migration forming part of the soliflucted material and thus giving high values for Factor 3 at the surface also. The latter fact is also explained by the samples taken from the watershed area in the eastern part of the study region for these are of only shallow deposits of sandstone regolith over the sandstone bedrock.

9.84 Vertical Trend-Surfaces of Factor 4 Loadings

All the surfaces calculated are significant at the 0.1 level of significance or better. Factor 4 indentified as gelifluction deposit has a linear trend decreasing both with depth and down-valley. This is an expected trend showing values decreasing with movement away from the surface layer in the areas formerly of periglacial, now of temperate climatic type. The second degree surface shows a zone extending across the diagram from a depth of c.1.0 metres in the west to 3.0 metres in the east which seems to correlate values slightly higher than elsewhere. The third and fourth order trends are again the more easily interpreted trends and clearly indicate high values of Factor 4 in the upper 30 cms in the western part of the valley. Values appear to decrease from this to a low value at about 3.0 metres beyond which the values increase rapidly with depth. This latter fact is the result of the surface equation and does not reflect the actual distribution of values in this portion of the diagram as they are almost non-existent. An exception to this is the local deposit at about 2.0 metres at easting 910 which exhibits higher values than those adjacent to it.

In total these trends are completely compatible with the nature of the Factor 4 identified above. It remains only to account for the local deviation at about easting 910.

9.85 Vertical Trend-Surfaces of Factor 5 Loadings

None of the vertical trend-surfaces obtained was of statistical significance. This result complements the result obtained for the maps and described in 9.65 above.

9.9 Conclusions on Trend-Surface Analysis

The result of the trend-surface analyses outlined above has been in accord with the definitions of the factors as deduced in Chapter 8. Similarities between the distribution of gravel, sand, silt and clay in the vertical diagrams and the distribution of factor influences are somewhat predictable as the factors are generated from particle-size data. However this consistency is not necessarily present and its existence confirms the general concept of zones of dominance for certain deposit types. An interesting fact has been the definition of an anomalous zone at about easting 910 the existence of this requires further consideration below. In terms of the investigation of the superficial deposits of the area this trend-surface work concludes the objective evaluation of regional patterns and the definition of distinct deposit types in the study region. The broad patterns established need to be considered in terms of the individual samples and their sites to provide a more subjective and comprehensible synthesis of the data so far analysed.

It is apparent that trend surface analysis can provide valuable evidence of the nature of the distribution of various environmental influences both in maps and in the vertical surface diagrams. That the results demonstrate trends which are compatible with the nature of the factors established by data analysis of the whole suite of sediments would seem to be an endorsement of the existence of these factors as meaningful influences. Further interpretation requires a much more subjective analysis based on regional knowledge and the accumulated studies in the general field of geomorphology. The interpretation of both the factors and the trend surface maps and diagrams has been subjective. It is considered to be an important attribute of the present study that the generation of the factors and the maps and diagrams is completely the result of the application of rigorous mathematical procedures. This means that any investigator undertaking a study in the region would arrive at precisely the same set of factors and maps and diagrams if he were to adopt the same techniques. In consequence these items form a valuable data source for future investigators and are not subject to changes in terminology or interpretation of field sites or landforms. The ensuing chapters are, however built upon the evaluation of the author's own interpretation (therefore a subjective one) of the objectively determined data described above. The following chapters are without doubt the subjective procedures of Figure 5.2.

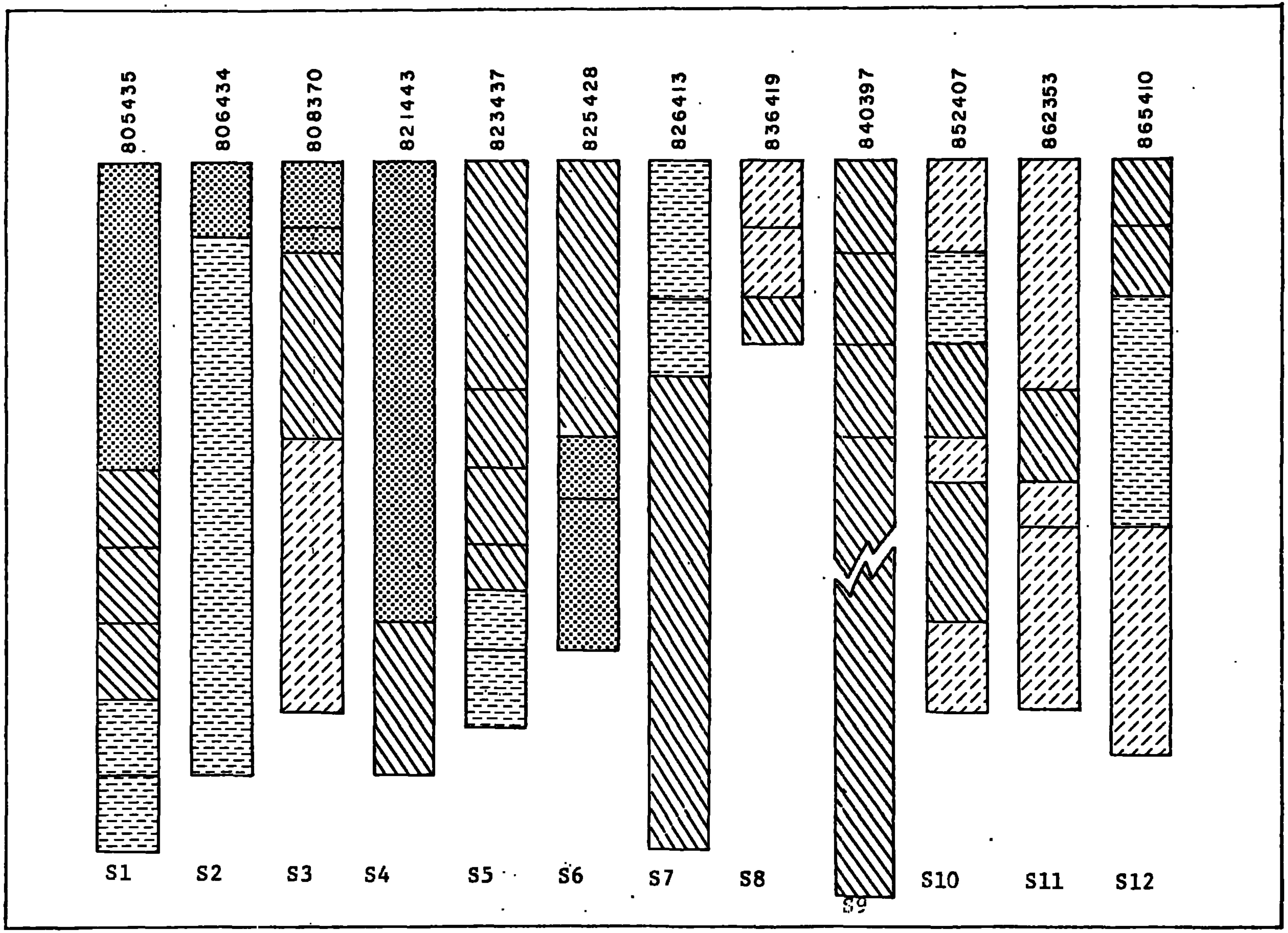
Chapter 10

Interpretation of the Deposits

General trends and influences of the factors were established above. This section considers in greater detail the sequence of dominant factors in the deposits at each site and the interrelationship of the factor loadings for each sample. From this it is possible to draw conclusions about the significance of the layers of superficial deposit in Upper Weardale and thus develop some concept of the history of the geomorphology of Weardale.

10.1 Dominant Factors in the Deposits

Figure 10.1 presents the sequence of dominant factors in each section for each site studied in this work. Reference to Appendices I and II reveals the site descriptions as taken in the field, and these may be compared with the dominant factor influences shown in Figure 10.1. The presentation of the data as in Figure 10.1 reveals that Factor 1 is commonly present in the sections and frequently a major influence near or at the surface. It is difficult to examine this complete set of site profiles in the superficial deposits without reference to their location. Considering groups of profiles on a local basis it can be seen that certain consistencies exist amongst these data. For ease of reference the sites are numbered S1-S45 and these reference numbers are associated with the profiles (see Figure 10.1) and the sample sites (see Figure 10.2). The grid references for each of these sites are given where appropriate in the text, otherwise reference to Figure 10.1 will



Factor 10.1 Dominant Factor by layer at each site

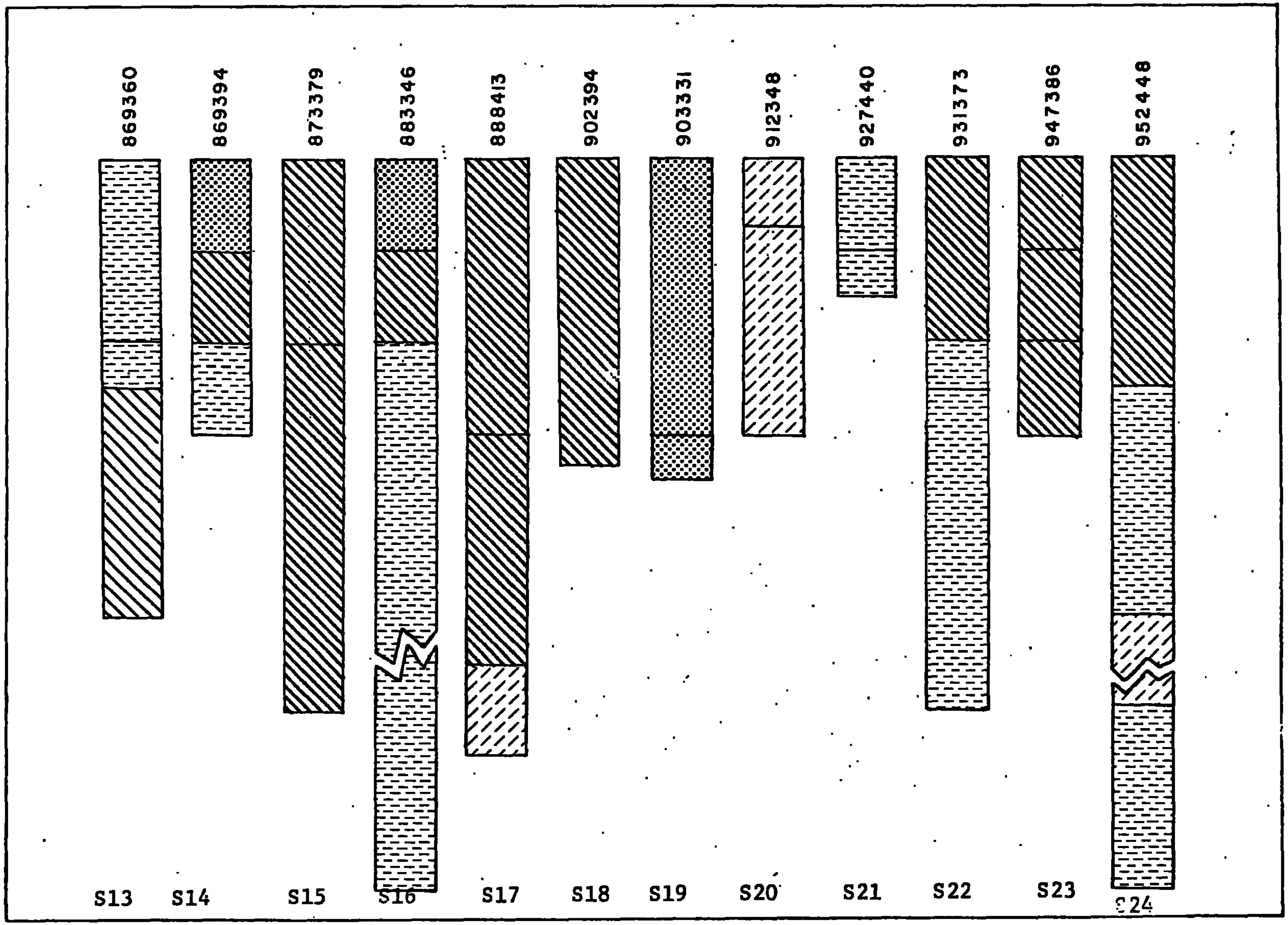


Figure 10.1 (cont'd)

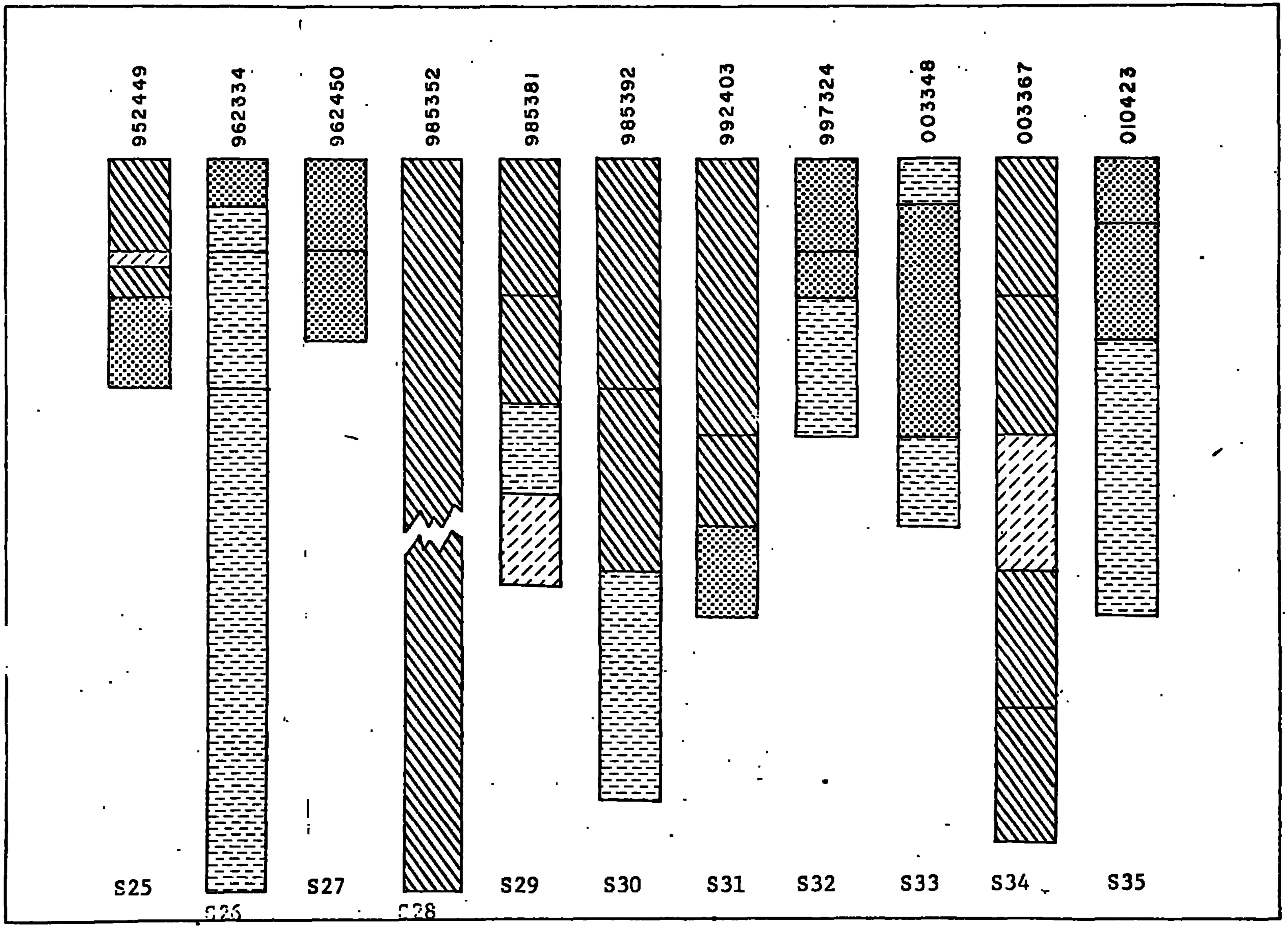


Figure 10.1 (cont'd)

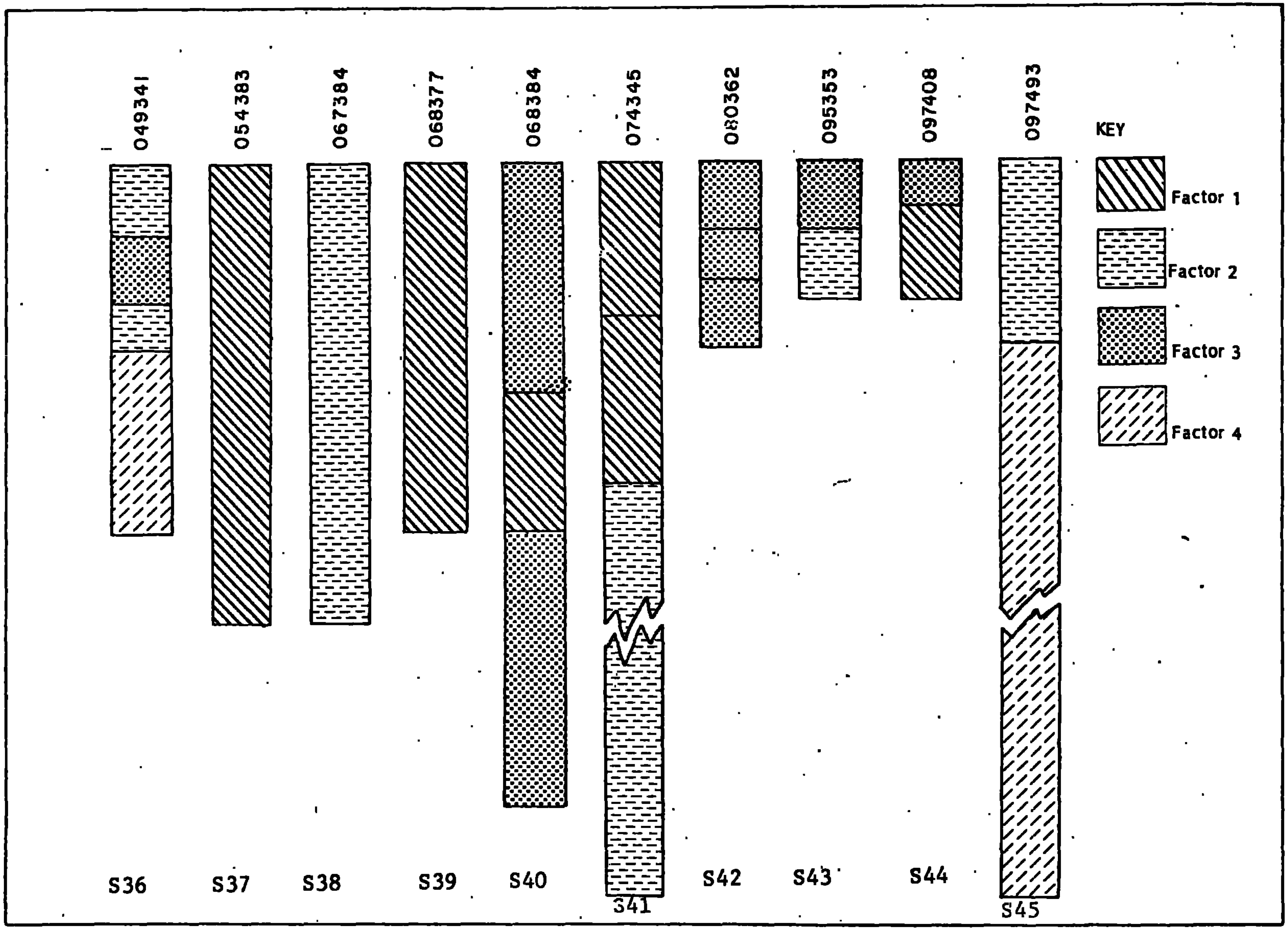


Figure 10.1 (cont'd)

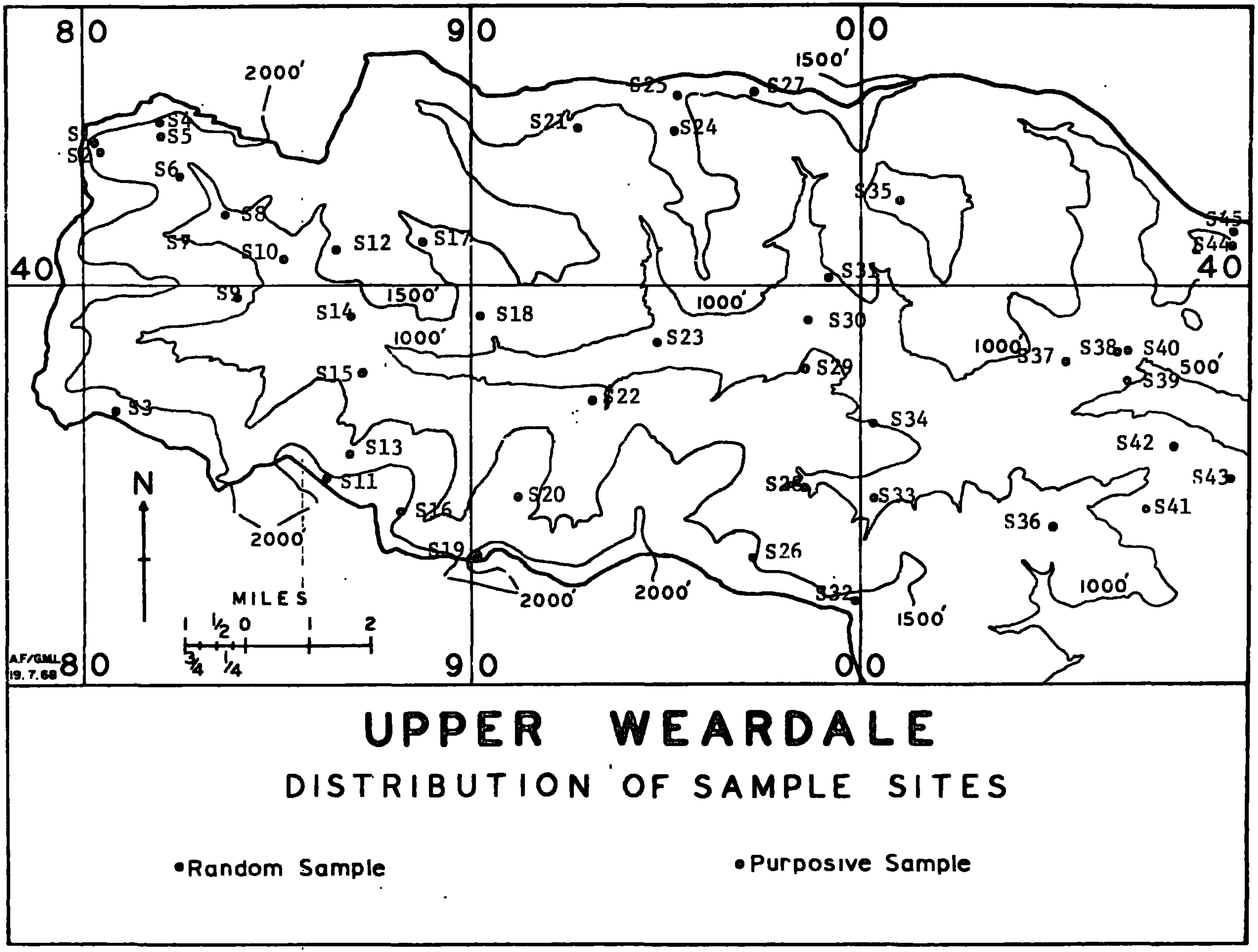


Figure 10.2 Key to Figure 10.1

supply the information to facilitate reference to field descriptions contained in Appendices I and II.

At the head of the valley the results of the analyses of sites S1-S12 (grid references 805435-865410) exhibits only one site (grid reference 806434) where Factor 1 influence (glacial influence) is not detected. All other sites indicate Factor 1 dominant at some level. Of these sites four, S5, S6, S9 and S12 exhibit a dominance of Factor 1 at the surface. Only S9, which demonstrates no other dominant influence throughout the profile, appears to be totally developed in glacial till, on the basis of this evidence. The other three sites exhibit till overlying rainwashed slope material (S5), sandstone regolith (S6) and in the case of S12, both rainwashed slope material and gelifluction deposits. Four sites close to the watershed show sandstone regolith overlying other deposits (S1-S4) and three of these have till immediately below this material. The exception (S2) has sandstone regolith overlying rainwashed slope detritus. Site S1 also has rainwashed slope detritus beneath the till. At site S3 the till overlies gelifluction deposits and at site S4 the till is apparently not underlain by other material. The remaining sites in this group (S7, S8, S10, S11) all have layers of till, S7 having a depth of till overlain by rainwashed slope detritus and S8 being a gelifluction deposit overlying till. Site S10 is more complex having a gelifluction layer at the surface succeeded by rainwashed slope detritus, till, gelifluction deposits. Similar stratigraphy is illustrated by site S11 which has a layer of till between layers of gelifluction material.

Evaluation of the sites S13-S24 reveals similar relationships.

Six of these sites (S15, S17, S18, S22, S23, S24) have till at the surface and in three cases (S15, S18, S23) there appears to be no underlying material of different nature. All three are in the floor of the valley where slope processes are less active. Sites S22 and S24 both have rainwashed slope detritus underlying the till and S24 has alayer of gelifluction material included within this. Site S17 has gelifluction material immediately underlying the till. Site S20 reveals only the presence of gelifluction material and site S21 only rainwashed slope detritus. Site S19 indicates only the presence of sandstone regolith. The remaining three sites of this group reveal a different pattern all having till deposits occurring below the surface. Site S13 has rainwashed slope detritus overlying till and site S14 has till overlain by sandstone detritus and underlain by rainwashed slope detritus, a pattern also observed at site S16.

Sites S25-S35 show that even more samples in this area (see Figure 10.2) have no layers of till in the sequence. The five sites (S26, S27, S32, S33, S35) which do not have layers with Factor 1 dominant exhibit sandstone regolith overlying rainwashed hillslope deposit with the exception of site S27 which only has a depth of sandstone regolith. Site S33 has this same sequence overlain by a further layer of rainwashed hillslope deposit. All sites with till layers (S25, S28-S31, S34) have a layer of till at the surface. Both site S34 and site S25 have a layer of gelifluction material between two layers of till and this sequence is overlying a layer of sandstone regolith at site S25. Site S28 only demonstrates the presence of till whereas sites S29, S30, S31 have till overlying sandstone regolith (S31), and rainwashed slope deposit (S30, S29). Site S29 has this sequence overlying a layer of gelifluction material.

The final group of sites (S36-S45) are the eastern-most sites in the study area and these as a group show three sites where till is present at the surface (S37, S39, S41). Both sites S37 and S39 demonstrate the presence of no other type of material. Site S41 shows that till overlies rainwashed slope deposit. Sites S40 and S41 both show sandstone regolith overlying till and in the case of site S40 this sequence overlies a further layer of sandstone regolith.

At site S38 only rainwashed slope deposit is observed and site S42 records only the presence of sandstone regolith. Site S36 has a more complex stratigraphy. At this point rainwashed slope deposit overlies sandstone regolith. This overlies a further layer of rainwashed slope deposit and site S45 shows rainwashed slope deposit overlying gelifluction material.

10.2 Interpretation of the Sequence of Deposits

The preceding description, of sequences of deposits at each site is the basis for several important observations. Because these sites are listed by grid reference in numerical order, the four groups shown in Figure 10.1 are each progressively further east of the head of the valley. An immediate observation is that with increasing distance east of the head of the valley there are fewer sites which exhibit till layers only at depth. The first set of diagrams in Figure 10.1 have seven sites which show till layers at depth but not at the surface. This only applies to three of the diagrams in the second group, none in the third group and two in the final group.

It should be stressed that whilst Factor 1 has been associated with glacial influence and deposits of till, samples in which Factor 1 is dominant are considered to be till but are not therefore considered to be unaltered till. Consequently a sample for which Factor 1 is dominant may be a rainwashed till or a soliflucted till, it is only by examination of secondary loading (see below) that such polygenetic diagnosis may be completed. However, if Factor 1 is dominant the deposits are considered to have been glacially processed.

An initial indication of order in this confusion of results is particularly welcome. One possible explanation of this increase in the occurrence of till at the surface with progress down valley is that the upper portion of the valley with a much restricted valley floor and generally steeper slopes (based on the information in Atkinson (1968) Figure 9) would be an area in which solifluction (creep, slumping and geliflucticn) would be more active and therefore more likely to yield a complex stratigraphy with till occurring in various positions in any profile.

With increasing distance from the head of the valley the wider valley, more extensive valley floor and gentler slopes would give an environment in which solifluction processes were less active, deposits of till in this region would therefore be more likely to remain in situ, hence the more frequent occurrence of till deposits at the surface in the lower part of the valley.

The general scrutiny of the sections shown in Figure 10.1 reveals a tendency for a stratigraphic sequence of regolith overlying till, overlying rainwashed slope detritus over gelifluction deposits. This sequence is complete in no individual case. Deducing the stratigraphy from simple frequency observations of the sections, sandstone regolith overlies only slope deposit or till. Rainwashed slope deposits occur above each of the other categories in at least two separate sites. Till occurs above each of the other categories in the sections studied, it occurs most frequently above slope deposits, less frequently over gelifluction material and least frequently over sandstone regolith. Gelifluction material occurs over till and in one case (site S24) over slope deposits. It is never observed over regolith.

Deductions based on this evidence lead to the tentative suggestion that the non-occurrence of gelifluction over regolith indicates that regolith did not exist as a distinct deposit at the time this process was active. The process implied by gelifluction no doubt created regolith giving the stratigraphy observed by Ragg and Bibby (1966) of coarser material (stone layer) underlain by the siltier gelifluction material. It is significant that this material only overlies deposits of till, suggesting the absence of existing mantles of regolith onto which the gelifluction material may have spread. The one sample of slope deposit overlain by this gelifluction material is not easily accounted for except in terms of a local pocket of slope material.

Sandstone regolith overlying only till and slope deposit suggests that it has developed after the gelifluction material had been buried by other deposits. Gelifluction material is overlain by slope deposit and till. This can be interpreted to indicate that periglacial processes giving gelifluction layers were followed by glacial action depositing till and then by ameliorating climate giving slope deposit and finally the development of regolith. It is considered more plausible to view the gelifluction layers as created after the retreat of the ice and presumably occupying areas left bare by ice erosion. The clay nature of some of the till would seem to indicate that it was not all conducive to extensive gelifluction. This opinion is based on Washburn's comments cited above (Chapter 8). The gelifluction deposits would therefore overlie till in areas where there was active downslope migration onto the till deposits in valley floor locations.

Subsequent climatic improvements would lead to the development of more active slope processes as precipitation increased in total and frequency, thus giving slope detritus overlying both categories of deposit so far considered. In addition the increased activity on slopes would probably involve the re-deposition of small pockets of till deposited on slope facets, and slowly, as regolith was produced from the disintegration of rock faces previously beneath the ice, the migration of this material would form rainwashed slope deposit adding the final member to a chaotic deposition sequence typical of that demonstrated by Figure 10.1.

10.3 Implications of the Areal Distribution

The map of the areas of dominance of the factors based on a consideration of the surface layer is produced as Figure 10.3. The relationships of the factors as revealed by this map appear to endorse Dwerryhouse's work which indicates (Figure 10.4) that the watershed areas were ice-free. Maling's (1956) map of boulder clay (here equated

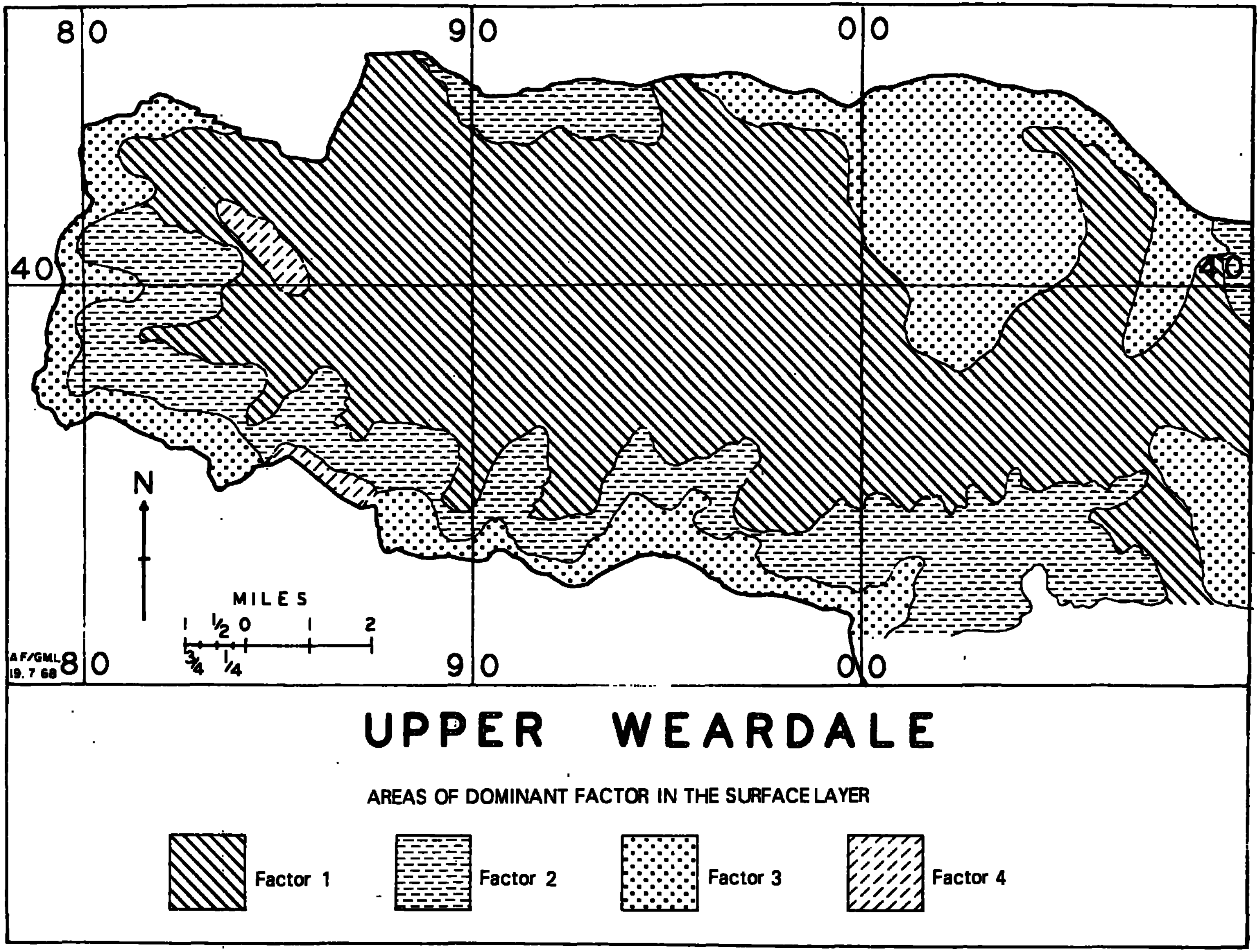

80
90
00
40
N
MILES
1 ½ 0 1 2
¾ ¼
AF/GML
19.7.68
UPPER WEARDALE
AREAS OF DOMINANT FACTOR IN THE SURFACE LAYER
Factor 1
Factor 2
Factor 3
Factor 4

Figure 10.3

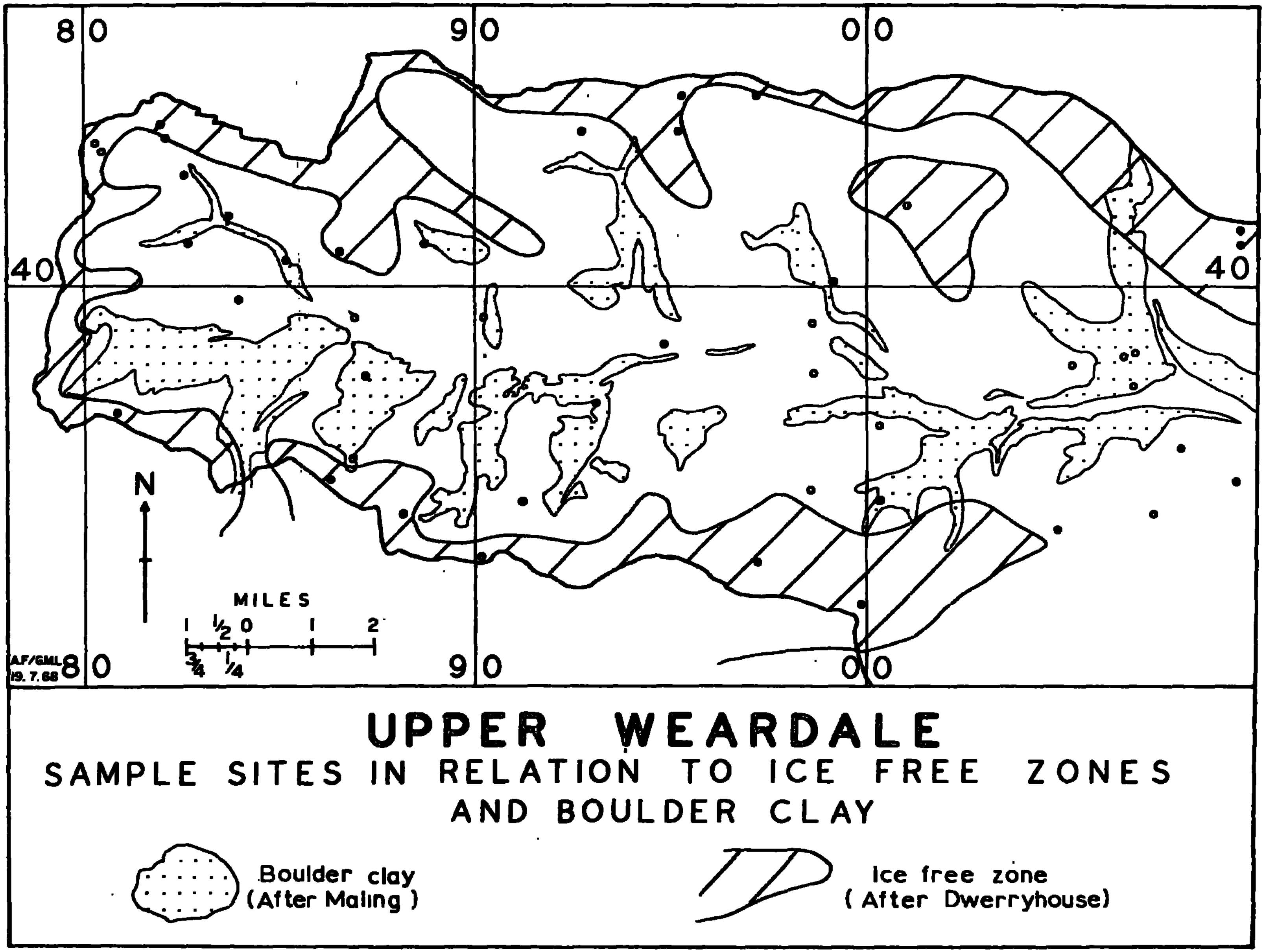

80
90
00
40
40
N
MILES
1 ½ 0 1 2
¾ ¼
AF/GML 19.7.68
UPPER WEARDALE
SAMPLE SITES IN RELATION TO ICE FREE ZONES AND BOULDER CLAY
Boulder clay (After Maling)
Ice free zone (After Dwerryhouse)

Figure 10.4

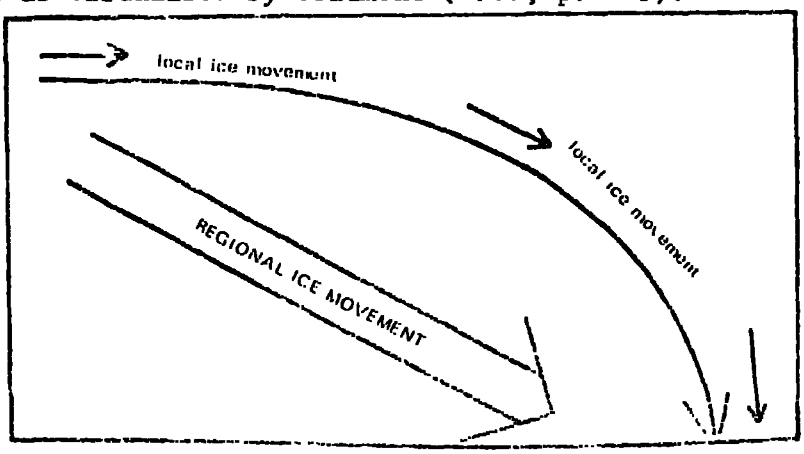
with 'till') is also compatible with Figure 10.3. It is necessary to consider that Dwerryhouse designated his ice free zones in the absence of positive evidence of ice action in these areas. Maling's drift map probably underestimates the extent of the till because of the difficulties of accurate deposit mapping in areas of thin mantles of superficial deposits.

Figure 10.3 reveals the influence of Factor 1 in places so close to the northern watershed it would be difficult to categorically state that ice never entered Weardale in these areas. Sites shown in Figure 10.4 as within Dwerryhouse's (1902) ice-free zone show surprising agreement with the original concept. Site S35 shows no dominant influence of Factor 1. Site S45 also shows no Factor 1 influence although it is present in site S44 indicating a need to modify the boundary slightly in that region.

Sites S32, S27, S26, S19, and S2 all within Dwerryhouse's ice-free zone show no dominant influence of Factor 1. Sites S24 and S25 do indicate Factor 1 influence and are within the boundary of the ice-free zone as drawn on Figure 10.4. They are close to the margin of it and neither the re-drawing nor the original map are intended to precisely define the ice-free zone. Both these sites, S24 and S25, are very close to the suggested ice-limit in the north-western part of the study area and demonstrate a major influence of Factor 1 in their stratigraphy. So too do sites S3, S11, S12 and S16. This latter group of sites represents a basic incompatibility with Dwerryhouse's ice free zone in these areas although the surface layer (as demonstrated by Figure 10.3) does not reveal this Factor 1 influence.

Dwerryhouse's concept of a diffluent trough at the head of Ireshopeburn could be an indication of his understanding of the extent of glacial ice across the watershed in this area. That it should slightly exceed the limits he suggested would be compatible both with his work and the evidence presented here. It would seem that, from the evidence presented above it would be necessary to dispute only the concept of an ice free zone at the head of Weardale. Both Figure 10.3 and the evidence of sites S3, S11, S16, S1, S4 and S5 suggest that ice extended across the western area of the Wear watershed.

The south-easterly trends visible in the linear trend surfaces generated by Vincent (1969, Figures 12.6, 12.5, 12.3) are also in general agreement with this concept. The south-easterly trend of the linear surface map of Factor 1 loadings in the present work (see Chapter 9 and Appendix III) also appears to confirm this hypothesis. If Vincent's model of ice movement in areas of strong relief control is applied in this case it can be seen that a general regional movement of ice may have taken place in a south-easterly direction, the basal ice of this sheet being forced to flow in a more easterly direction by the existing topography. The ultimate effect of this would be to give a pattern of ice movement as visualised by Beaumont (1967, p. 105).



10.4 Stone Orientations and Striae

Evidence of the types of movement mentioned above should be recorded in the preferred orientations of stones in the till and in striae on the bedrock surfaces. The evidence available has been briefly presented as Figure 3.4. It is necessary to evaluate it in greater detail here.

Stone orientations have been widely used in studies of Pleistocene geomorphology. The most valuable account of the orientation of stones in till and an attempt to account for the orientation of different stone shapes and their orientation is the one by Holmes (1941) and subsequent work by Harrison (1957b) has related Holmes' ideas to process. Other workers concerned with differentiating ice sheets on the basis of the orientation of stones in till (West and Donner,1956, Beaumont, 1967) have applied the technique effectively. Still others have used orientation data to establish the general patterns of regional ice movement. (Notably Virkkala, 1951, Dremanis and Reavely, 1953, Kirby, 1961, Penny and Catt, 1967, and Andrews, 1963).

The general nature of the technique is such that it offers useful confirmatory evidence of the former presence of ice within a region and indications of the direction of flow. It is adopted in the present study to provide additional evidence of ice action and to evaluate the direction of ice movement deduced by Dwerryhouse on the basis of observed striae.

The procedure adopted was that recommended by Beaumont (1967). Sites which were apparently undisturbed deposits of till were selected, in available exposures, and orientations measured at a depth of at least

4' from the present surface. The very limited number of such exposures accessible in Weardale placed a severe limitation on the amount of this work the author was able to undertake. It was initially hoped orientations could be measured for each layer at each site sampled. The great increase in time that was thus required rendered this procedure totally impractical. To keep an inspection pit open for two or more days on the moorland was considered to be too great a hazard to man and beast. Consequently the inspection pits had to be dug, sampled and closed within one day. This latter fact precluded the collection of the detailed orientation data that was desired.

The results of these data analyses are presented as Figure 10.5. All orientations were tested for significance using the Chi-square test as outlined by Beaumont (1967, p. 94). All orientations presented in Figure 10.5 are significant at the .05 level.

Conclusions from this work are that the preferred orientation directions demonstrate a west to east movement of ice. All strongly preferred orientations occur within the zone in which Factor 1 is a dominant surface influence and with the foregoing interpretation of Factor 1 as glacial till it appears to be conclusively demonstrated that the Wear valley has been occupied by a west-east moving ice mass which deposited a silty-clay till.

The results of Atkinson's stone orientations in till (Atkinson, 1968, Figure 26) are in complete agreement with those demonstrated in Figure 10.5 above. In the present survey the author was unable to test the use of orientation as a diagnostic property of deposit type because to do so only provided problems of application of the technique to layers

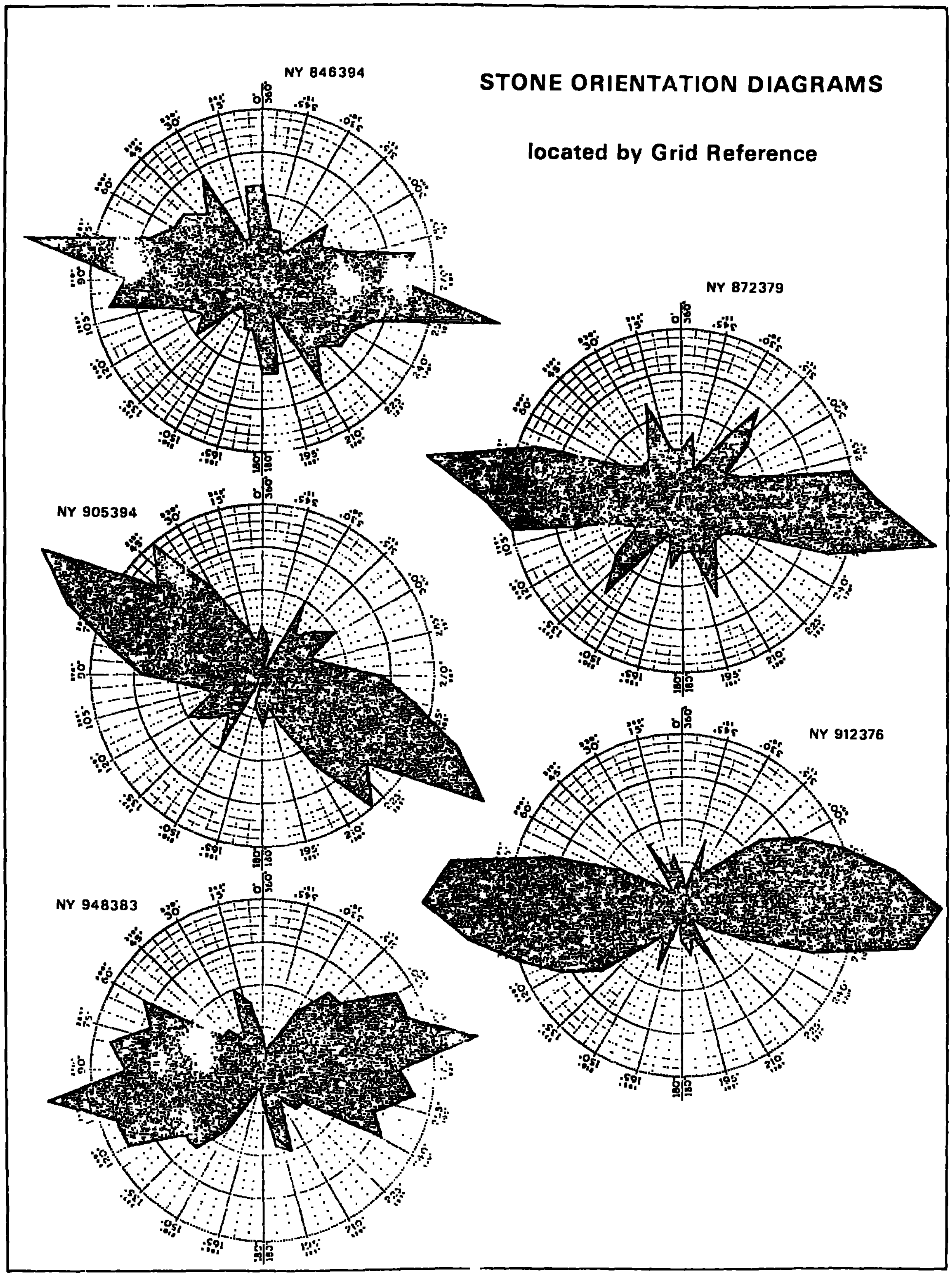

STONE ORIENTATION DIAGRAMS
located by Grid Reference
NY 846394
NY 872379
NY 905394
NY 912376
NY 948383

Figure 10.5

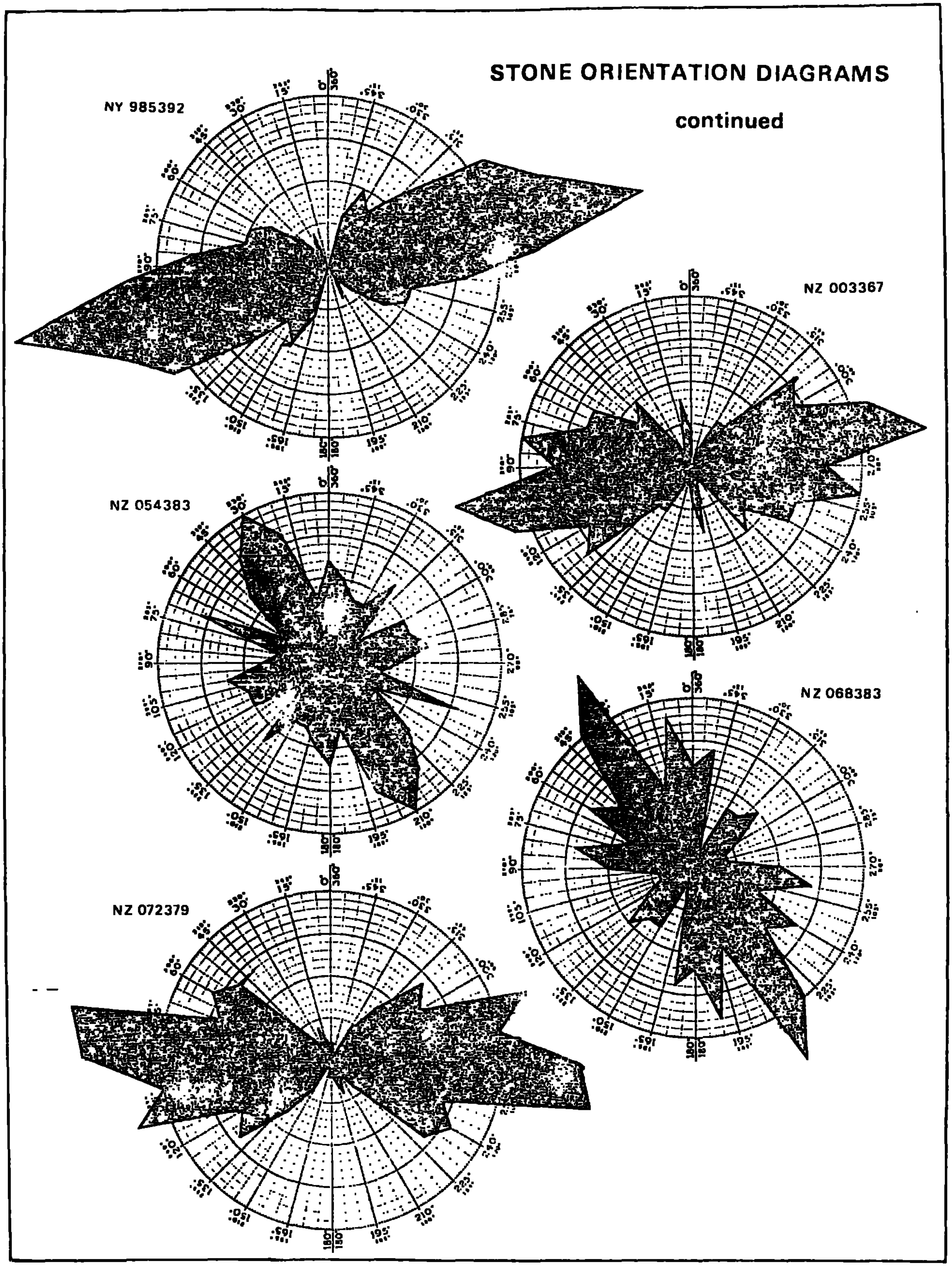


Figure 10.5 (cont'd)

of deposit which "could be till". The only way this could be evaluated would be by the collection of fully detailed orientation data which was not possible for reasons already given above. As a general comment the author is able to state that for deposits which are clearly "till" (or equally clearly "slope deposit") in field section, these orientation results given by Atkinson are valid. In the case of less clearly classifiable deposits (the majority in this study) this technique is much reduced in value.

10.5 Lithology

Atkinson's presentation of histograms of the lithology of the till of Weardale (Atkinson, 1969, Figure 25) are a useful summary of the nature of the stone content of the Weardale boulder clay. In the present study the lithology of the till was only briefly examined. Stone counts on selected samples indicate that the pattern emerging in the histograms presented by Atkinson is substantiated for the group of Factor 1 deposits. There is a variation of between 52 and 76 percent of stones retained on the No. 8 sieve. Limestone content also varies between 16 and 27 percent of the included stones with shales forming the remaining group varying between 4 and 16 percent.

To the east of the outcrop of Whin Sill dolerite at Eastgate (grid reference 950380 and region) fragments of dolerite occur. These vary in percentage occurrence from 12 to 0 percent of the included stones in the till to the east of this site. The small outcrop of quartz-dolerite at Copt Hill (grid reference 851408) does not appear to yield any detectable amount of quartz-dolerite in the till between Copt Hill and Eastgate.

This is probably a reflection of the very small area of the outcrop at Copt Hill (area not given because the outcrop has been opened up by a quarrying operation and abandoned) and the very small sample of the total till deposit which was analysed (c.250 Kg.).

Lithological data are not included because they are based upon uncontrolled counts of stones remaining on the No. 8 sieve. This does not meet the rigid procedure, used by Beaumont, of taking a measured volume of till, disaggregating it and passing it through the standard sieves for gravel-size before compiling the stone count data. The procedure established by Beaumont is excellent but time consuming. This latter attribute was the major consideration in the adoption of the very subjective assessment of lithology undertaken here.

Slope deposits on a similar subjective assessment have high content of the local bedrock fragments in many cases but often contain the other rock-types found in the till. All variations in proportions of limestones, sandstones and silts were encountered at the sites examined and from this continuum it was not possible to classify the material into distinct groups.

Factor 3 grouping of sandstone regolith was the one group clearly defined by lithology as having high contents of sandstone fragments (> 90%) although other rock fragments are occasionally found in this deposit - presumably the result of local down slope migration. The Factor 4 group, defined as geliflaction material exhibits the presence of all rock types but only as small pebbles or granules, usually of shale or limestone. Small inclusions of rotted sandstone are also found in these deposits. It is also important to stress that the layer of large flat stones (up to 30 cms. or greater in length) frequently associated with this geliflfluction material does not appear in the analysis of the material. Thus a field description (as in Appendices I and II) may note the presence of large platy stones but the analysis conducted will probably indicate a Factor 4 deposit i.e. a silty gelifluction layer which represents the results of the analysis of the matrix.

10.6 Secondary Influences and Polygenetic Deposits

The difficulties encountered in trying to assess the influences of four genetically significant factors in 150 individual samples were finally resolved by presenting each section as five parallel divisions each one representing a factor of the group of five analysed and each shaded according to the factor loading at that depth. This diagram is presented as Figure 10.6 and can be usefully interpreted as an extension of the information contained in Figure 10.1.

Considering the samples which have a dominant loading on Factor 1, it is possible to draw some further conclusions about their composition. The layer of till at site S1 is completely dominated by Factor 1. It is therefore concluded that this layer is indisputably till. Similar complete dominance by Factor 1 is indicated for the till layer site S3. At site S5 Factor 1 dominates the till layer in all but one segment at c.120 cms. where Factors 1 and 2 have similar loadings. This probably represents the effect of downslope migration of this till deposit as it overlies a deposit with Factor 2 completely dominant at c.200 cms. and this Factor 2 deposit shows influence of Factor 1 at c.160-180 cms. This association would be the probable result of soliflu-

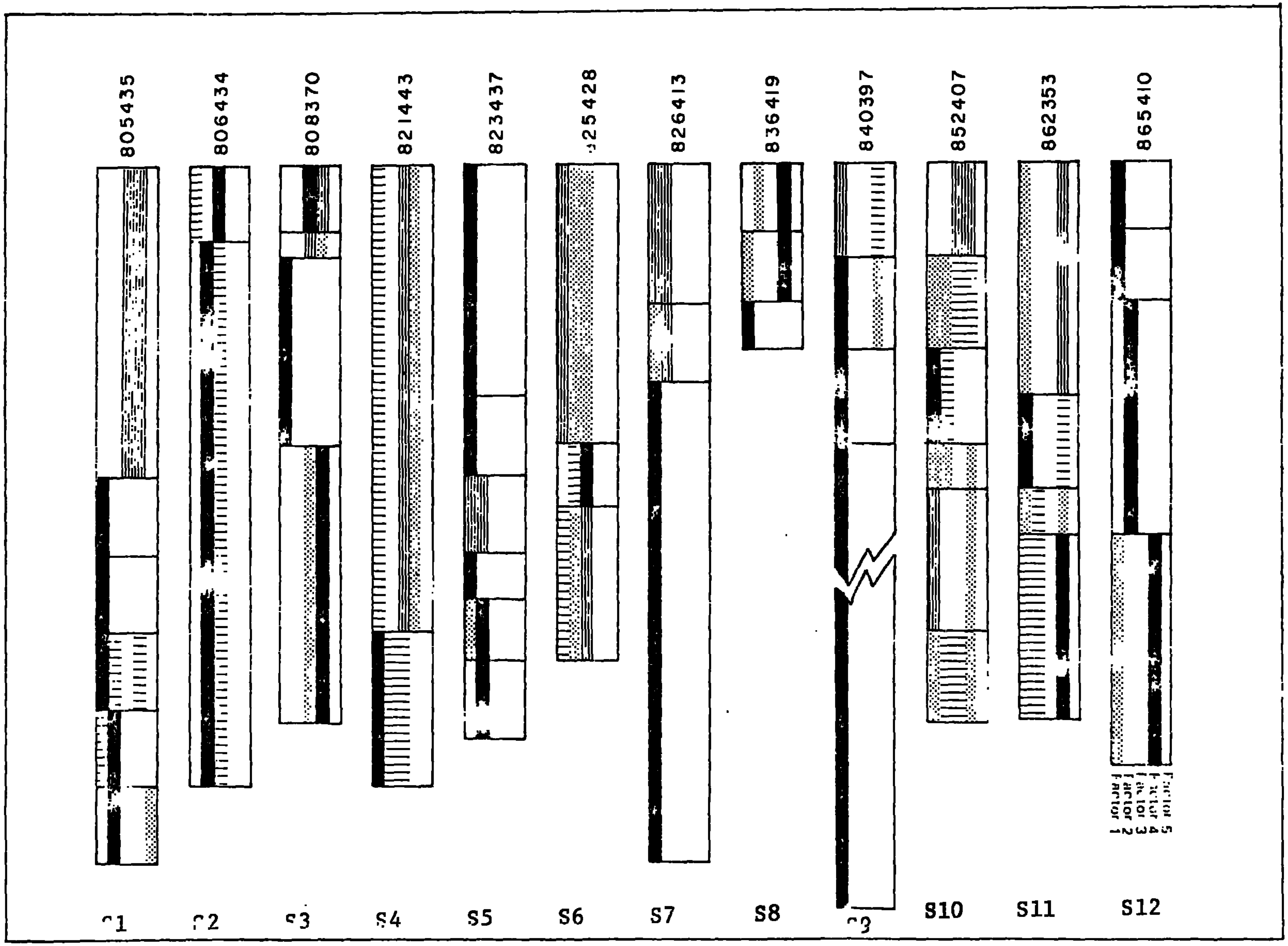


Figure 10.6 Loadings on each factor by layer and site

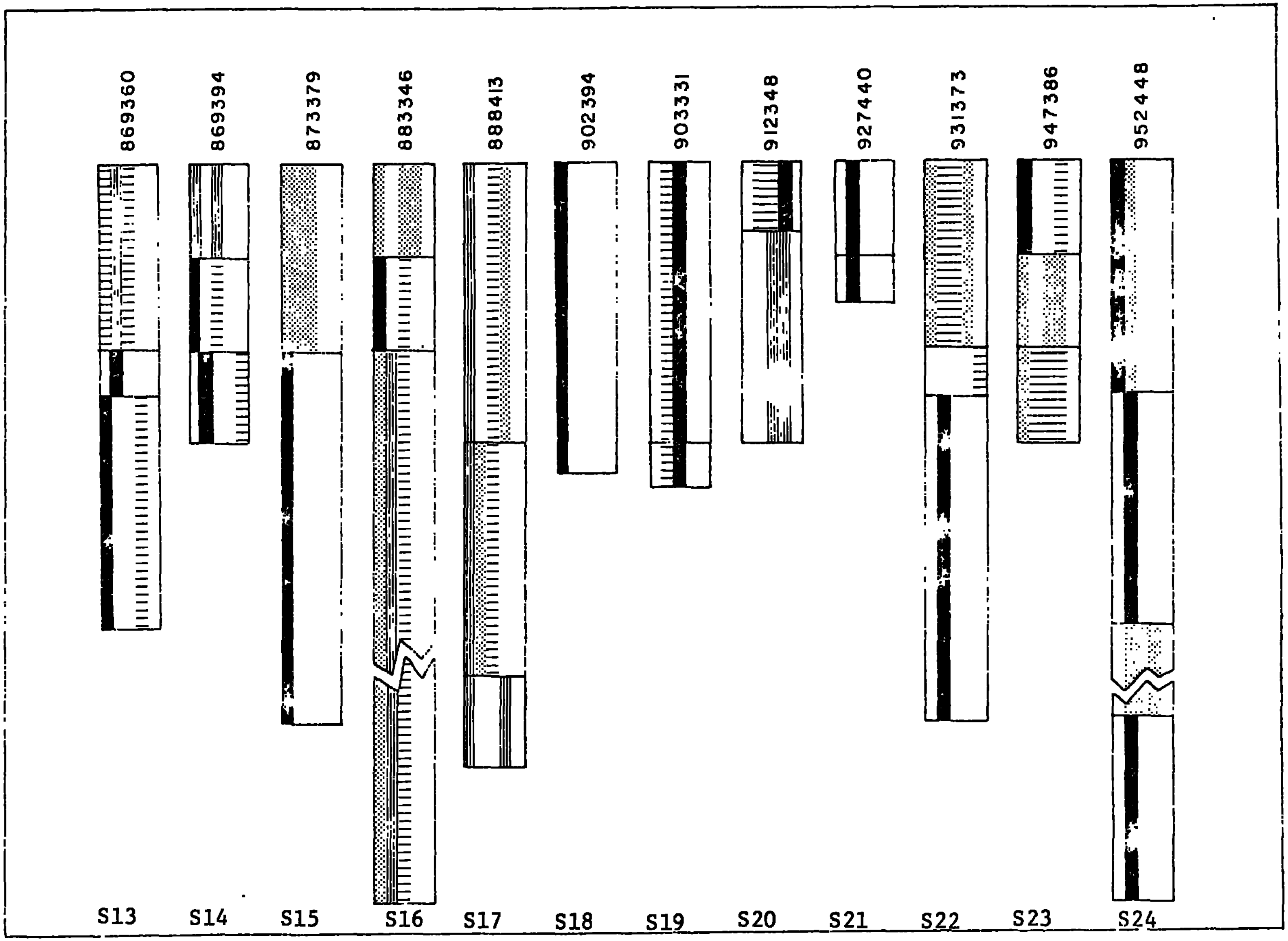


Figure 10.6 (cont'd)

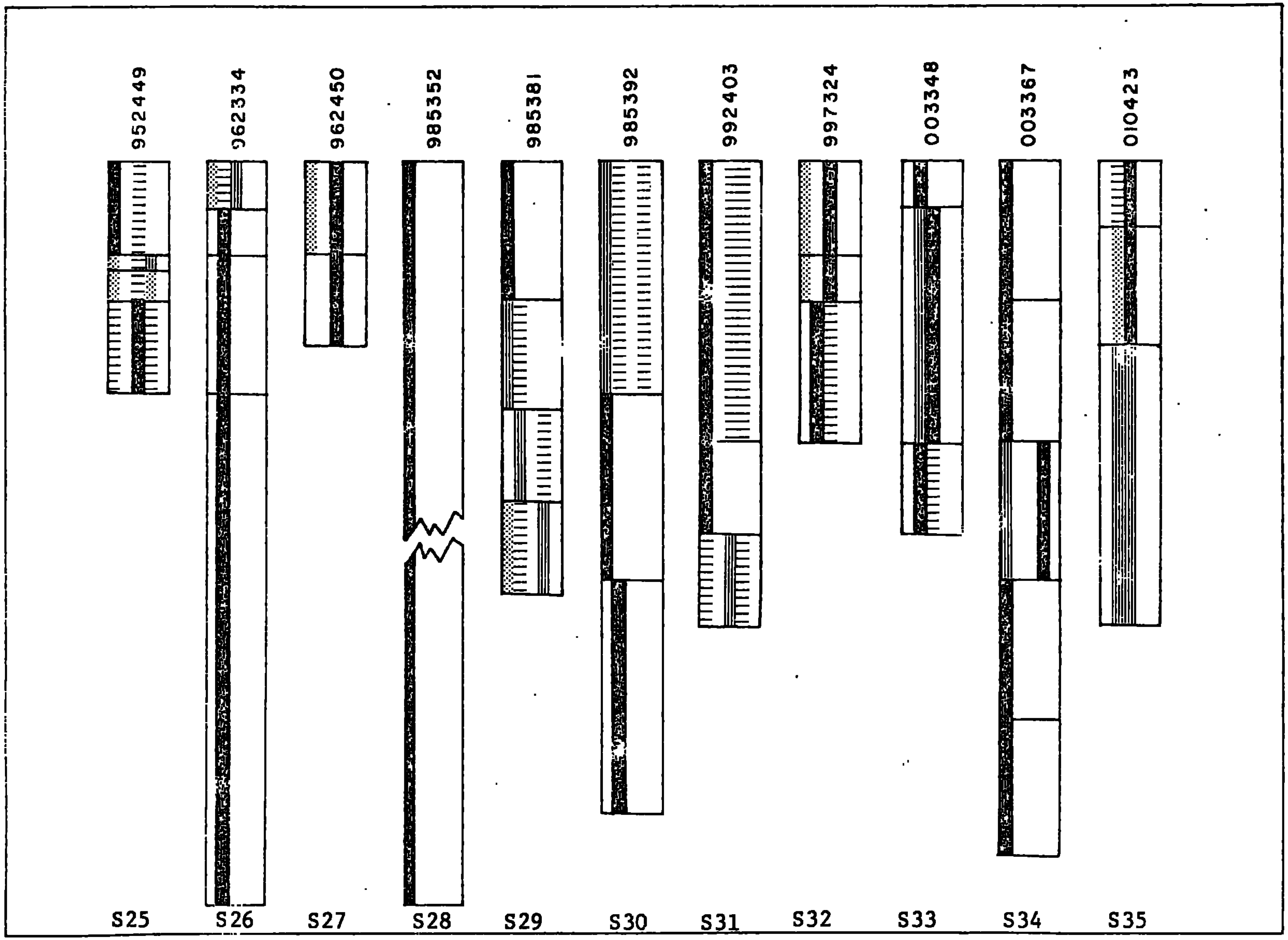


Figure 10.6 (cont'd)

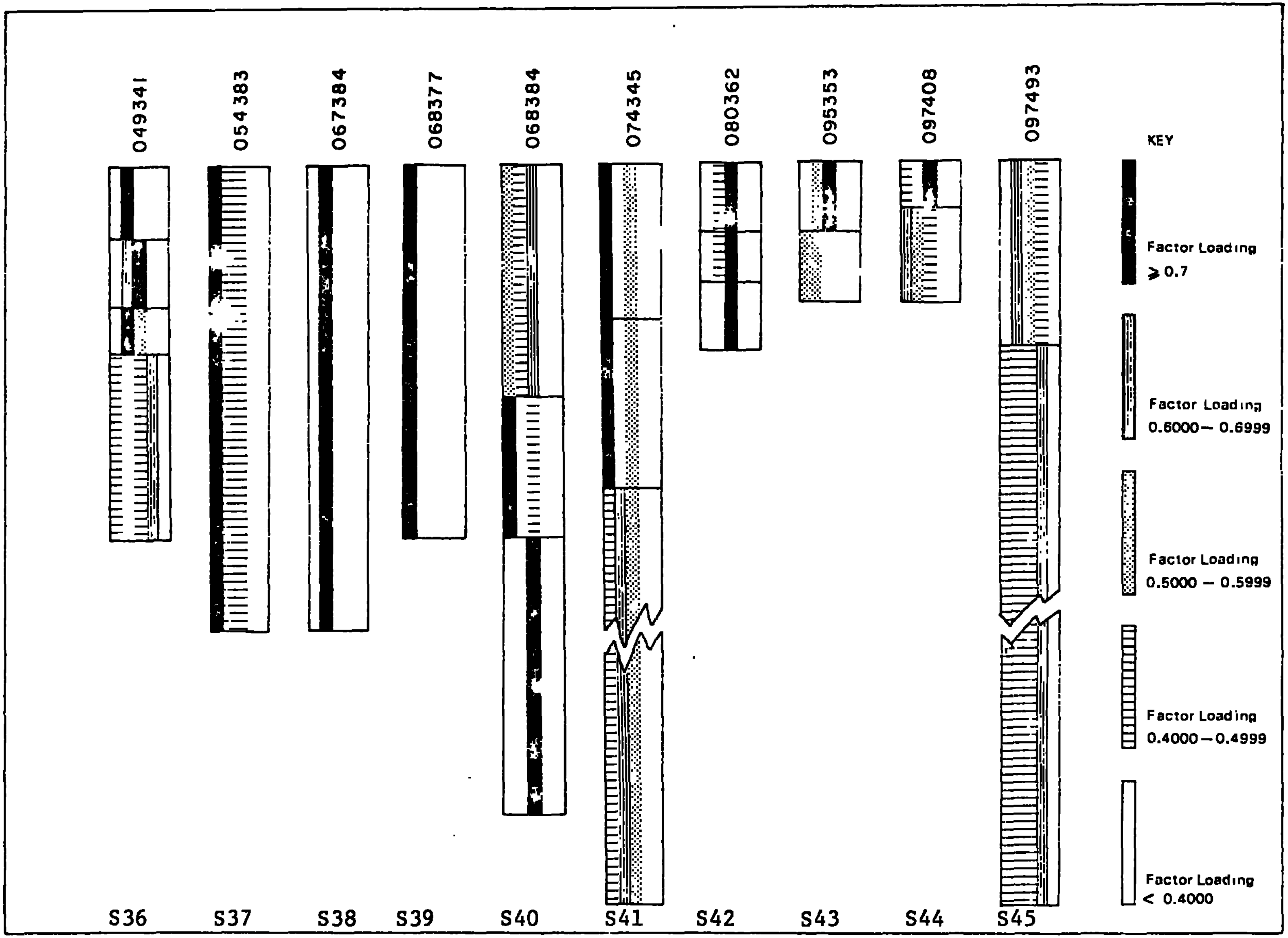


Figure 10.6 (cont'd)

tion of a till deposit.

It is more constructive to consider each section as a total record of the geomorphological history and consequently consider each layer in its relationship to the deposits adjacent to it. Whilst this necessitates a considerable amount of description it is a useful summary of the significance of each sample site in the understanding of the geomorphology of Weardale. With such a background it is possible to summarise the stratigraphy in a meaningful way. The descriptive analysis of all sites is therefore presented below.

The sub-groups of Figure 10.6 are the same as those for Figure 10.1 each page of the figure being considered as a group of sites for the purposes of descriptive analysis alone. Sites S1 and S12 demonstrate a variety of associations between the factor influences. At site S1 the dominant factor sequence of regolith over till over hillslope deposit is amplified by the consideration of secondary loadings. The surface layer of regolith has an almost equal loading on both Factors 3 and 4 indicating geliflution to be a major secondary influence on the deposit. This overlies about 50 cms. of till (Factor 1 dominant with no secondary loadings on other factors). Below this till layer is more till (25 cms) with weak secondary loadings on Factors 2 and 4. This is underlain by 50 cms. of hillslope deposit the upper 25 cms immediately below the till showing a minor secondary influence of Factor 1.

At site S2 the two layers recognised are a surface layer in which Factor 3, sandstone regolith, is dominant, with a very weak loading on Factor 1 as a secondary influence, overlying a layer in which Factor 2 dominates with a secondary loading on Factor 3. The interpretation of this sequence appears to be a decrease in the activity of hillslope processes which have previously dominated an area of sandstone regolith, the surface layer indicates that the regolith is now less disturbed.

Site S3 appears to demonstrate a clear case of till migrating downslope in periglacial conditions to overlie a gelifluction deposit. At the surface is a layer primarily influenced by Factor 3 with a secondary influence of Factor 4. This overlies a layer dominated by Factor 1 (till) which in turn rests on a layer in which Factor 4 is dominant and Factor 3 a secondary influence. Site S5 could be interpreted in a similar manner as it too has a surface layer dominated by Factor 3 but with a secondary loading on Factor 4 and a minor influence of Factor 1. This overlies a layer in which Factor 1 is dominant with minor secondary influences of Factors 2 and 3. Solifluction is again a likely agent to create these conditions.

At site S6 the deposit of till at the surface shows secondary loadings on both Factors 2 and 3 (the hillslope deposit type and regolith). It seems most probably that this deposit is till which has undergone considerable re-working in a solifluction situation. It overlies sandstone regolith which itself has secondary loadings on the hillslope deposit factor, indicating again that this is probably a solifluction environment. Site S4 reveals a layer of regolith with a subsidiary influence of gelifluction overlying a layer of till. This presumably represents downslope migration of regolith on to existing masses of till.

Sites S7, S8 and S9 all reveal a complete dominance of Factor 1 at depth indicating that the sites examined are all developed over till. Site S7 has two upper layers in which Factor 2 is dominant but both show secondary loadings on Factor 1 indicating the influence of glacial till on the nature of this upper layer of hillslope detritus. Again the conclusion indicated is that this is till being reworked in a solifluction situation. Site S8 has two upper layers dominated by Factor 4. The surface layer demonstrates a secondary influence of Factor 2 and the layer between this and the till deposit demonstrates the secondary influence of Factor 1. The logical interpretation of this as a gelifluction layer developed on till with its surface subsequently reworked by hillslope processes seems to be in complete accord with both the hypothesis of deposit genesis in the area and the demonstrated factor loadings. Site S9 has a surface layer demonstrating a dominance of Factor 1 but a weak secondary influence of Factor 4, the conclusion is that this till deposit has been slightly affected by gelifluction processes.

Site S10 is complex the surface layer shows loadings of similar magnitude on Factors 3 and 4 with Factor 4 the larger value. This overlies a layer in which Factor 2 is dominant almost equalled by the loading on Factor 1 and Factors 3 and 4 both have low subsidiary loadings in this case. These two layers are immediately above a layer of till (with a minor secondary influence of slope deposit) in which there is a thin layer (20 cms.) for which Factor 4 has the highest loading. This thin layer has almost equal loadings on Factors 1, 2 and 4. Below this is till with a secondary loading on Factor 4 and at depth Factors 4 and 1 both are significant with subsidiary loadings on Factors 2 and 3. In this, the deepest layer sampled, Factor 4 dominates. Clearly this is a section in which periglacial solifluction has resulted in gelifluction, overlain by till moving downslope in this environment but greatly affected overlies this and it too has been buried by hillslope deposit and gelifluted regolith.

Sites S11 and S12 seem to offer variants on the same explanation. The surface layer at site S11 is gelifluted till (Factors 4 and 1) overlying till (with slight gelifluction influence) overlying gelifluted till (Factors 4 and 1) over a gelifluction deposit with slight loadings on Factors 1 and 2. S12 shows a more definite stratigraphy with Factor 1 dominating the surface layer and overlying a hillslope deposit. Both of these overlie a gelifluction deposit which has a secondary loading on the till factor.

Sites S13-S24 provide an equally complex record. Site S13 itself shows a layer of hillslope deposit (with minor influences of till and regolith) overlying a thinner layer (20 cms.) of hillslope deposit (no secondary loadings) and this sequence is over a 80 cms. layer of till. This section indicates only the hillslope deposit over till showing as significant influence of Factor 4. Sites S14 and S15 also show no influence of Factor 4. S14 has a surface layer of till with a similar loading on regolith. This overlies a layer of till with a minor regolith loading and beneath these in a hillslope deposit. Site S15 offers a sample record of a till deposit with the influence of Factors 2 and 3 on the surface layer.

Site S16 records a layer of regolith with similar loadings on Factors 3, 4 and 1 overlying a layer of till with a subsidiary loading on regolith. Below this is a considerable depth (360 cms.) of slope deposit with subsidiary loadings on till and regolith. At site S17 there is a consistent loading on Factor 1 throughout the profile. This is dominant in the upper two layers. Secondary loadings on Factors 3 and 4 accompany the Factor 1 loading near the surface and below this the secondary loadings are on Factors 2 and 3. At 170 cms. Factor 4 has a slightly higher loading than Factor 1. Site 18 demonstrates only the dominance of Factor 1, site S19 the dominance of Factor 3 with a minor influence of Factor 2.

Site S20 has Factor 4 dominant throughout although the surface layer has minor loadings on Factors 2 and 3. Below this the Factor 4 loading is almost equalled by the Factor 3 loading. Site S21 demonstrates only the dominance of Factor 2 throughout. Site S22 is again more complex. At the surface site S22 shows a dominance of Factor 1 with a subsidiary loading on Factor 4 and minor influences of Factors 2 and 3. This Factor 2 is completely dominant. Site S23 shows Factor 1 dominant throughout. At the surface Factor 1 is clearly dominant and there is a minor loading on Factor 4. Below this Factors 1, 3 and 4 have almost equal loadings and this overlies a layer in which Factor 1 dominates with minor loadings on Factors 2, 3 and 4.

The final site in this group, site S24 shows Factor 1 dominant at the surface with a subsidiary loading on Factor 2 below this Factor 2 is dominant except for a layer in which there are loadings of similar magnitude on Factors 2, 3 and 4 the latter being the highest loading.

Sites S25-S35 record a less complex stratigraphy than the previous group. Of the group, site S28 demonstrates only the complete dominance of Factor 1. Site S25 has Factor 1 dominant at the surface with two thin layers (10 cms. and 15 cms.) below this having loadings on both Factor 1 and Factor 4. Factor 4 dominates in the layer immediately below the surface layer. Underlying this sequence is a layer in which Factor 3 is dominant with minor loadings on Factors 1 and 4. Site S26 shows a surface layer in which Factor 3 dominates with a subsidiary loading on Factor 1 and minor influence of Factor 2. Below this Factor 2 is completely dominant. Site S27 has Factor 3 dominant throughout with a subsidiary loading on Factor 1 in the surface layer. Site S29 has Factor 4 completely dominant at the surface with continued dominance in a second layer where a minor influence of Factor 2 exists. The layer below this has Factor 2 dominant with a minor influence of Factor 4. Below this Factor 4 dominates with a minor influence of Factor 2 and a subsidiary loading on Factor 1.

Apart from site S28 clearly in unaltered fill, the remaining sites demonstrate influences and sequences compatible with a solifluction environment. Site S30 has a surface layer with Factor 1 dominant and minor influences of Factors 2 and 4. Below this is a layer dominated by Factor 2. Site S31 has two layers dominated by Factor 1 (with minor influences of Factors 3 and 4 in the surface layer) overlying a layer in which Factor 3 is dominant with minor influences of Factors 1 and 4. Site S32 has two layers. The surface layer dominated by Factor 3 with a Factor 1 subsidiary loading and the lower layer dominated by Factor 2 with a minor influence of Factor 3.

Site S33 has major loadings on Factor 2 throughout its three layers. The upper layer has no other significant loadings, the layer below this is dominated by Factor 3 and the lowest layer has a minor influence of Factor 3. Site S34 shows two layers of till with no other factor influence separated by 50 cms. of a Factor 4 layer (gelifluction material) which has a subsidiary Factor 1 loading. Site S35 has high Factor 3 loadings throughout with a minor influence of Factor 2 in the surface layer, and increasing influence of Factor 2 in the lower layer and a dominance of Factor 2 in the lowest layer.

The final group, sites S36-S45, has a much simpler stratigraphy the previous groups. Site S36 has Factor 2 with high loadings in three layers at the top of the section. The surface layer has Factor 2 dominant,the lower layer has Factor 3 dominant and the lowest of these three layers has Factor 2 dominant with a subsidiary loading on Factor 3. Below this is a deposit in which Factor 4 is dominant with minor influences of Factors 1 and 3. Site S37 demonstrates a dominant influence of Factor 1 with minor influences of Factors 2 and 3. Site S38 is completely dominated by Factor 2 and site S39 by Factor 1.

Site S40 has Factor 3 dominant in the surface and the lowest layers with a third layer in which Factor 1 dominates, separating these two. The surface layer has a subsidiary loading on Factor 1 and a minor influence of Factor 2. Site S41 shows Factor 1 dominant in the surface layer with subsidiary loadings on Factor 3. Below this Factor 2 dominates with a subsidiary loading on Factors 3 and a minor influence of Factor 1. Site S42 is dominated by Factor 3, site S43 has Factor 3 dominant at the surface with a subsidiary loading on Factor 2, below this Factor 2 dominates with a loading of similar magnitude on Factor 1. Site S44 has Factor 3 dominant at the surface with Factor 1 dominant below this, the lower layer also having a subsidiary loading on Factor 2. Site S45 has two layers the upper one in which Factor 2 is dominant has subsidiary loadings on Factors 3 and a minor influence of Factor 4. Below this

Factor 4 dominates a deposit in which there are minor influences of Factors 1, 2 and 3.

10.7 Conclusions

The descriptions given above all point to complex deposit types in such a sequence as to suggest chaos in their vertical and horizontal distribution. Hillslope deposits were underlying till in several cases. Whilst either regolith or gelifluction material in such a position is compatible with extreme periglacial action causing considerable downslope movement it is difficult to envisage the manner in which hillslope detritus is able to accumulate to any great depth beneath a layer of till. The author suggests the possibility that such deposits may not be rain-washed hillslope deposits but deposits from a wasting ice mass which have been washed by local movement of meltwater. A possible confirmation of this tentative hypothesis is in the fact that samples of glacio-fluvial sand from S.E. Iceland loaded most highly on Factor 2.

An attempt to evaluate this complex of data is presented below. The continuing assessment of the meaning of the factors derived in this study reveals that they present information which may be analysed at any pertinent level. It is possible to generalise from the factor loadings to give regional trends as in the trend surface mapping. It is also possible to view the vertical sequence of deposits in the same way, considering only dominant factors in either the surface layer (as in Figure 10.3) or each sample (as in Chapter 10.1 above). Full detail of the factor loadings may be derived from the information as presented in

Figure 10.6 The final summary and evaluation of these factor loadings in terms of the geomorphology of Upper Weardale must necessarily be subjective and be undertaken with a knowledge of the landforms and their field relationships. This is attempted in the following chapter.

Chapter 11

Summary

This work has presented a series of deductions based on a data analysis of particle-size measurements of the deposits occurring in Upper Weardale. Data analysis whilst it has the advantages of objectivity, mathematical rigour and reproducibility does not have any true sensitivity in terms of the local nature of geomorphological process or the understanding of the relationships between these processes. Subjectivity - of itself an acceptable attribute in the design and execution of scientific investigations, inevitably becomes a part of the evaluation process. It is this process which is the concern of the present chapter.

11.1 Ice in the Northern Pennines

Dwerryhouse (1902) clearly bases his concept of ice-free zones on the lack of both erratics and boulder-clay in the watershed areas between the Wear and the Tyne and Tees drainage systems. Vincent (1969) from his studies is sceptical of this and by considering ice gradients and firn lines (based on the work of Manley 1955 et seq) concludes that at the period of maximum glaciation there were no ice free areas. (Vincent, 1969, p. 311). Before considering this in the light of the evidence accumulated in the present thesis a more general survey of ice extent and regional movements appears necessary.

Vincent provides an excellent summary of ice movements and centres of ice dispersal in the area of the Alston Block. It is necessary to repeat several of the points he makes in order to discuss the ice movements in relation to Upper Weardale, which is immediately adjacent to his study area. The work of both Atkinson (1968) and Vincent (1969) is so directly pertinent to this study that it is difficult to avoid repetition and quotation of their observations. For a fully detailed understanding the reader is strongly advised to refer to these existing studies with which this present work was contemporaneous in its design, field study and data collection.

The maps presented by Beaumont (1968) of glaciation both in the Alston Block and adjacent areas and in Northumberland and Durham are reproduced as Figures 11.1 and 11.2. They are based on the work of Trotter (1929a) and Raistrick (1931) respectively and reveal ice streams in a pattern very much as envisaged by Dwerryhouse for the Weardale area. The clear separation of ice streams at the head of Weardale, as illustrated by Figure 11.1 is compatible with the limit of Lake District erratics as illustrated by Figure 11.2 but neither provides a clear picture of ice movement within the area of Upper Weardale.

Patterns of ice movement on a broad regional scale are clearly established showing incursion of Lake District ice through the Stainmore Gap and through the Tyne Valley. The existence of Cross Fell as a major centre for ice accumulation is also well established. Dwerryhouse summarised this work in a particularly valuable description contained in his paper on the glaciation of this region. The patterns of regional ice movement shown by Dwerryhouse are summarised in Figure 11.3.

In his work Dwerryhouse considered that, at maximum glaciation,

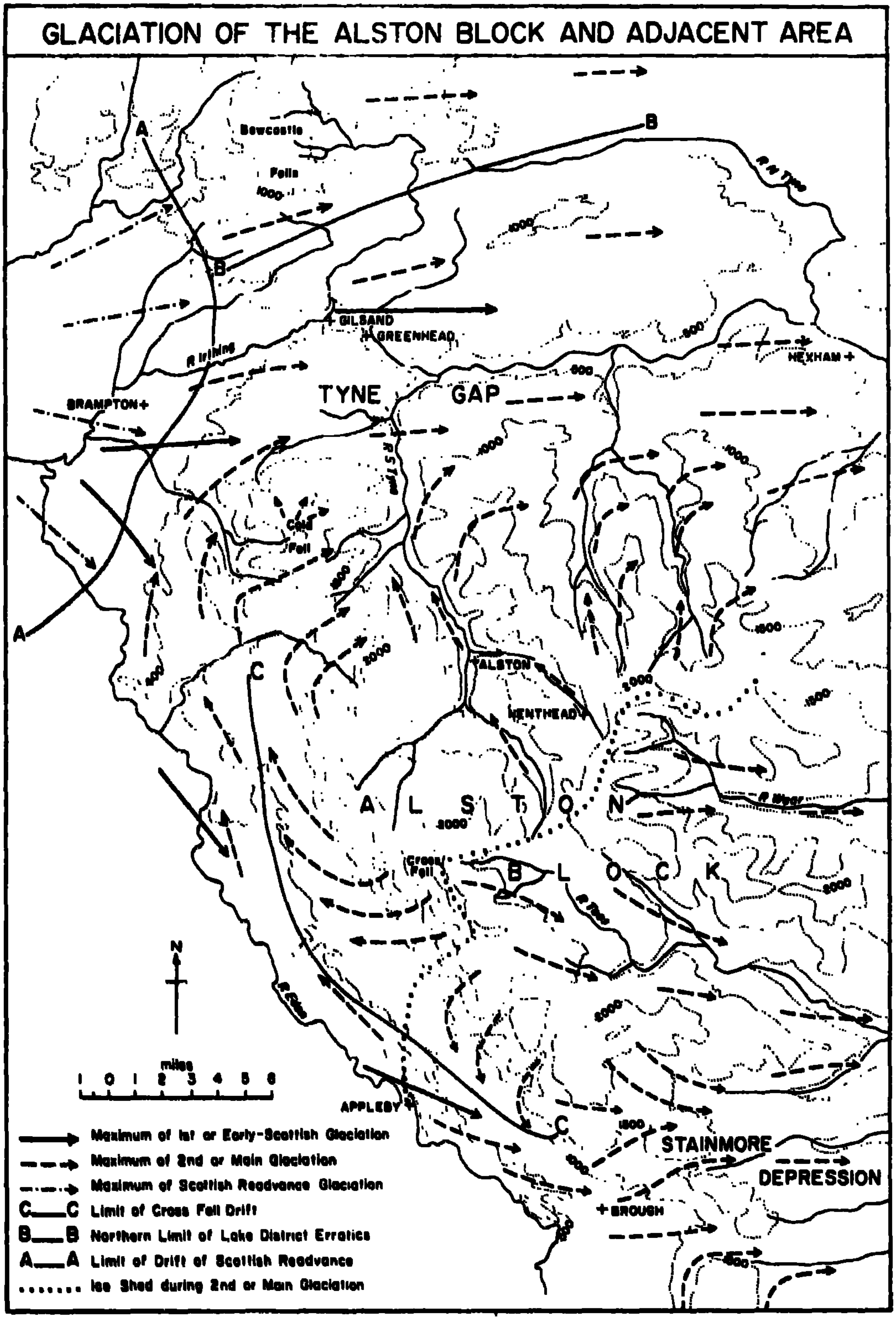

GLACIATION OF THE ALSTON BLOCK AND ADJACENT AREA
Bewcastle
Fells
BRAMPTON+
R Irthing
GILSAND
GREENHEAD
HEXHAM +
TYNE GAP
R S Tyne
R N Tyne
Cold Fell
ALSTON
NENTHEAD
A L S T O N
B L O C K
Cross Fell
R Wear
R Tees
R Eden
APPLEBY
STAINMORE
DEPRESSION
+ BROUGH
N
miles
1 0 1 2 3 4 5 6
Maximum of Ist or Early-Scottish Glaciation
Maximum of 2nd or Main Glaciation
Maximum of Scottish Readvance Glaciation
C—C Limit of Cross Fell Drift
B—B Northern Limit of Lake District Erratics
A—A Limit of Drift of Scottish Readvance
.... Ice Shed during 2nd or Main Glaciation

Figure 11.1

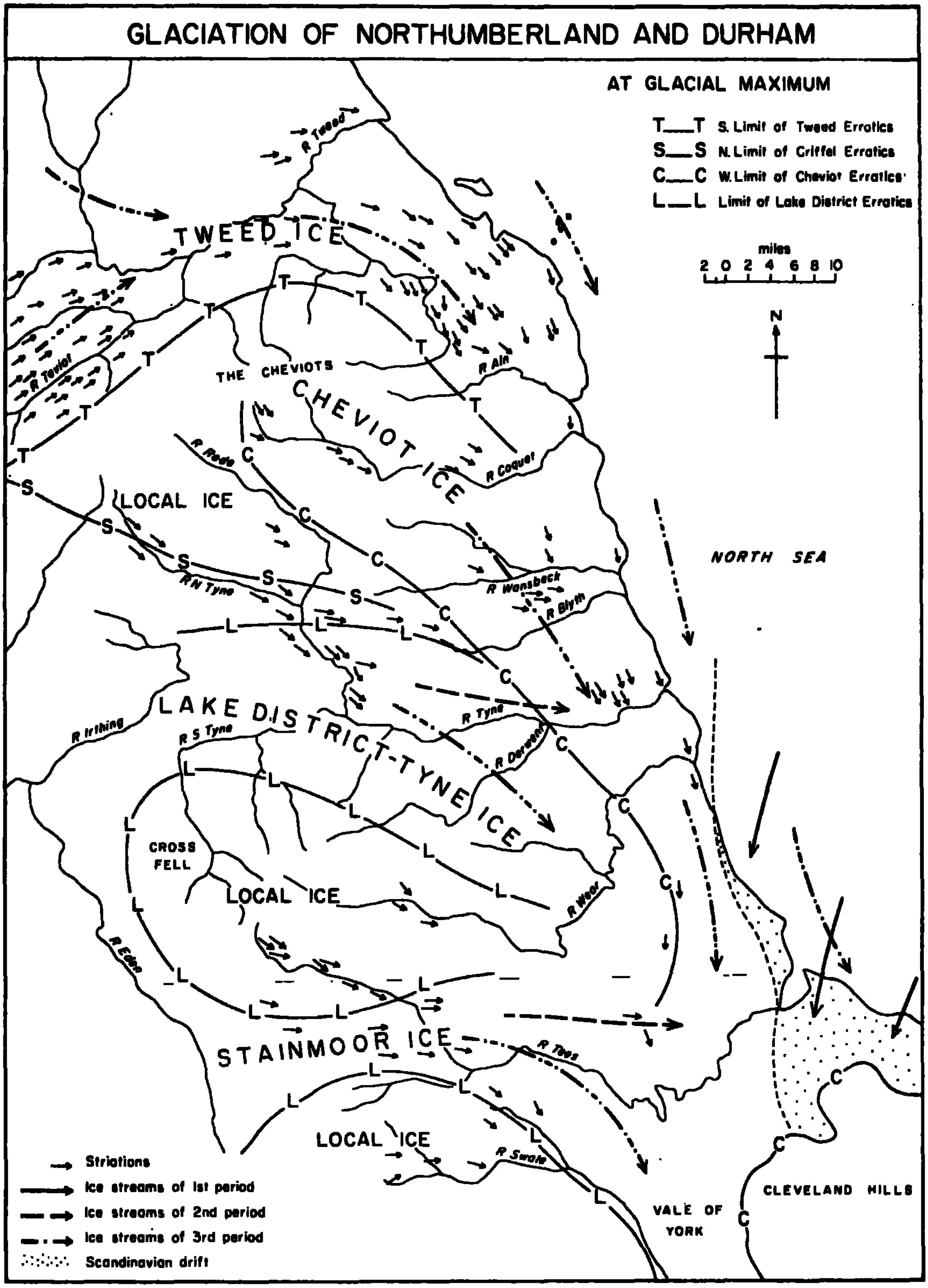

GLACIATION OF NORTHUMBERLAND AND DURHAM
AT GLACIAL MAXIMUM
T—T S. Limit of Tweed Erratics
S—S N. Limit of Criffel Erratics
C—C W. Limit of Cheviot Erratics
L—L Limit of Lake District Erratics
miles
2 0 2 4 6 8 10
N
TWEED ICE
R Tweed
R Teviot
THE CHEVIOTS
CHEVIOT ICE
R Aln
R Coquet
R Rede
LOCAL ICE
NORTH SEA
R N Tyne
R Wansbeck
R Blyth
LAKE DISTRICT-TYNE ICE
R Irthing
R S Tyne
R Tyne
R Derwent
CROSS FELL
LOCAL ICE
R Wear
R Eden
STAINMOOR ICE
R Tees
LOCAL ICE
R Swale
VALE OF YORK
CLEVELAND HILLS
Striations
Ice streams of 1st period
Ice streams of 2nd period
Ice streams of 3rd period
Scandinavian drift

Figure 11.2

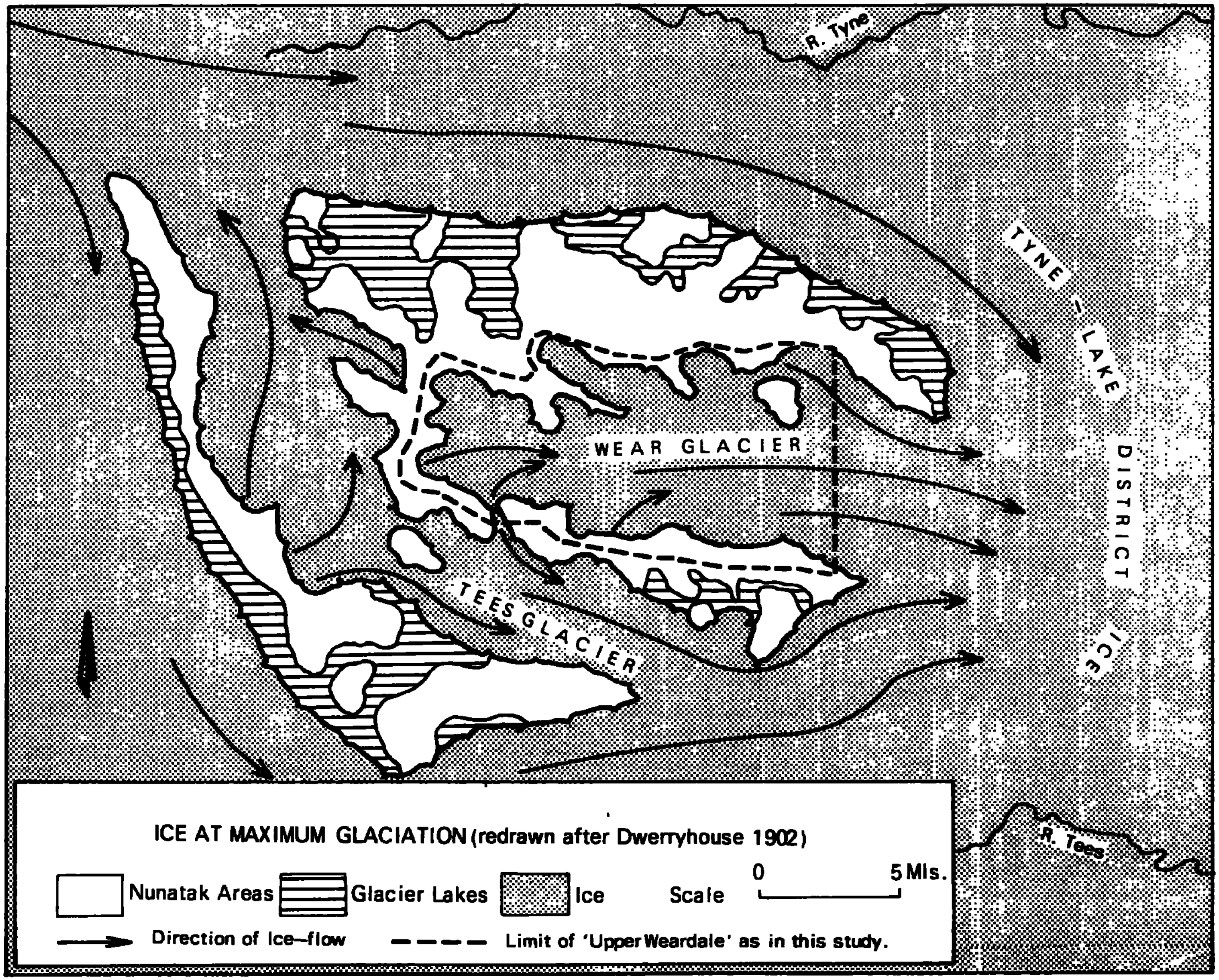

R. Tyne
TYNE - LAKE DISTRICT ICE
WEAR GLACIER
TEES GLACIER
R. Tees
ICE AT MAXIMUM GLACIATION (redrawn after Dwerryhouse 1902)
Nunatak Areas
Glacier Lakes
Ice
Scale
0
5 Mls.
Direction of Ice-flow
Limit of 'Upper Weardale' as in this study.

Figure 11.3

ice from the west poured through the Tyne Gap causing an eastward deflection of the local ice in the South Tyne valley. This ice fused into a major glacier occupying the valley of the Tyne, and ponding ice-dammed lakes in the north facing valleys of the Tyne-Wear watershed. It is the meltwaters from these lakes that subsequently cut the meltwater channels discussed by Peel (1949, 1956) and Vincent (1969). This view does not allow that the higher areas of the Tyne-Wear watershed were ever overridden by ice during the last glaciation. Dwerryhouse in his "Map of the Glaciers and Glacier-dammed Lakes in the Teesdale, Weardale and Tynedale areas" (Dwerryhouse, 1902, plate XXIX) clearly defines these higher areas of the watershed as "nunatakkr".

To the south Dwerryhouse envisages a comparable situation in which ice from Edenside moved through the Stainmore syncline to merge with ice moving south in the valley of Harwood Beck. This ice mass then occupied the Tees valley and was presumed to have entered the lower part of Weardale by overriding the watershed in the area of Bedburn Beck. Again Dwerryhouse envisages no ice overriding large areas of the Wear-Tees watershed and a series of ice dammed lakes ponded against the watershed on the south side. Dwerryhouse does allow that ice occupied the col at the head of Ireshopeburn but no clear statement of direction of ice movement is made. Goodchild (1875) suggests higher limits for the ice in the Eden valley (2200-2400' O.D.) and this is reflected in the work of Raistack (1932) who describes nunatak areas very much smaller than those suggested by Dwerryhouse. The map of this area at "an early stage of glacial retreat" as presented by Raistack is redrawn as

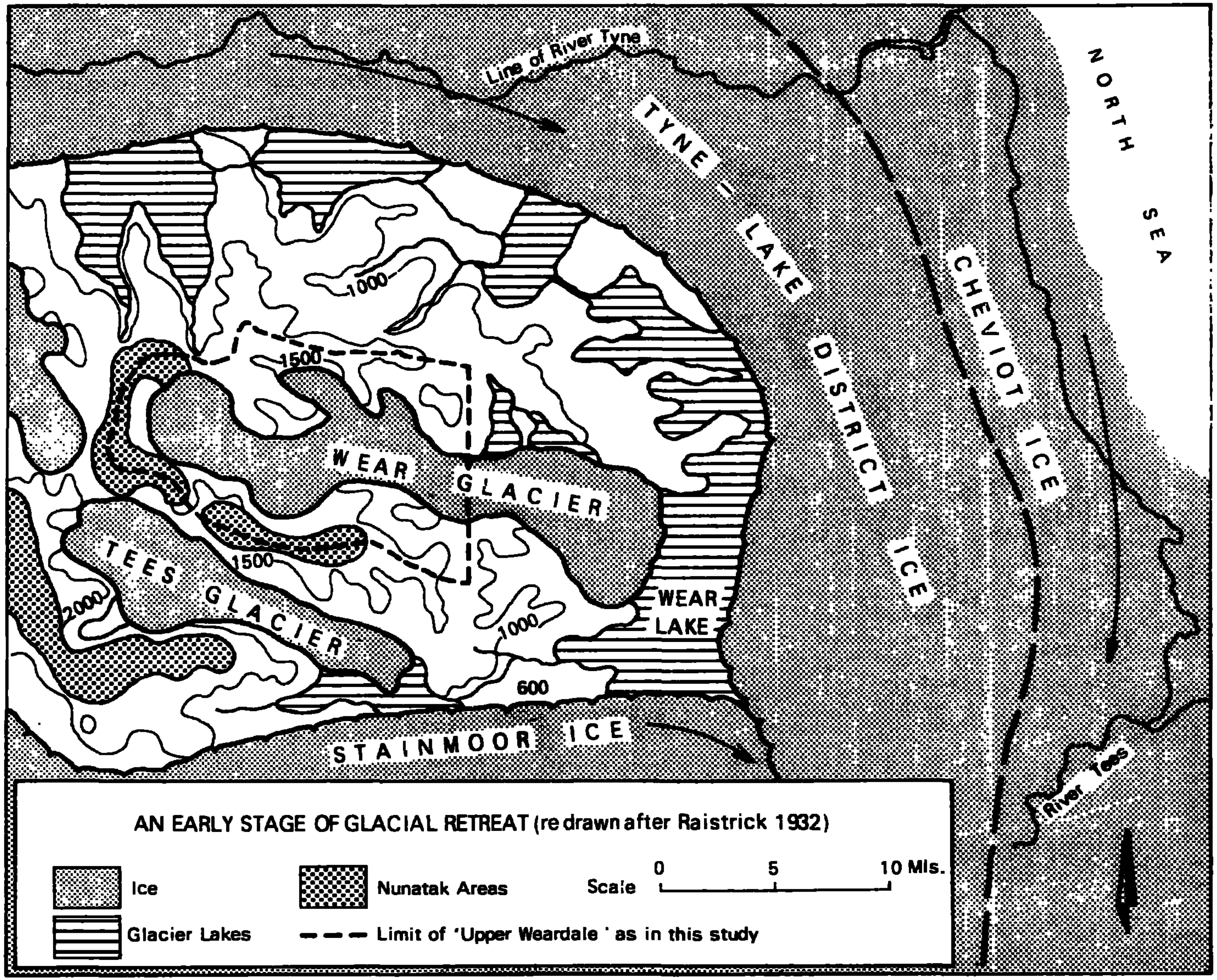
Figure 11.4. It is presumed by all writers that the evidence is only that of the last glaciation. Indeed there is no basis on which to reject this presumption as no absolute dating of the glacial deposits in the Alston Block has been accomplished in spite of the claims of Lewis (1904) who described an "interglacial peat deposit". Godwin and Clapham (1951) reexamined and rejected this claim.

Table 11.1 presents the correlation table of glacial deposits in the north of England as proposed by Trotter and Hollingworth (1932). Of these glacial episodes we may conclude only that the fourth glacial episode is the one in which the till of Weardale was given its present character and distribution. Raistrick (1931) comments on this and expands the available information into a regional study of glacial action which is summarised in Figure 11.2. The following year his discussion of ice-free areas in the Pennines during maximum glaciation provided the concept illustrated by Figure 11.4 showing only limited ice-free areas at the head of Weardale, and on Cross Fell and Mickle Fell.

Trotter suggested that local glaciers in the Tyne valley severed themselves from the main mass of ice flowing through the Tyne Gap and retreated up valley. This same concept is implicit in Raistrick's map presented as Figure 11.4 showing a local "Wear glacier" in splendid isolation occupying the area designated for this study as Upper Weardale.

11.2 Deposits in Upper Weardale

Maling (1955) discusses the retreat of the Wear glacier and the deposits of Weardale in some detail. His conclusions are interesting



Line of River Tyne
NORTH SEA
TYNE – LAKE DISTRICT ICE
CHEVIOT ICE
WEAR GLACIER
TEES GLACIER
WEAR LAKE
STAINMOOR ICE
River Tees
1000
1500
1500
2000
1000
600
AN EARLY STAGE OF GLACIAL RETREAT (re drawn after Raistrick 1932)
Ice
Nunatak Areas
Scale 0 5 10 Mls.
Glacier Lakes
Limit of 'Upper Weardale' as in this study

Figure 11.4

TABLE 11.1

TABLE SHOWING THE CORRELATION OF THE GLACIAL DEPOSITS IN THE NORTH OF ENGLAND

(after Trotter and Hollingworth 1932)

	WEST		EAST	
	Southern Part of the Irish Sea Basin	Lake District and the Solway Firth	Northumberland and Durham	Yorkshire
FIFTH GLACIAL EPISODE		Retreat Phenomena: lakes, channels, sands and gravels, and laminated clays Scottish Readvance Boulder Clay	Not represented	Not represented
FOURTH GLACIAL EPISODE	?Upper Boulder-Clay of Liverpool district	Retreat Phenomena: lakes, channels, sands and gravels, and laminated clays, (=Middle Sands of Carlisle). Boulder-clay of Lake District-Edenside Maximum and N.Pennines	Retreat Phenomena: lakes, channels, sands and gravels Prismatic Boulder-Clay Cheviot and Scottish Ice with Western Ice in the west	Retreat Phenomena: lakes, channels, sands and gravels Hessle Clay and its inland equivalents
THIRD GLACIAL EPISODE	Middle Sands and Gravels ?Lower Boulder-Clay of Liverpool district	Gravels and laminated clays Boulder-clay of "Early Scottish Glaciation" (including Lake District Ice).	Gravels and laminated clays Boulder-clay of Western Ice	Gravels etc. Upper Purple Clay
SECOND GLACIAL EPISODE		?Weathered Boulder clay of Upper Caldew Valley	Gravels Boulder-clay of Scottish and Western Ice	Gravels Lower Purple Clay
FIRST GLACIAL EPISODE	Represented Farther south		Loess Scandinavian Clay	Basement (Scandinavian) Clay

in that they represent the product of a field investigation which is used to supplement a morphological analysis. The observations are, therefore, subjective but valuable as a considered opinion in the light of morphometric analyses of the area.

In his remarks about the part of the Wear valley which corresponds to "Upper Weardale" in this study Maling makes several important comments on the nature of the superficial clays. He states:

> "The ... (boulder clay) ... can certainly be attributed to deposition by an active glacier; the ... (other superficial clays) ... may be glacial deposits which have remained in situ or which have been much altered by weathering. On the other hand, these clays may be peri-glacial deposits formed by the comminution of material below and around snow-drifts and which have later been transported by solifluction or soil-creep. It is possible, also, that certain of these clays have been formed in situ by the deep weathering of the bedrock, in those areas where shales predominate, just as, in the Millstone Grit uplands, deep weathering has often reduced the grit to a coarse sand which may be four or six feet thick". (Maling, 1955, pp. 87-88).

The present author considers the evidence from the Q mode factor analysis presented in this thesis to be a major contribution to the better understanding of these deposits. In particular the consideration of interrelated factor influences in Chapters 10 and 11 would seem to offer a great deal of clarification to the situation described by Maling:

> "The clays are so variable in texture, composition and distribution that it is difficult to generalise or formulate adequate definition of the different types of material. It is, however, possible to express the belief that true boulder clay is less extensive than has hitherto been supposed."
> (Maling, 1955, p. 88).

The present author believes that Maling's concept of different types of material is erroneous. As demonstrated in Chapters 7 and 8 above, the results obtained from data analysis suggest four major genetic influences which can be detected in an otherwise continuous area of texture type. The complete interrelationship of the set of factors, revealed in Chapter 7 tends to further support this concept of a suite of closely related deposits. It is therefore not surprising that Maling found difficulty in formulating adequate definitions of the different types of material.

Dangers inherent in the field classification of texture were noted by Young (1965) and further exemplified above in the comparison of texture zones on the sand-silt-clay diagrams based on field classification. Maling himself provides excellent illustration of the problems of field classification with his statements:

> "On the higher hills of Weardale, clay may be recognised at considerable altitudes. Some clay may exist below the peat right to the summit of the moors. Examination of this clay has shown that it is often sandy in texture." (Maling, 1965, p. 88).

Also illustrating the point is Maling's definition of true boulder clay as

> "a stiff clay which contains proven foreign erratics or local rocks which are smooth and striated. This definition is sufficiently loose to cover the local variations in composition and texture but maintains the essential criterion of transport by moving ice. The other clays may approximate to boulder clay in texture, but they are either devoid of erratics or, if stones are present, these are often sub-angular and do not show recognisable striae". (Maling, 1955, p. 88).

Such a definition of boulder clay is considered to represent the traditional use of field classification of a deposit as presented in Figure 5.1 above. The terminology contains imprecisely defined genetic implications. Is boulder-clay necessarily transported by ice? If so what is the minimum distance of transport which is required? Should such a deposit be legitimately divorced from glacially processed bedrock remaining close to its original location (as in Vincent's model of ice action in watershed areas see Figure 4.1 above). In a situation such as that obtaining in Upper Weardale these points become of vital importance.

Raistrick's suggestion (1931, 1933) that certain of the deeply weathered upland clays of the Pennines represent the drifts of an early glaciation reflect at least the fact that these clays may be considered as glacial in origin. Maling's objection to this interpretation is stated as follows:

> "This view cannot be supported from field evidence in Weardale, for it is not possible to show, anywhere, that the true boulder clay overlies an older drift. Indeed, in many places, it can be seen that the sandy clay overlies true boulder clay. It can be argued, however, that the sandy clay (sic) irrespective of its origin, has been deposited upon the true glacial drift by later solifluction, soil-creep or land-slip."
> (Maling, 1955, p. 88).

The present author considers that the techniques employed in this thesis and the influences which emerge from an assessment of the factors generated, clearly indicate the action of solifluction (including gelifluction, hillslope processes and regolith formation). The techniques also imply that glacial processing of the deposits in Upper Weardale is widespread. They do not define a deposit which is specifically "glacial till" or "boulder-clay" as Maling uses the term. However, the results do indicate the degree of association of all deposits with Factor 1. That the properties of samples which are primarily associated with Factor 1 also have relationships which are observed elsewhere as relationships holding true for deposits of till seems to indicate that this group are primarily influenced by glacial processing.

Such a classification does not proclude the influence of other processes, nor does it exclude the possibility of other deposits having a subsidiary influence of glacial process. Therefore whilst the author takes exception to some of Maling's concepts his overall view of the deposits is considered to be correct. If this overall view is itself considered in the light of the polygenetic effects of the system postulated above (a result of detailed data analysis) it can be of greater value in understanding the morphological history of Upper Weardale.

This discussion reveals that, whilst Maling provides an accurate description of the deposits, his use of genetic terminology provides an unfortunate block to the full understanding of the importance of the deposits he describes. Thus his conclusion, summarised by Vincent is somewhat misleading.

> "... Maling suggested that true boulder clay was less extensive than was formerly thought, and that many of the superficial clays of the area were the products of in situ weathering or periglacial erosion".
>
> (Vincent, 1969, p. 43)

It is the opinion of the present author that an investigation of the suite of deposits present, rather than a quest for "true boulder clay" is a more appropriate and rewarding research aim. Concern with the detailed definition and description of a field classification terminology is ultimately misleading.

11.3 Conditions at Maximum Glaciation

Vincent's work in the N.W. Alston Block has led him to conclude that ice free areas did not exist (Vincent, 1967, p. 311). This conclusion has far reaching implications as it means that the arguments offered by Maling for his interpretation of the upland clays and the conclusions reached by Dwerryhouse and Raistrick must necessarily be re-appraised in the Weardale context. Vincent's conclusion that ice movement in the lower East Allen Dale was in a south-easterly direction is particularly important. This concept was developed from an examination of stone orientations and led to Vincent's model of ice overriding the watershed as illustrated in Figure 4.1 above. The movement of ice in West Allendale is also concluded to have been from the north-west and this is based on the evidence of stone counts, stone orientation, melt-water channel orientations and the general direction of linear trend surfaces.

In the present study the author has considered the nature of Factor 1 and concluded that it represents glacial influence. This conclusion is based on the similarity between the properties of the sample in which Factor 1 is dominant and published clay till analyses. That the trend of Factor 1 values across Upper Weardale should so closely correspond to the trend of Vincent's linear surfaces (of erratic content and mineralogy of the tills) is considered to be a significant pointer to the conclusion that a major ice-mass moved across the region from the north-west and over-rode the Wear-Tyne watershed. The present author is therefore of the opinion that the watershed areas of the Tyne-Wear and Tees-Wear were over-ridden by ice during the last major glaciation.

The interpretation of the deposits developed in Chapter 10 is also in agreement with this result and clearly indicates ice processed material in locations close to the watershed. Figure 10.3 illustrates this and shows that the dominance of Factor 1 extends to the watershed in the region of East Allen Dale. A further indication that ice movement from the north-west was a major influence can be deduced from the distribution of till shown on the Alston map of the Geology series of Great Britain (sheet no. 25). Across the map area including the valleys of the Upper Tees, South Tyne, Harwood Beck and Wear, the north-west facing slopes are drift-free, the south-east facing slopes are drift-covered. This appears to be a result of the situation envisaged by Vincent in his model of ice movement in areas of strong relief control.

The shear zone shown in his model (see Figure 4.1 above) is clearly devoid of glacial debris (Vincent, 1969, p. 287) and applying his concept to a regional ice cover moving from the north-west, the shear zones would occur in locations corresponding to the north-west facing steeper slopes. In Weardale itself the resulting deflection of ice movement would give basal movement in the ice sheet in an easterly (down valley direction) which is the direction confirmed by stone orientations taken in the till of the valley floor (see Chapter 10.4). This clearly is the consideration of conditions at the time of maximum glaciation and the deglaciation stages must be considered below.

11.4 Deglacierization of Upper Weardale

Again Vincent concludes that at some stage ice moving across the Pennines from Edenside became less powerful and Cross Fell became a focal point from which ice streams radiated out (Vincent, 1969, pp. 305-306). Calculations of ice gradients are advanced which seem to conclusively support this hypothesis. However, it is the concern of this work to establish the sequence of events in Upper Weardale.

Because exotic erratics have not been found in Upper Weardale (Dwerryhouse 1902, Maling 1955, Atkinson 1968) (and the present author similarly found no extra-regional erratics) there appears to be no great significance in the decline of the ice mentioned above. A mechanism by which the major ice movement from the north-west submerged the Wear watershed but did not contribute foreign erratics has been considered and found to be acceptable within the available evidence. A change to a centre of ice dispersal located on Cross Fell would not radically alter the established pattern. Ice flowing eastwards from Cross Fell could still move into Weardale from the west and not bring about any change in the situation already described.

At later stages of deglacierization however it is pertinent to consider ice dispersal in more detail. Inevitably the wasting ice mass would be segmented as its surface fell below the level of the watersheds. At such time basal meltwater would be moving within and beneath the major ice mass. In Weardale drainage along the west-east valley would not be impeded by structure and so extensive deposits of lake clays or waterlain materials are unlikely to have been significant. In any case deposits in this region would be annually reworked by periglacial processes at such a time. This combination of effects could account for the observed peculiarities in the stratigraphic location of deposits dominated by Factor 2.

This latter group of deposits was tentatively designated as rainwashed hillslope material. In the conclusion to Chapter 10 it was noted that they correlate also with some of the meltwater washed deposits sampled in S.E. Iceland. This fact was considered to be an indication that Factor 2 deposits overlain by till could represent meltwater washed deposits subsequently buried by till as the basal ice melted and freed layers of till from within it.

Discussion contained in Maling's thesis (Chapter 9) is very useful in a consideration of the detail of deglacierization. If his general assertion that "The complete isolation of the Weardale glacier has been confirmed by the present research" (Maling, 1955, p. 115) is considered to be correct only for the time of ice dispersal, then he raises several useful points. He states

> " ... there are virtually no fluvio-glacial deposits in Weardale, certainly none which could correspond with an esker. The notion that abundant meltwater was present in Weardale throughout the glacial maximum cannot therefore be accepted."
> (Maling, 1955, p. 115).

This observation is fully endorsed by the present study. The present author did not discover any major deposits of glacio-fluvial material during this investigation. The lack of retreat features in Weardale especially the notable absence of terminal moraine is also commented upon by Atkinson (1968) and Maling (1955).

Because of his acceptance of the idea that the Weardale glacier was isolated from regional ice movement Maling is left only with the analysis of a closed system. He therefore has to account for the features of Weardale and yet have the sequence of accumulation zone, trunk glacier and terminus all within the relatively small region within the Wear watershed. From the inception of this study the present author was totally unable to envisage the head of Weardale acting as a neve field sufficiently large to support a trunk glacier some 20 miles or more in length and yet unconnected with ice masses in immediately adjacent valleys.

Maling does, however, consider Weardale in this way and states

> "It is reasonable to suppose that a glacier with such a limited neve would respond more rapidly to climatic amelioration than the lowland ice-sheets. Consequently the Weardale glaciers (sic) might show signs of retreat before there was notable diminution in the size and thickness of the lowland ice. The retreat in Weardale may have been upstream, as Dwerryhouse (1902) supposed. Alternatively, the glacier may have retreated downstream, as Carruthers (1946) has suggested. The reason for supposing the latter is that there are no recognisable terminal moraines which might indicate pauses in the headward retreat of a diminishing valley glacier".
> (Maling, 1955, p. 115).

The present author whilst endorsing the observations on which this reasoning is based suggests that if the ice occupying Weardale was formerly a part of a regional ice cover, the waning of the ice cover would lead to the increasing stagnation of the ice mass. As the Weardale watershed emerged above the surface of this ice mass the ice in the valley itself would not have a continued source of supply. This is not necessarily a situation in which large volumes of meltwater would be produced. The presence of active ice in the adjacent valleys to the north (giving the patterns described by Vincent for the later stages of deglaciation in the N.W. Alston Block) would suggest that the climate would still be harsh.

The ice, finally isolated in Weardale would therefore be subject to active ablation from the surface directly into the atmosphere. The duration of this process would have been considerable. It would certainly extend through the time required for the active ice in the adjacent valleys to stagnate and for the Cross Fell ice-cap to begin to disperse. It could well be that ablation was the major mechanism by which the Weardale ice diminished leaving only a minimum of ice to provide meltwater and to rework the suite of deposits it left behind.

It is, of course, most probable that undermelt also took place. This concept propounded by Carruthers in his monograph is particularly interesting and could be the mechanism by which many of the deposits in Upper Weardale obtained their stratigraphic characteristics. In this context the Factor 2 or water-washed deposits occurring between layers of till may have been washed by 'undermelt melt-water'. The author does not consider a detailed evaluation of Carruthers' concept is pertinent to the study, but it is perfectly in accord with the deposit sequence revealed in this study at the various sites sampled. Carruthers' (1953) monograph is very valuable in that it calls attention to the general assumption that a complex stratigraphy is the product of a complex of processes acting individually through time. That this is not always so is clearly demonstrated by some of the examples he cites.

The present author has observed lenses of glacial detritus within blocks of glacier ice detatched from the active glacier. Such features have been commonly observed by detailed investigations of ice front conditions in the time since Carruthers published his work. The recent paper by Price (1969) makes reference to much of this work and indicates the significance of englacial debris in deposit genesis. It seems that Carruthers concept may ultimately become widely accepted, although probably not in its extreme monoglacial form.

11.5 Diagenesis

The full study of diagenetic effects is beyond the scope of the present work. It is necessary to consider the implications of these effects and the latter stages of the formation of the deposits in Upper Weardale, although much of this consideration is necessarily speculative.

Evidence of the nature of Factors 3 and 4 is not conclusive. It must be so because the author was not in a position to do detailed frost-weathering and periglacial studies as they apply to slope detritus and rock decomposition. Consequently their interpretation is also tentative. It does appear that the significance assigned to them is compatible with published work in the areas of regolith analysis (Ragg and Bibby 1966) and of gelifluction processes (Washburn 1967).

Comments on the nature and depth of the upland regolith existing in Weardale have led to speculation that it could be a Tertiary-deep weathering product (Wright 1955). The present author suggests that recent work in frost disintegration process could provide some important indicators for the understanding of the nature of this material.

It has been established above that ice over-rode the Wear-Tyne and Wear-Tees watershed areas. Consequently the rocks in these areas would be subjected to the conditions of the sub-glacial environment. As the ice masses on these watershed areas began to stagnate they would also be undergoing some basal melting. The meltwater, presumably, to some extent clay charged, would therefore be an active agent in rock disintegration as described by Dunn and Hudec (1966), Anderson (1967) and Falconer (1969). The importance of clay-charged water as a major factor in rock decomposition is being increasingly recognised and recent work by Ford (personal communication) indicates that meltwater in Rocky Mountain glaciers is a particularly complex chemical solution which produces distinctive features on calcareous rocks. The significance of this latter work is still to be established but its importance is the Upper Weardale context should not be under-rated.

Percolation of water through the deposits and their reordering by solifluction processes must be significant factors in the creation of the present topography and stratigraphy. Both these processes are considered by Atkinson and indeed, the effects of diagenesis in the deposits of Upper Weardale are more properly the study of the soil scientist. Atkinson's (1968) study of the pedology of this region provides many useful details of these processes which are the real focus of his study, since a major effect of diagenesis in post-glacial times has been the development of soil profiles.

11.6 Dating of the Deposits

The evidence for correlation of the deposits of the Wear valley with those in adjacent region is limited. Beyond the similarity between the Lower Clay of Eastern Durham (as identified by Beaumont 1967) the till of the N.W. Alston Block (as described by Vincent 1969) and the Factor 1 deposit type described here there is little other evidence. The author therefore accepts the conclusion of Vincent (1969) that the till is probably of Weichselian Age. This is based on evidence recently discovered by Catt and cited by Vincent as a personal communication (Vincent, 1969, p. 45) and accepts Catt's correlation of the Lower till of E. County Durham with the Drab Till of Holderness. The observed field similarities between the till of Weardale and the lower till of County Durham, the lithological similarities and apparent stratigraphic continuity are considered sufficient evidence that the Lower Till of County Durham correlates with the till of Weardale.

11.7 Conclusions

The import of the foregoing summary serves only to endorse the view that the effect of glaciation was a major influence in the creation of Upper Weardale's superficial deposits. The concepts of subsequent solifluction and periglacial action seem to be amply confirmed by the stratigraphic evidence and the conclusion that ice moved across the whole region from the north-west seems both appropriate and logical if the evidence accumulated here is considered in detail.

Chapter 12

Conclusions

The final conclusions from this work fall naturally into two distinct groups. The first group presented below are conclusions which apply directly to the suite of deposits in Upper Weardale and to the understanding of the development of the geomorphology of Upper Weardale. The second group are those conclusions of a more general nature concerned with methodology and the structure of geomorphological studies. A final section is added which reviews the present work and briefly considers the logical extensions of it.

12.1 Conclusions about the Geomorphology of Upper Weardale

Conclusion 12.11

The most significant conclusion for regional geomorphology studies is that the whole of the watershed areas in Upper Weardale was overridden by ice moving from the north-west at sometime during the glaciation, presumably at the glacial maximum. Evidence for this conclusion is primarily from the results of an analysis of particle size data (by Q-mode factor analysis) which reveals a group of deposits which have the attributes of glacial till. The basis for this grouping, namely a predominate influence of Factor 1, provided a measure (the loading on Factor 1) of this influence across the region. Trend-surface maps of this influence indicate it has a north-west south-east direction. As the influence is considered to be that of glacial action the significant trends produced are therefore construed as a record of glacial influence. The trend detected is in accord with that found by Vincent in his study of the adjacent valleys, East and West Allen Dale and the South Tyne. By extending Vincent's hypothesis of glacial movement in regions of strong relief control, it is shown that the evidence accumulated here is in complete agreement with this conclusion about ice movement.

Conclusion 12.12

This study reveals that, contrary to the expressed opinions of Maling there is a deposit type (here correlated with glacial action) which is found on and near the watershed between the R. Wear and the R. South Tyne. This deposit type is also found adjacent to the head-waters of the R. East Allen the area studied by Vincent. Vincent detected the influence of ice moving into East Allen Dale from the north-west. That this deposit type should occur in the Wear valley but in such a position as to appear a logical extension of the same influence noted by Vincent is considered to be more than mere chance.

Conclusion 12.13

The results of Q-mode factor analysis provide a description of four major influences on the suite of deposits in Upper Weardale. Examining the characteristics of the groups of deposits which are primarily associated with each of the factors indicates that they have many of the attributes of certain deposits quantitatively expressed in sedimentological and geomorphological literature. The conclusion reached is that Factor 1 dominates the factor loading of a group which display the attributes of till. Factor 1 is therefore considered to be a factor representing glacial influence. Factor 2 has a composition closely resembling that cited as an example of rain-washed hillslope deposit cited in a major work on sedimentation (Twenhofel, 1932). It is tentatively concluded that Factor 2 represents the influence of a water-washed-slope environment. Factor 3 is shown to be dominant in a group of deposits which are sand rich. Further examination of this group reveals that they possess the characteristics of the disintegrating sandstone bedrock frequently encountered in Upper Weardale. Factor 3 is thus tentatively associated with the sub-aerial weathering of bedrock and designated as "sandstone regolith". Factor four samples occupy a texture zone similar to that described by Washburn (1969) in his study of solifluction under permafrost conditions. He uses the term gelifluction for this process and the samples which he finds are most susceptible to gelifluction have many of the characteristics of the group dominated by Factor 4 in this study. Factor 4 is therefore associated with the gelifluction process.

Conclusion 12.14

The results of Q-mode factor analysis tentatively interpreted as above are confirmed by the pattern of correlations between both particle size parameters and other data for each sample. Relationship between elevation, pH, soluble carbonate content and organic content of the deposits and their particle size parameters and factor loadings lead to an understanding of the nature of these deposit types which is fully in agreement with their "classification" by factor analysis. The factor scores indicating the particle sizes which are a major influence on each factor type are also completely in accord with the deductions emerging from the examination of the groups of deposits.

Conclusion 12.15

The confirmation thus given of the action of these various influences in the Weardale landscape is considered especially significant. The action of solifluction and periglacial processes previously suggested by Maling and others is here demonstrated from an analysis of the deposits. Of greater value is the fact that this study provides a measure of the influence of each factor on every deposit sampled. Thus the concept of defining "true boulder-clay" is rendered invalid. Interpretation of the factor loadings permits an assessment of the deposit history in a way previously regarded as impossible. The result of this interpretation (Chapter 10) is valuable as it illustrates the complete interrelationship between the processes acting and reveals that the action of post-glacial processes has partially influenced certain samples. A clearer understanding of the processes acting is produced, and the events can be more precisely evaluated.

Conclusion 12.16

The very close agreement between the particle size parameters for the Factor 1 group (till) in this study and those recorded by Beaumont for the Lower Boulder Clay of E. Durham, and Vincent's local till of the N.W. Alston Block lead to the conclusion that these deposits may be correlated. The precision with which the relationship between mean size and sorting may be stated for each study and the remarkably close values of the coefficient in the regression equations are considered significant evidence in this conclusion. Thus the till of Weardale may be considered to be Weichselian in age if Vincent's conclusions (based on evidence recently discovered by Catt) is accepted.

12.2 Conclusions about Methodology

Conclusion 12.21

The attempt to apply field mapping techniques and thus deposit classification in the field, in areas where the sediments do not fall into clearly distinguishable classes is both futile and misleading. This conclusion is reached on the basis of the evidence presented in Chapters 5, 6 and 7. Nowhere does the field classification of deposits undertaken by the present author adequately represent the variability or the multiple influences on the deposit which are clearly revealed by data analysis. The methodological pitfalls of the more traditional approach in regions where the deposits are not clearly distinguishable are illustrated by a comparison of the flow diagrams contained in Figures 5.1 and 5.2 above. The present author wishes to indicate that the deposits classified in the field were classified on the basis of published descriptions and often in consultation with other field-workers. It is felt that this classification was not intrinsically less valid than any other classification undertaken by fieldworkers in similar regions. The author wishes to indicate that Maling (1955) after presenting field descriptions of deposits, himself implies the inadequacies of the field classification method by making reference to "sandy-clays" with no supporting analysis. Atkinson (1968/59) readily admits these inadequacies of classification in his study of the pedology of this region when he states "It is extremely difficult to map the boundaries of regolith, solifluction deposits and till."

Conclusion 12.22

Purposive sampling is demonstrated to be a biased sampling and cannot therefore be taken as a basis for comments and conclusions about the association of deposits in a region. This conclusion is based on the comparison of purposive and random sample data in Chapters 6 and 7. It must be clearly stated that purposive sample data may be analysed to yield correct and useful results (in this study the results are virtually identical to those of the random sample) but only by taking a statistically valid random sample and comparing the results can this fact be verified. The results yielded by descriptive sediment analysis cannot be construed as descriptive of the sediments of a region if a purposive sample is used, although data analysis of the measured parameters may reveal influences of regional significance.

Conclusion 12.23

Q-mode factor analysis as proposed by Klovan (1966) has been demonstrated here to be a powerful technique in determining depositional processes from grain size distributions. It appears to have particular value in that it permits the assessment of the amount of influence of each factor on any individual sample thus giving a quantitative basis for the evaluation of the polygenetic sediments frequently encountered in Pleistocene geomorphology.

Conclusion 12.24

The objective nature of trend-surface analysis is complementary to the objective nature of Q-mode factor analysis and thus permits an unbiased assessment of the regional trends of the factor influences. This removes much of the speculation frequently involved in geomorphological studies at this point and permits the significance of the trends thus established to be clearly stated. The agreement between the results of this work and those of Vincent's study in the adjacent areas to the north-west can here be stated with some confidence as the results of his trend-surface analysis of till data correspond with the results of the trend-surface analysis of the till factor established here. Had Vincent simply speculated on the apparent nature of these trends, the present author's agreement or disagreement would be immaterial, it would be only a further opinion to be assessed by the reader. That the trend surfaces show such clear agreement of linear trends leaves only the possibility that the techniques are not applicable to the type of data used. There seems to be no basis for this opinion.

Conclusion 12.25

Relationships observed by Vincent and Beaumont in their studies of tills are consistent with the relationships observed for the tills of the present study. Their opinion that tills are not the disorderly sediments (as popularly considered) seems to be fully endorsed by the present study. Further investigation into the nature and process of till genesis is required before any final conclusions about the significance of these relationships may be drawn. The conclusion here is that the demonstrated consistency of some of these relationships is worthy of continued investigation.

12.3 In Retrospect

This project was designed to investigate the superficial deposits of Upper Weardale. It was acknowledged at the inception of the project that this was a vast undertaking and accuracy and completeness have been sacrificed at several levels in order to reduce the study to manageable proportions. It would be a more complete study if more sites had been sampled and more samples taken. It would also be a more complete study if more parameters had been measured for each sample.

The author considers that the value of this work lies in its clear demonstration of the power of data analysis techniques applied to grain-size data and the extension of these results by objective mapping techniques. The time-consuming nature of the laboratory determination of grain-size distribution and the need in this study to consider the detailed results of different groups of these data subjected to factor analysis meant that only few additional parameters could be considered. The author in conclusion, considers that a study of this type can best be undertaken by a research team which is able to subject a single set of samples to detailed mechanical, chemical, mineralogical and lithological examination as well as the detailed examination of the sedimentological properties of the grain-size distribution. Each body of data would then be available for detailed analysis by data processing techniques and the results of each analysis could be compared and synthesised to give a full record of the variability within and between sediment types. That this was not achieved in the present study is a reflection of the time consuming nature of the analyses which have been examined. Because such work has never previously been attempted for a complex terrestial environment of the type encountered in Upper Weardale there were also considerable difficulties of communication and a dearth of other data for detailed comparison. It is hoped that the results of this study will be of value to others studying in such perplexing areas as Upper Weardale.

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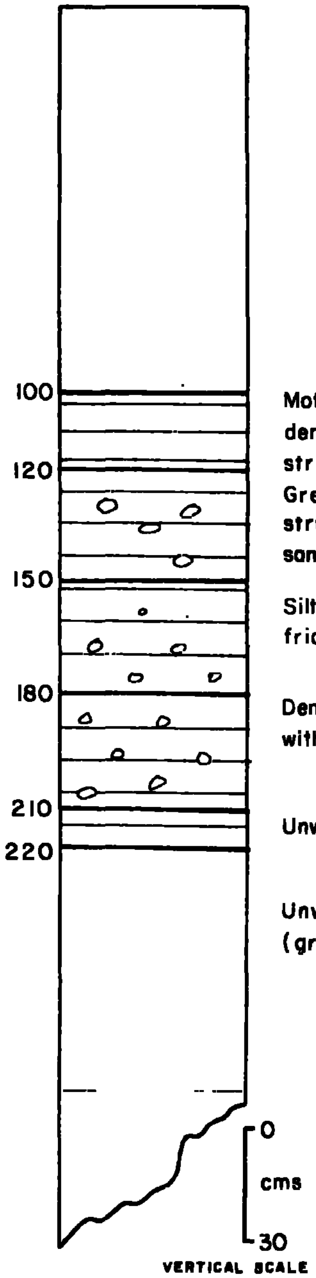
APPENDIX I

Containing field notes and descriptions of each site sampled together with the particle size curves for each sample analysed.

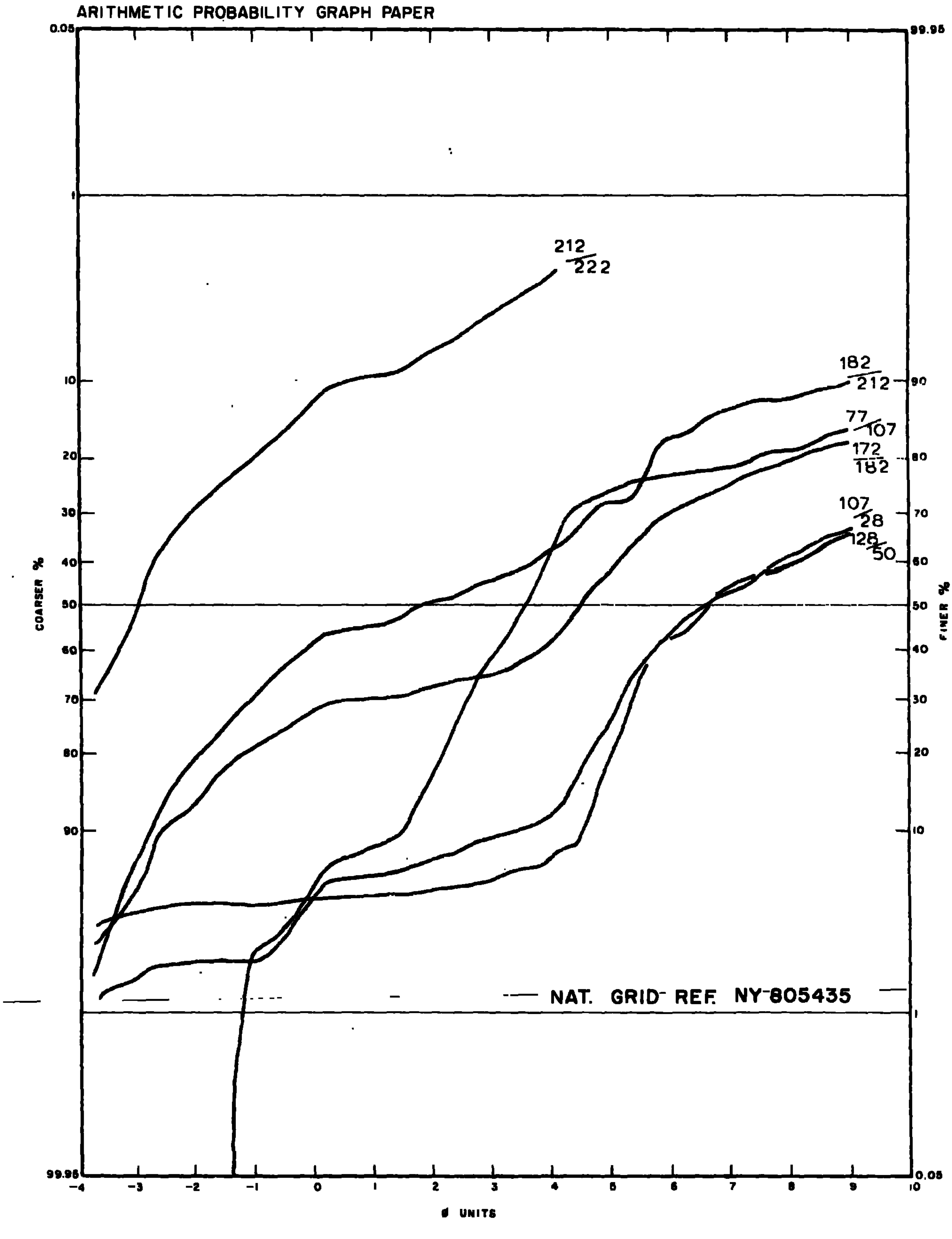
<u>N.B.</u> The "Laboratory data" have been omitted from this appendix and incorporated into the text as tables of particle-size data.

NAT GRID REF NY 805435

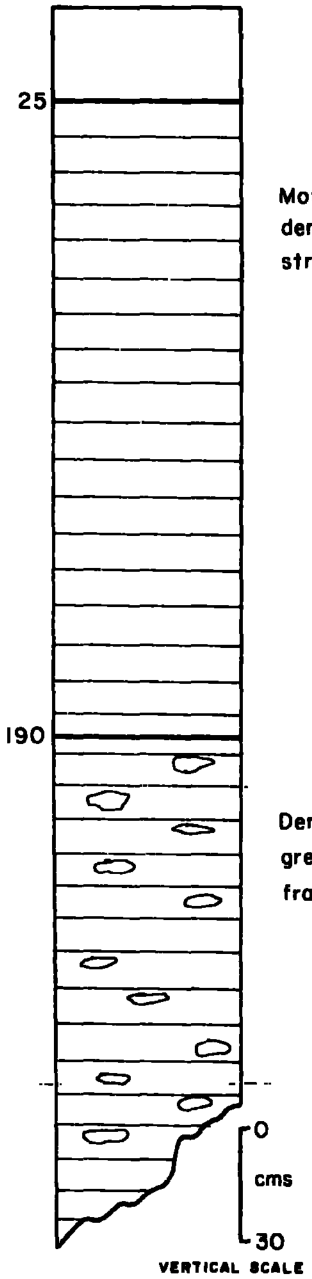
PROFILE

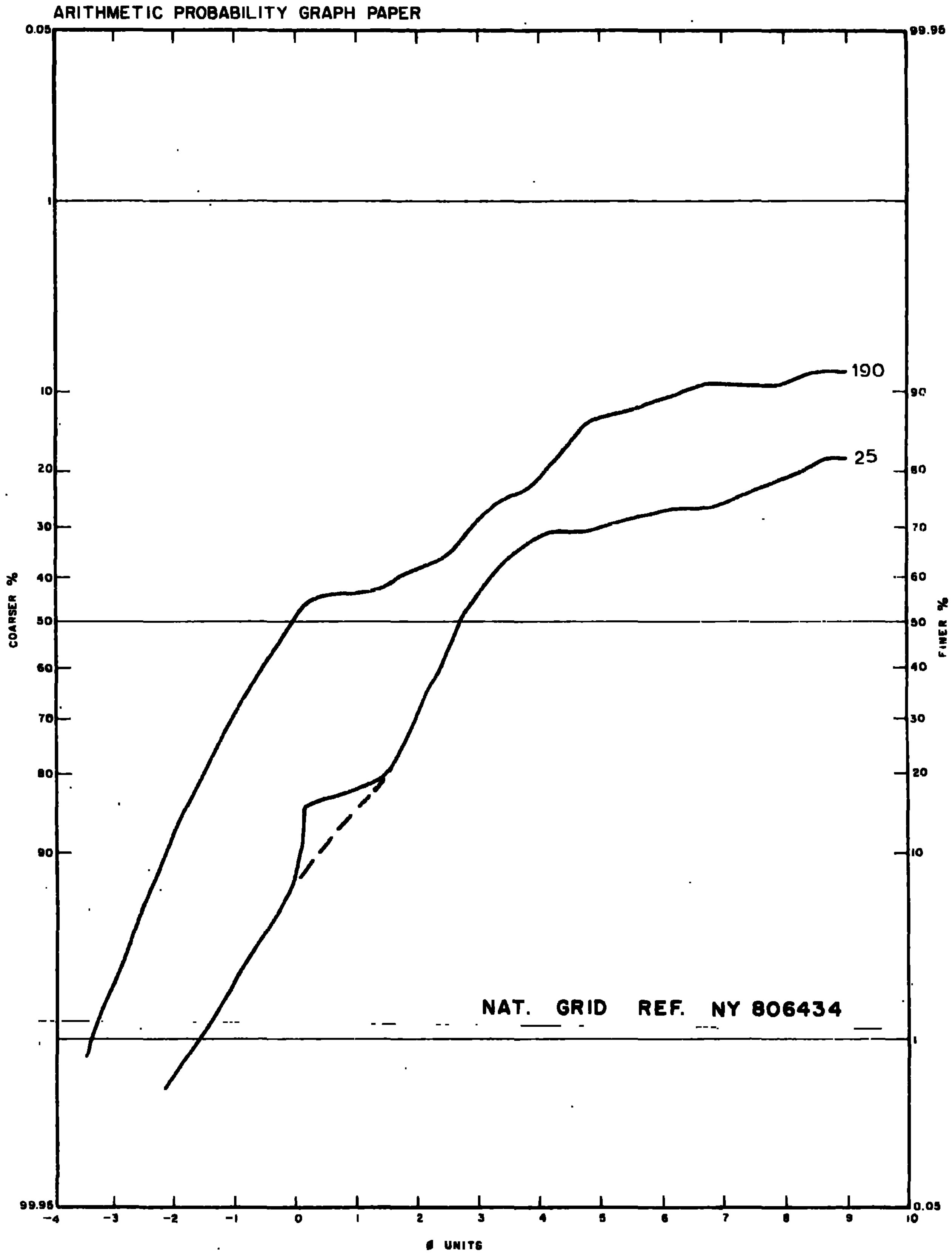


FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
Mottled olive-khaki clay dense, prismatic structure		3 (.6113)
Grey clay, large prismatic structure, pockets of sandy material.		1 (.9612)
Silty blue-grey clay friable, some stones		1 (.9389)
Dense friable grey clay with large sst. fragments		1 (.7476)
Unweathered shale (grey)		2 (.7218)
Unweathered shale (grey)		2 (.8219)


ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
Ø UNITS
212/222
182/212
77/107
172/182
107/28
128/50
NAT. GRID REF. NY 805435
0.05
1
10
20
30
40
50
60
70
80
90
99.95
99.95
90
80
70
60
50
40
30
20
10
1
0.05
−4
−3
−2
−1
0
1
2
3
4
5
6
7
8
9
10

NAT. GRID REF. NY 806434

PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
	Mottled olive clay dense with prismatic structure		3 (.8402)
	Dense friable clay, blue grey colour with shale fragments.		2 (.7466)



ARITHMETIC PROBABILITY GRAPH PAPER
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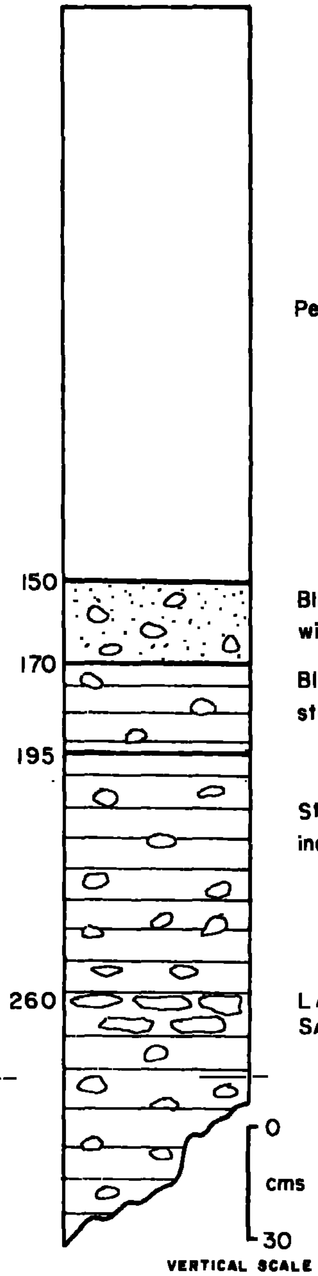
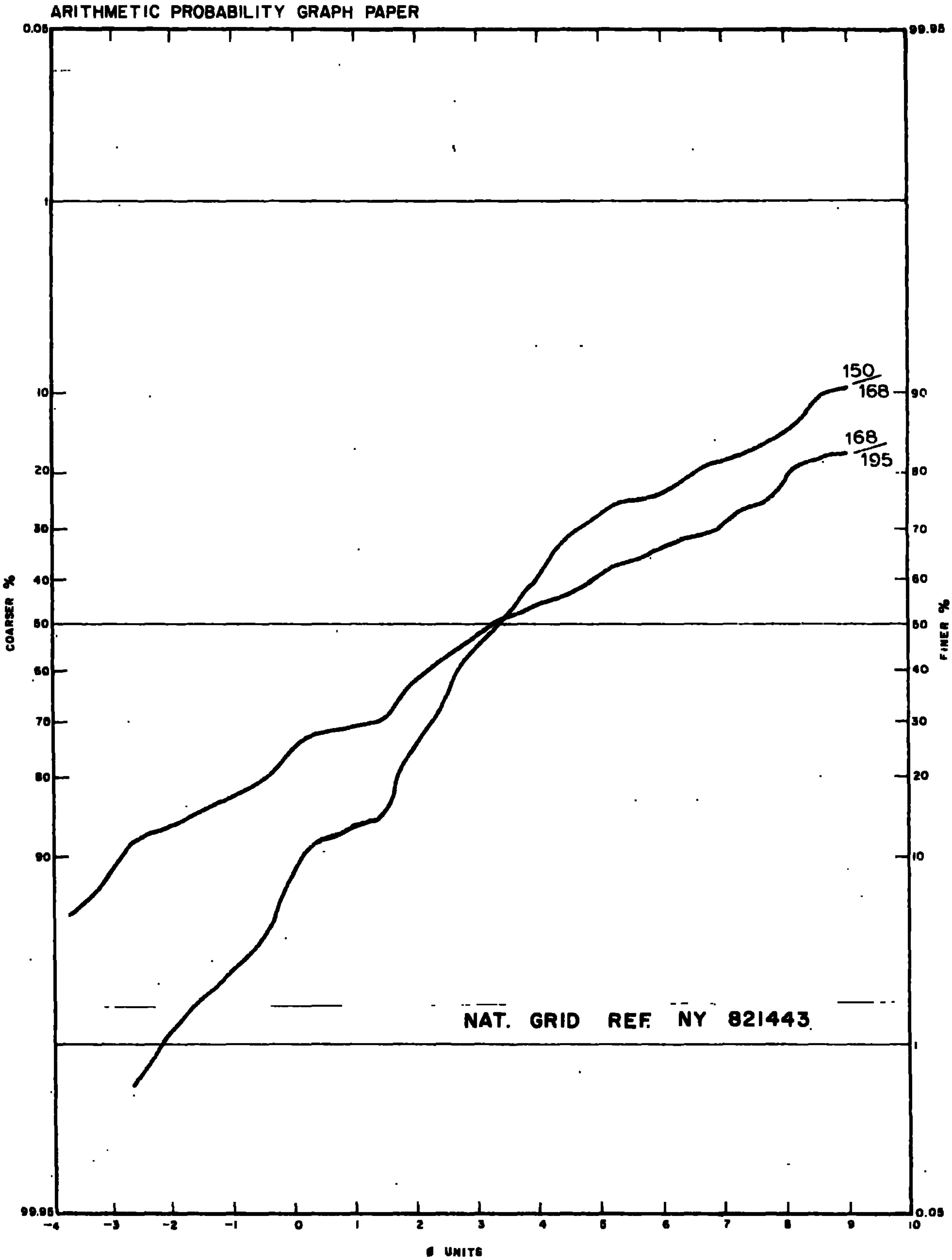
FINER %
190
25
NAT. GRID REF. NY 806434
ø UNITS

NAT. GRID REF. NY 821443



PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
	Peat		
150	Blue grey coarse silt with decomposing pebbles		3 (.6843)
170	Blue grey clay with few stones		
195	Stony blue grey clay including sst., sh.		1(.7138)
260	LAYER OF PLATY SANDSTONE		


ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
Ø UNITS
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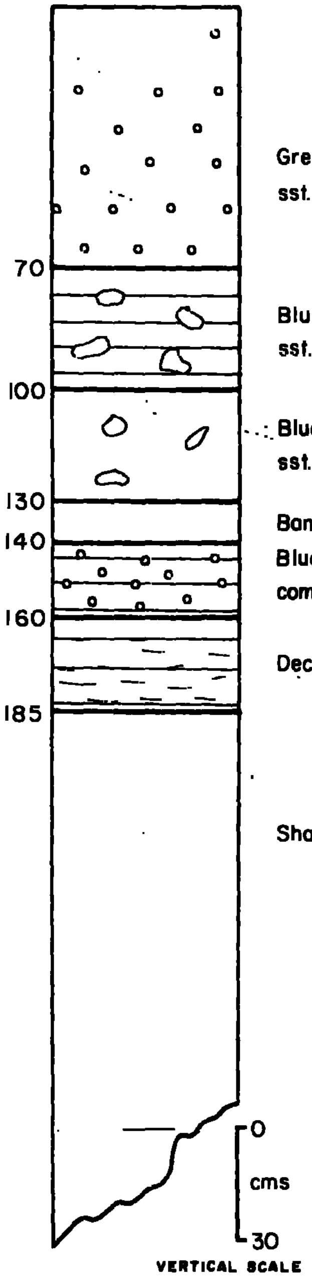
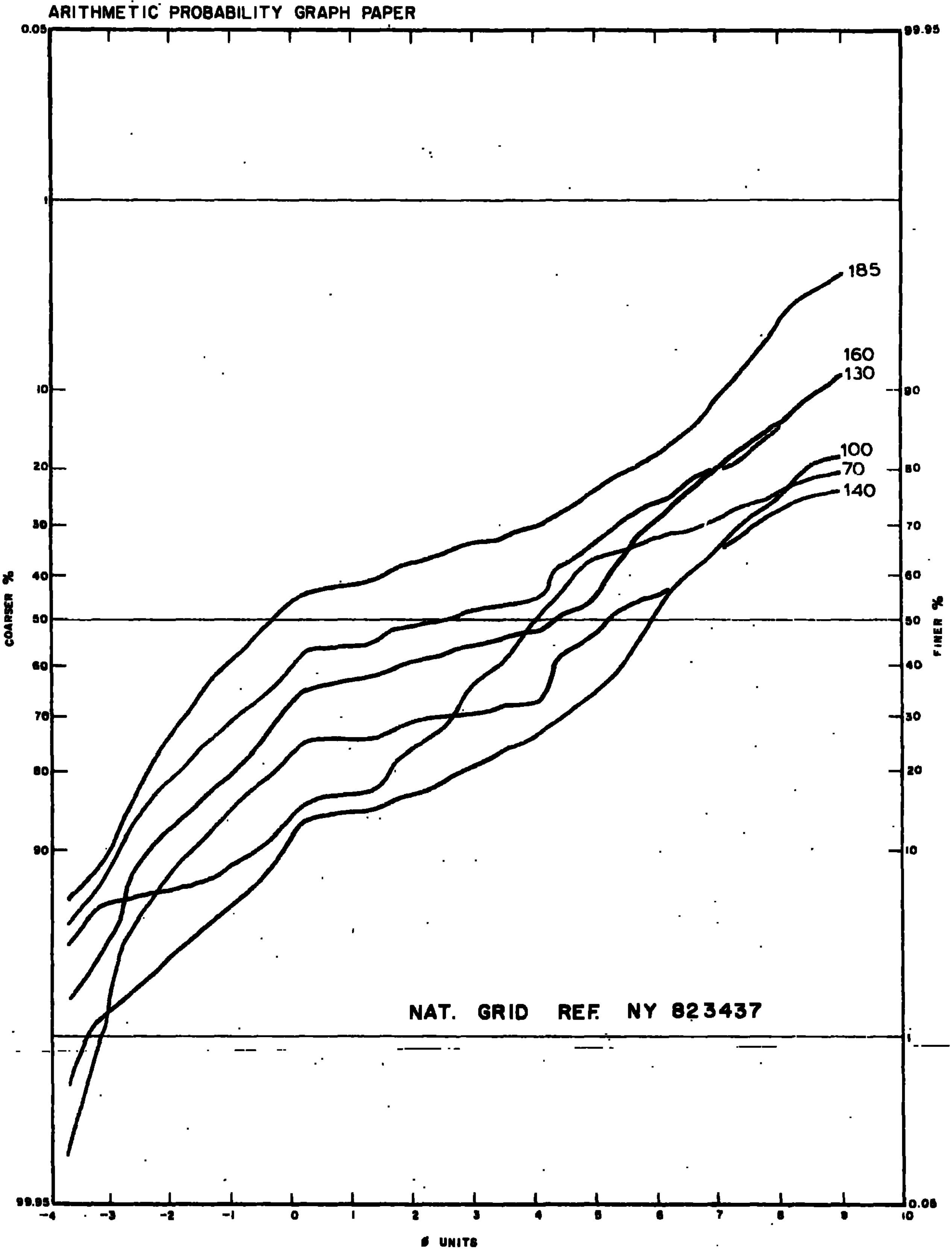
99.95
1
10
20
30
40
50
60
70
80
90
99
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
150/168
168/195
NAT. GRID REF. NY 821443

NAT. GRID REF. NY 823437



PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
0–70	Grey sandy soil with sst. fragments.		
70–100	Bluish stony clay with sst.		1 (.7108)
100–130	Blue grey clay with sst., sh., qzite.		1 (.8828)
130–140	Band of iron staining		1 (.6325)
140–160	Blue grey clay, dense compact with small stones.		1 (.8623)
160–185	Decomposed shale		2 (.7434)
185–	Shale		2 (.8834)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1
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40
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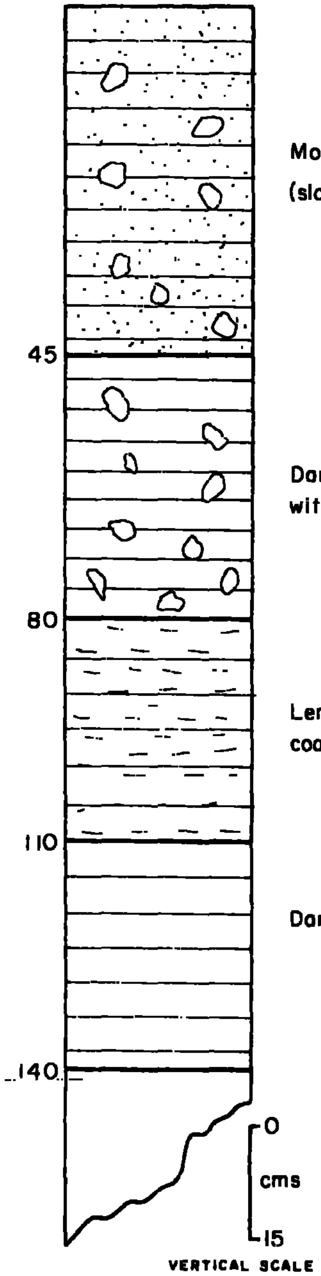
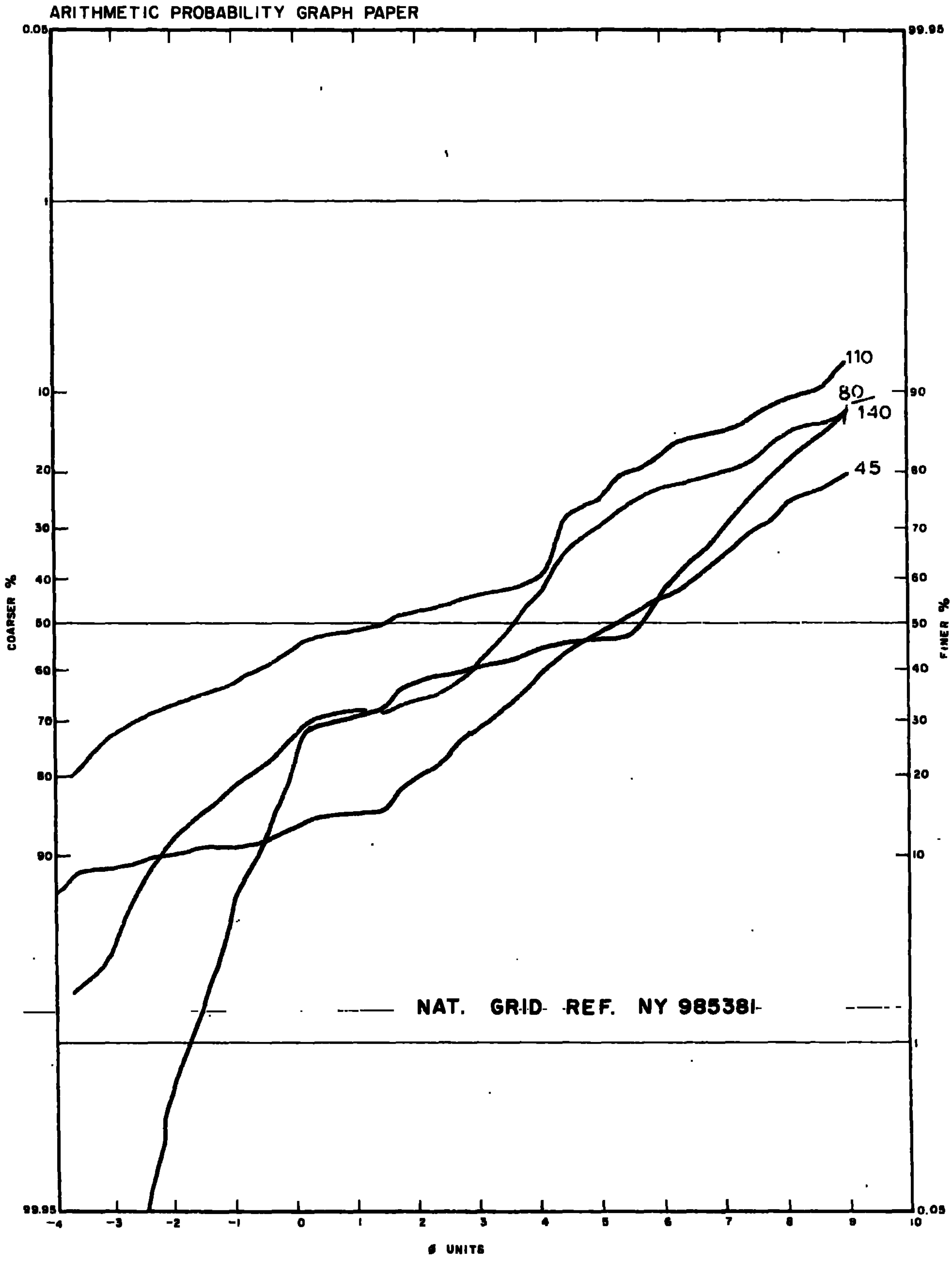
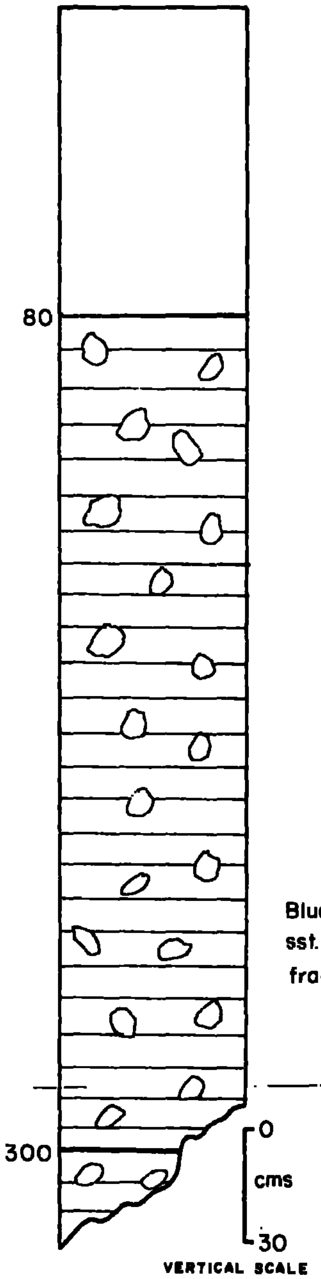
60
70
80
90
99.95
0.05
COARSER %
FINER %
185
160
130
100
70
140
NAT. GRID REF. NY 823437
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
ø UNITS

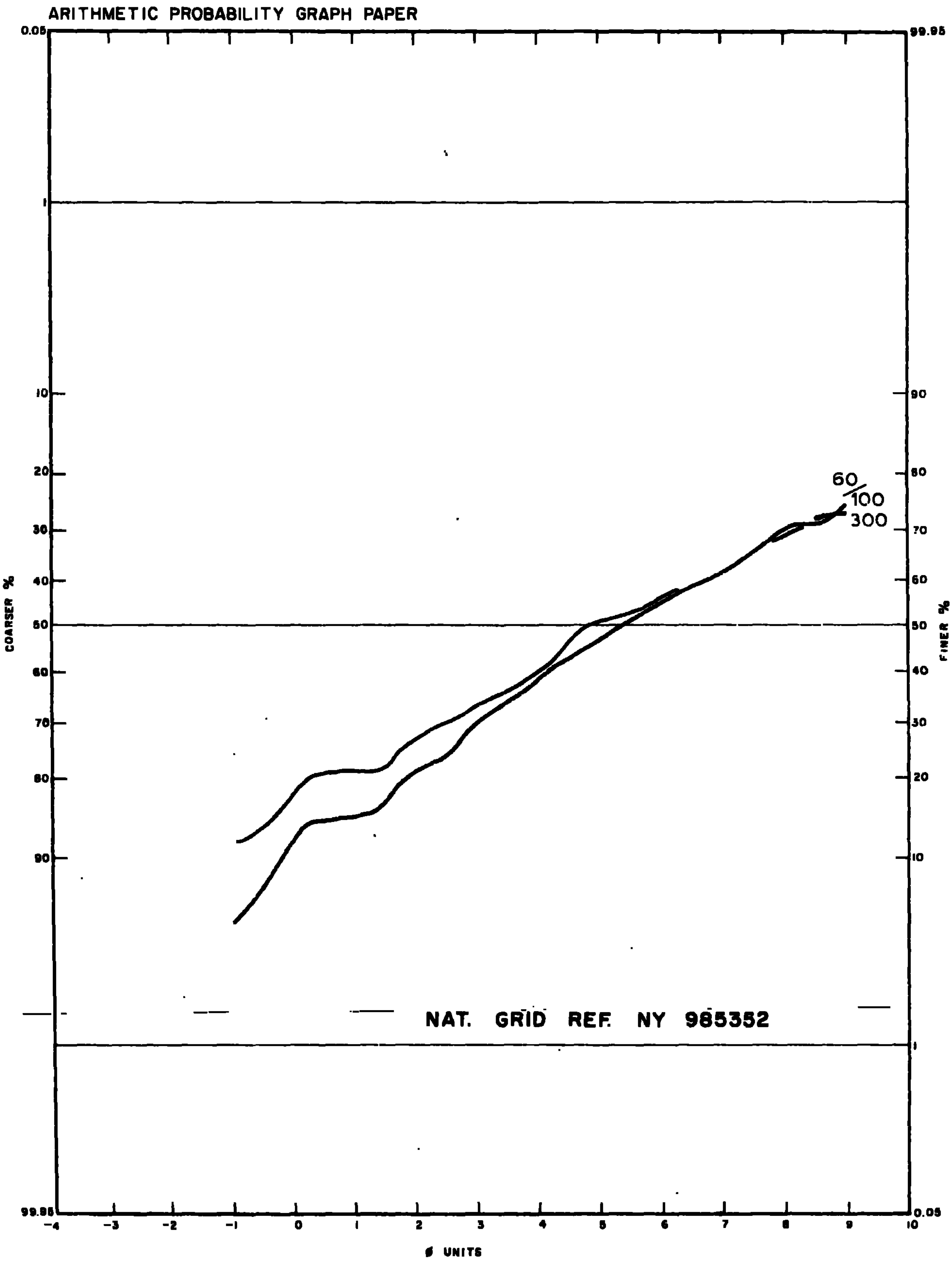
NAT. GRID REF. NY 985381

PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
			
	Mottled silver-grey clay (slope material)		1 (.8397)
	Darker grey stony clay with coal fragments		1 (.6882)
	Lens of disintegrated coal shale		2 (.6471)
	Dark grey clay		4 (.6407)


ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ø UNITS
110
80
140
45
NAT. GRID REF. NY 985381

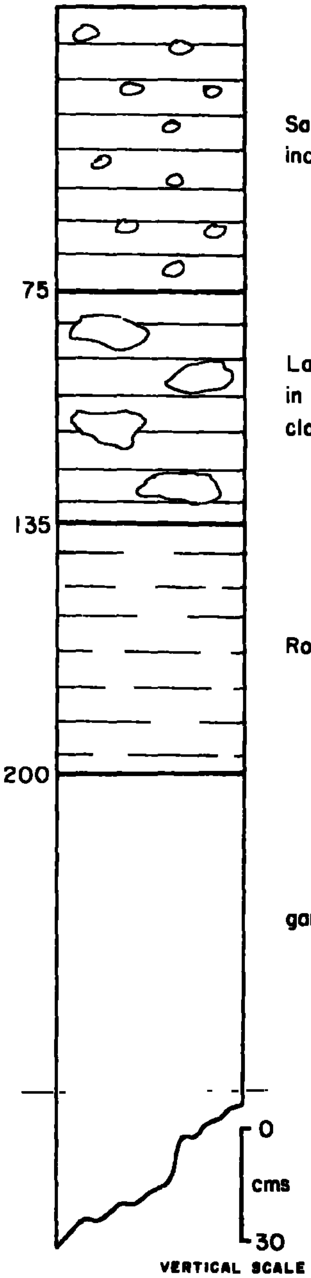
NAT. GRID REF. NY 985352

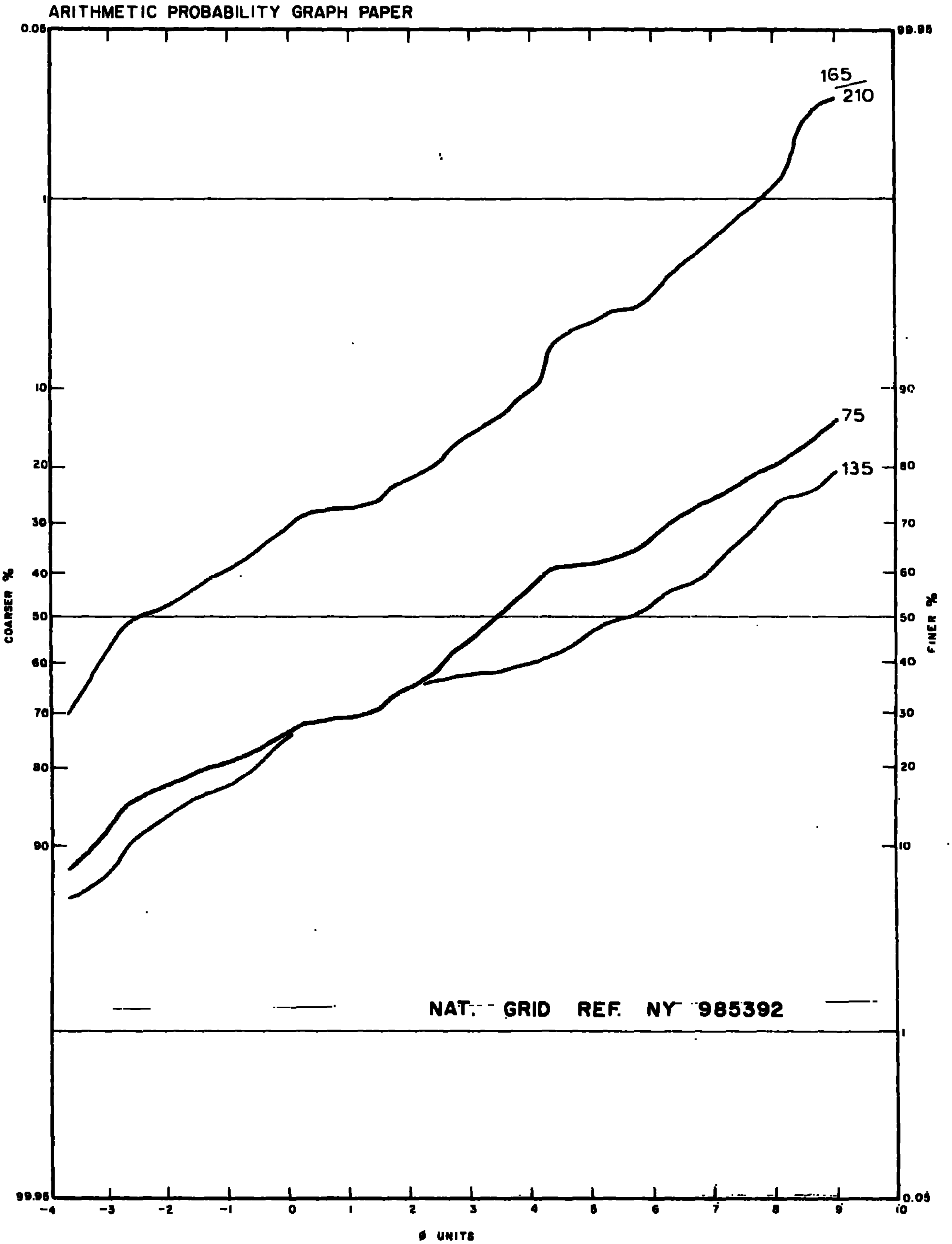
PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
	Blue grey clay with sst., sh., lst., qzite fragments.		I (.8375)



ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ϕ UNITS
60/100
300
NAT. GRID REF. NY 985352

NAT. GRID REF. NY 985392

PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
			
	Sandy-clay material including pebbles iron		1 (.6517)
	Large sst. fragments in matrix of grey/blue clay. Some mottling.		1 (.8645)
	Rotted gannister		2 (.7549)
	gannister		


ARITHMETIC PROBABILITY GRAPH PAPER
165/210
75
135
NAT. GRID REF. NY 985392
COARSER %
FINER %
ø UNITS
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30
40
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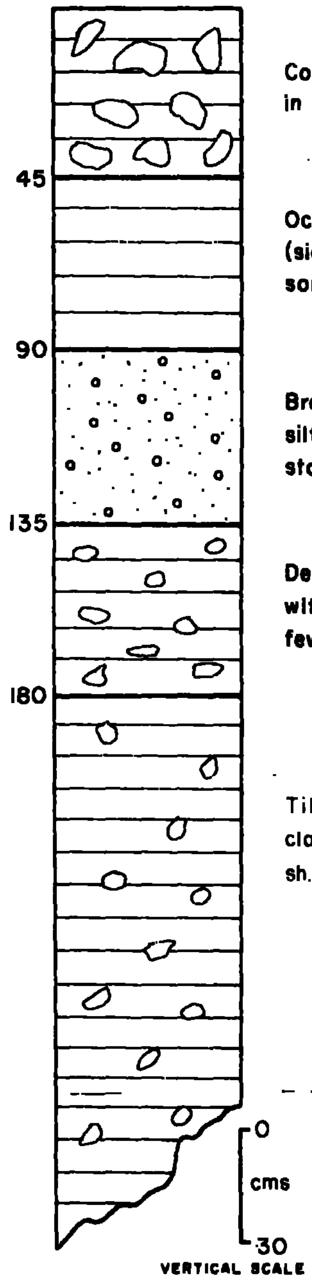
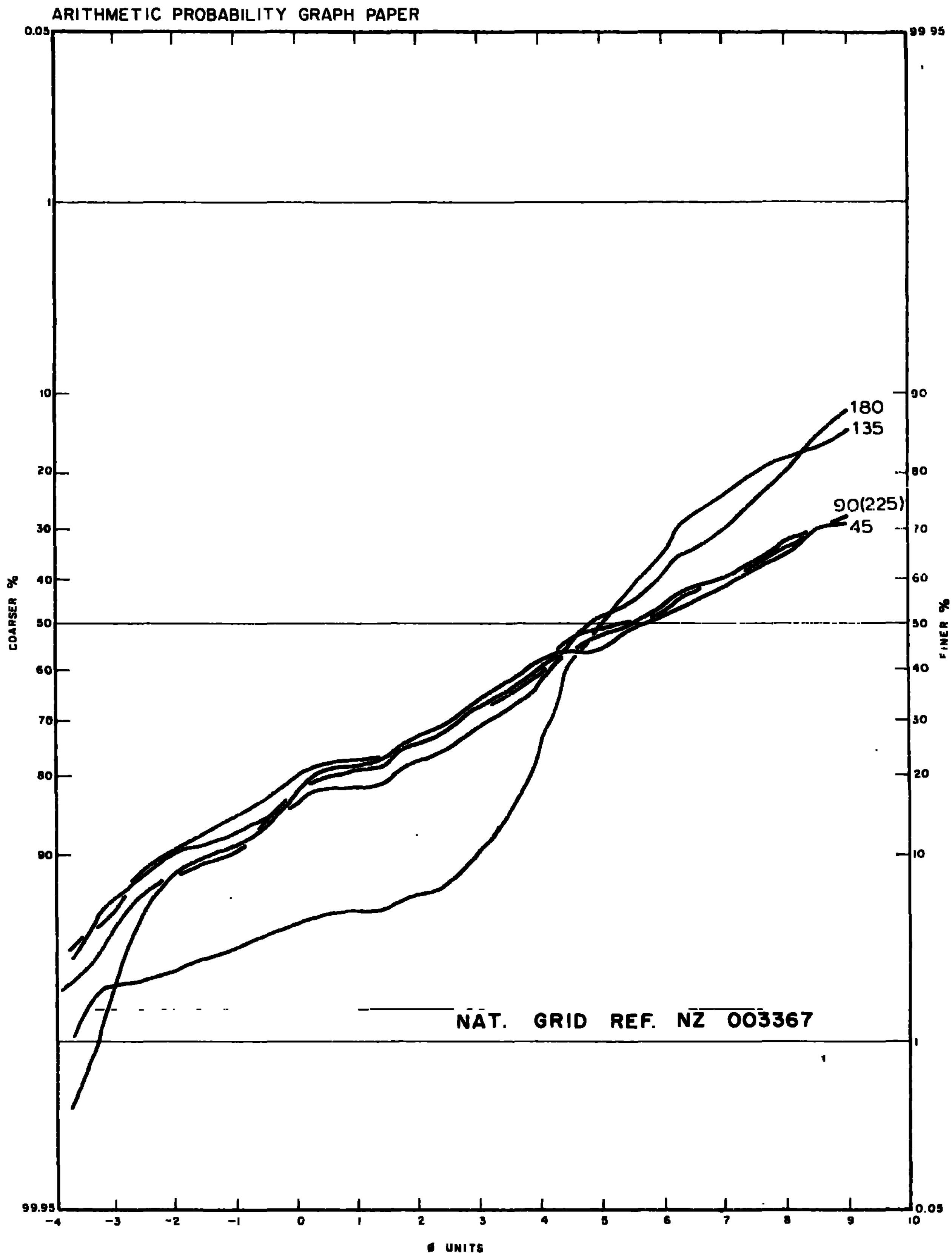
70
80
90
99.95
99.95
90
80
70
60
50
40
30
20
10
1
0.05
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10

NAT. GRID REF. NZ 003367

PROFILE



FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
Coarse angular stones in a matrix of grey clay		1 (.8874)
Ochre/grey clay compact (signs of foliation) some iron staining		1 (.8853)
Brown/grey sandy silty material few stones		4 (.7124)
Dense ochre/grey clay with rock fragments few large stones		1 (.7918)
Till. dense blue-grey clay with stones - sst., sh., qz., lst.		1 (.8701)


ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
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1
10
20
30
40
50
60
70
80
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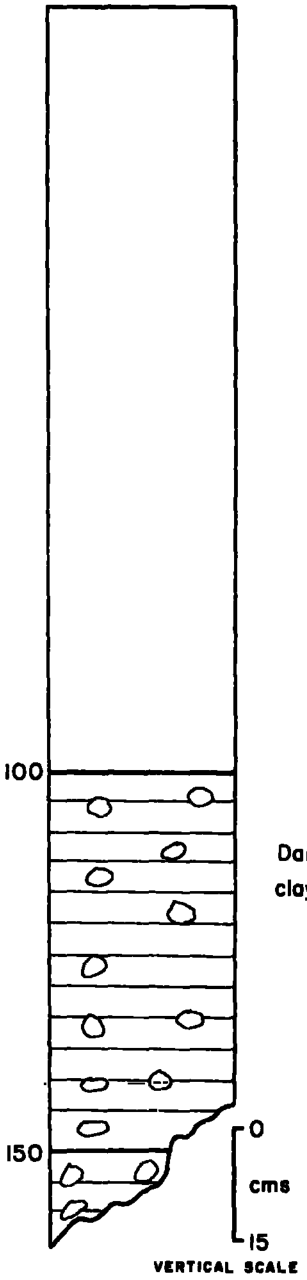
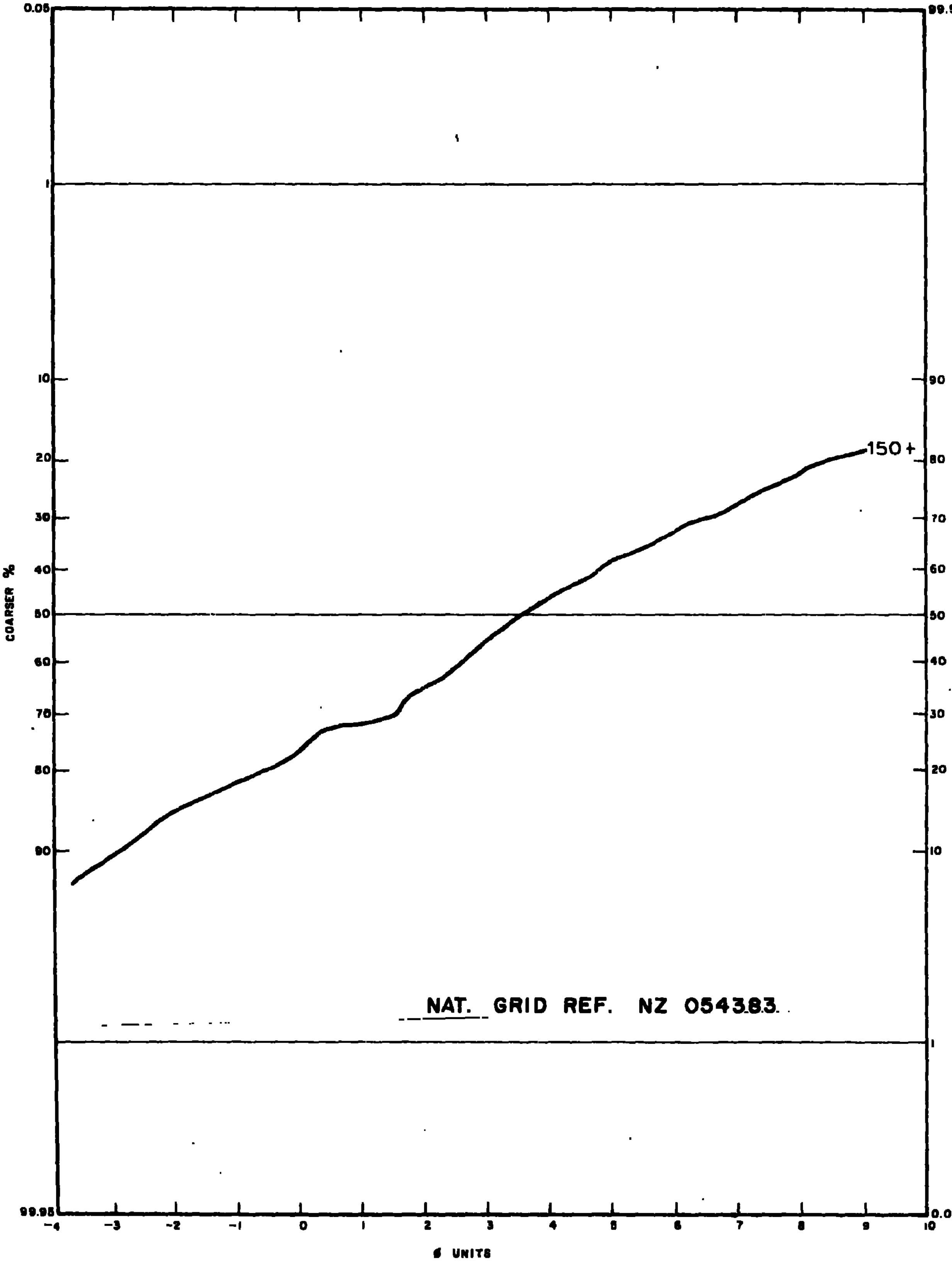
99.95
99 95
90
80
70
60
50
40
30
20
10
1
0.05
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
ø UNITS
180
135
90(225)
45
NAT. GRID REF. NZ 003367

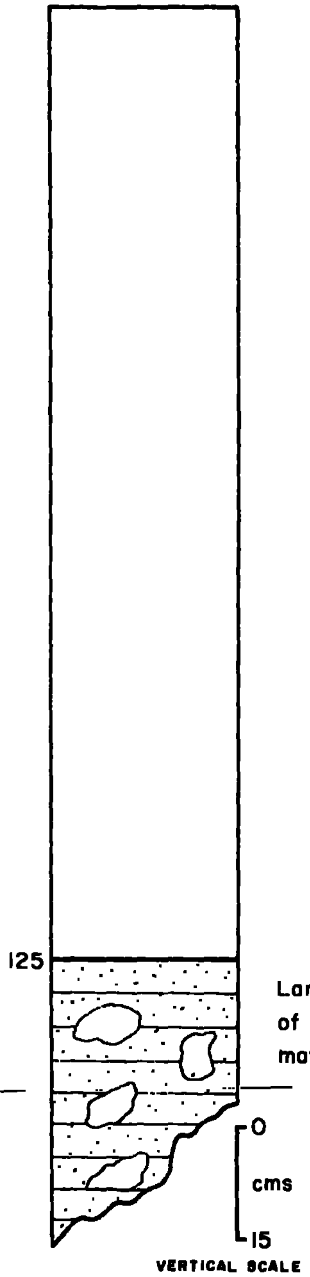
NAT. GRID REF. NZ 054383

PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
	Dark blue-grey silty clay with stones.		1 (.7273)

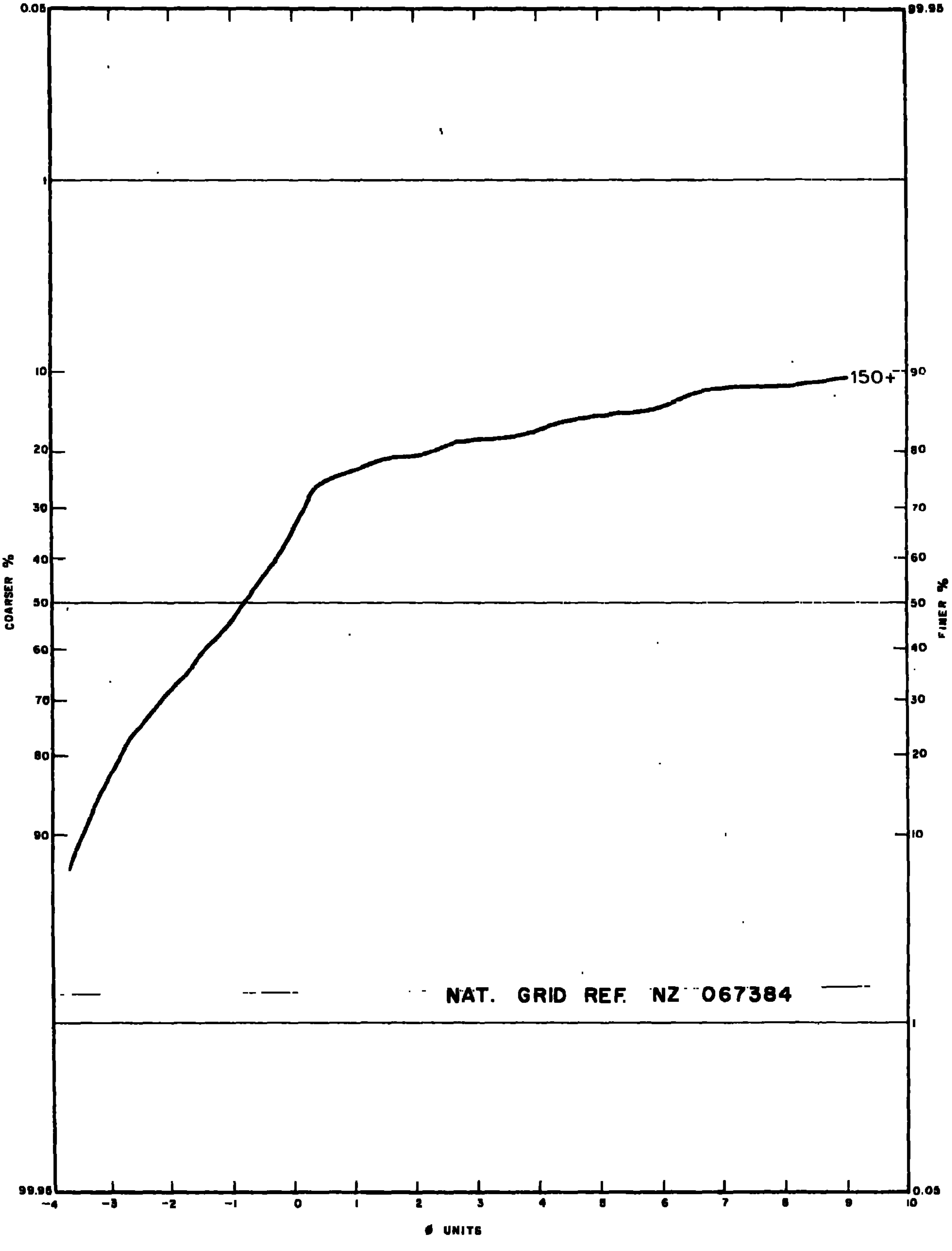
ARITHMETIC PROBABILITY GRAPH PAPER



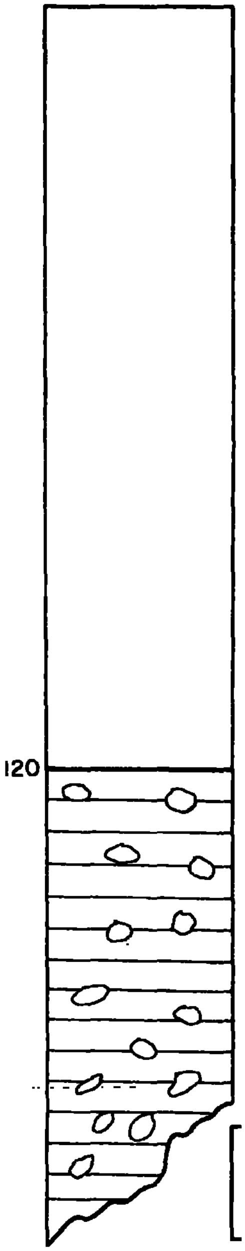
NAT. GRID REF. NZ 067384

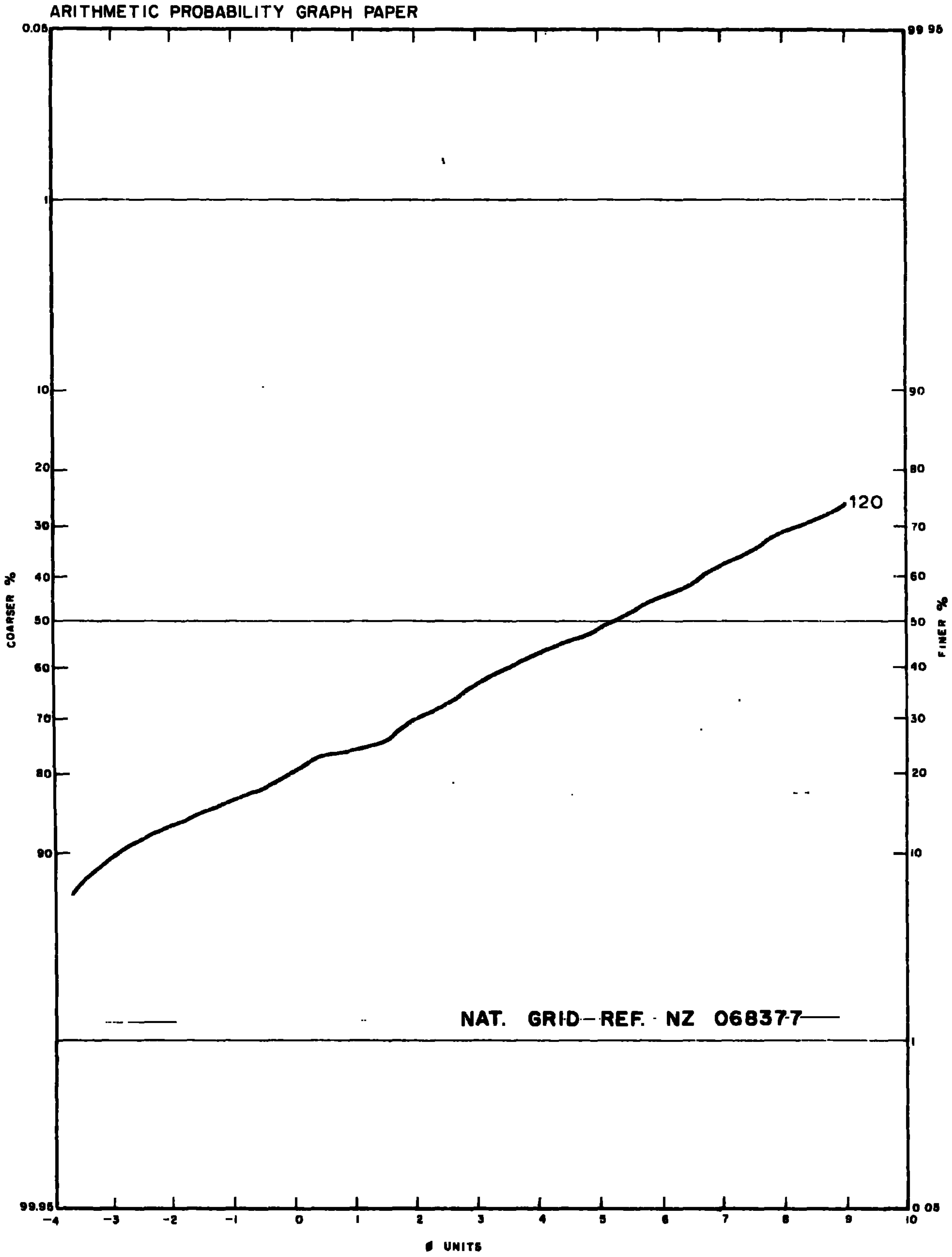
PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
	Large angular fragments of sst., in matrix of clay material.		2 (.9379)

ARITHMETIC PROBABILITY GRAPH PAPER

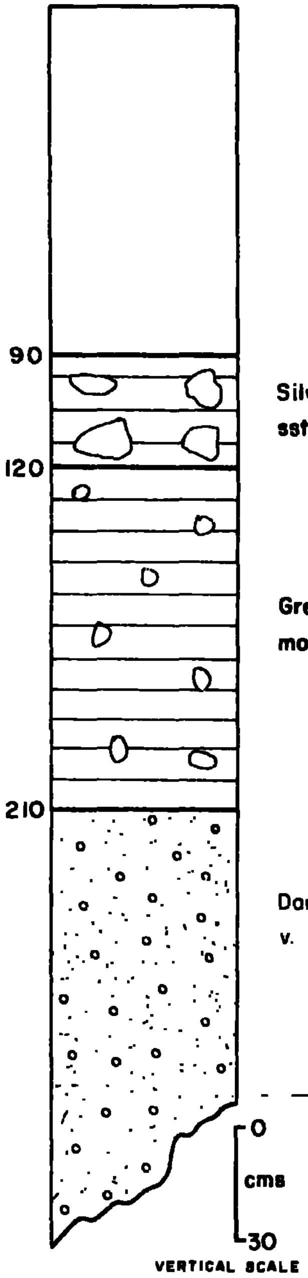


NAT. GRID REF. NZ 068377

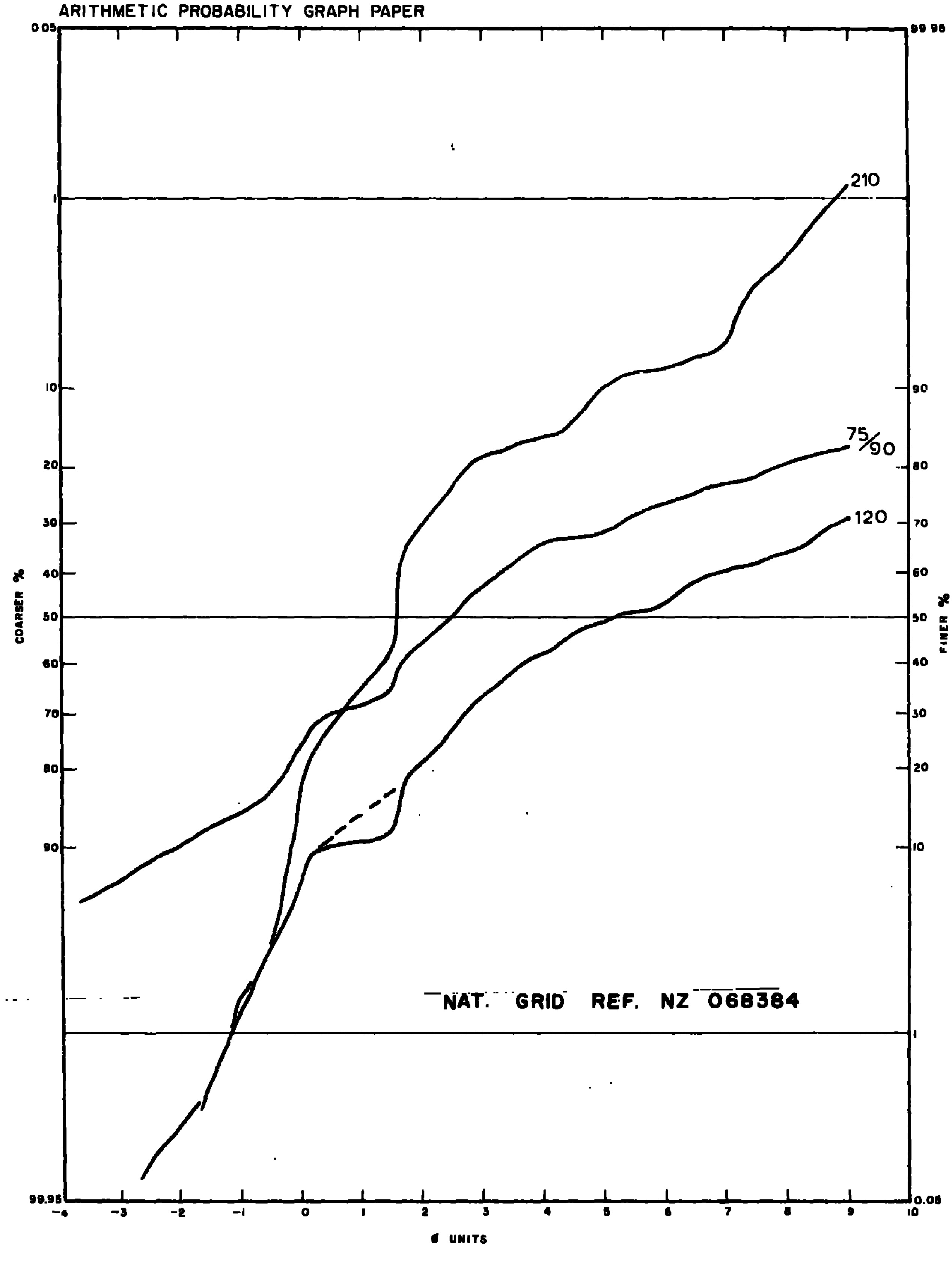
PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
 VERTICAL SCALE	Blue grey clay with stones, sst., sh., qzite (boulder – clay)		I (.8716)


ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ø UNITS
120
NAT. GRID REF. NZ 068377

NAT. GRID REF. NZ 068384

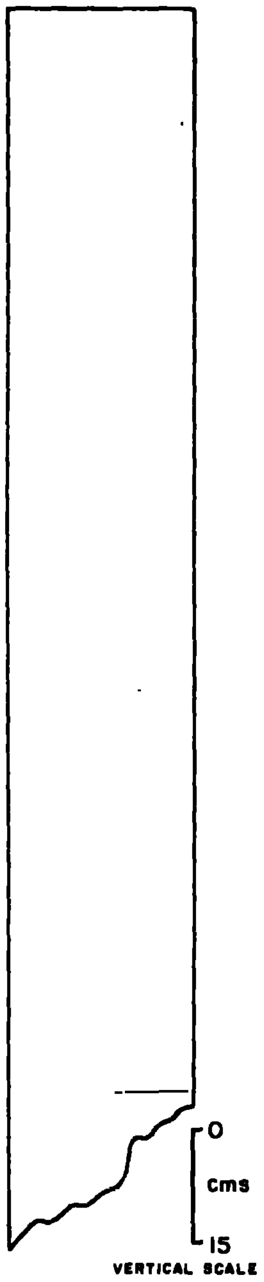


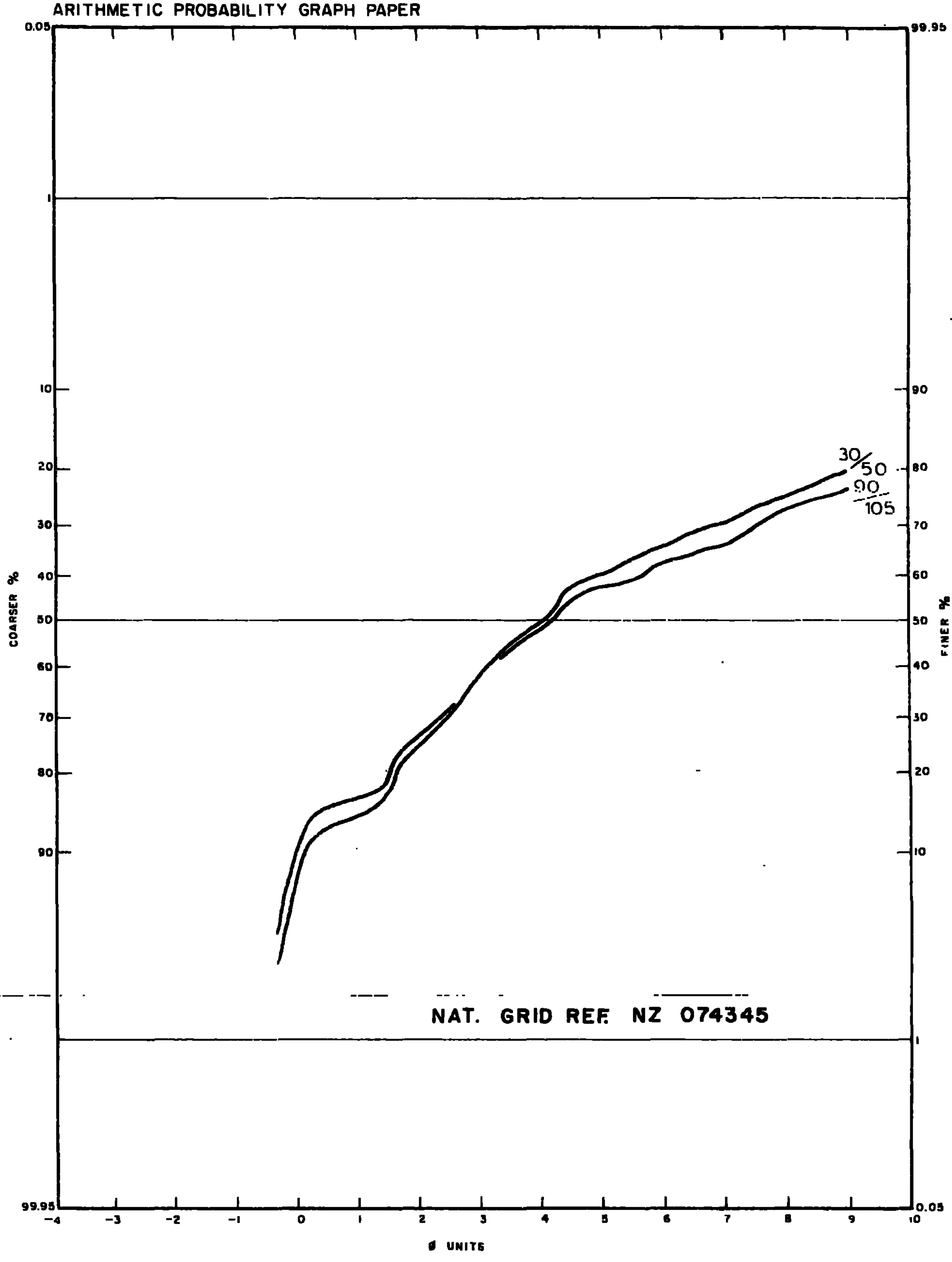
PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
90–120	Silver grey clay with sst. fragments.		3 (.6763)
120–210	Grey clay with ochre mottling		1 (.8057)
210–	Dark grey sand and silt v. compact		3 (.8925)


ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ø UNITS
210
75/90
120
NAT. GRID REF. NZ 068384

NAT. GRID REF. NZ 074345

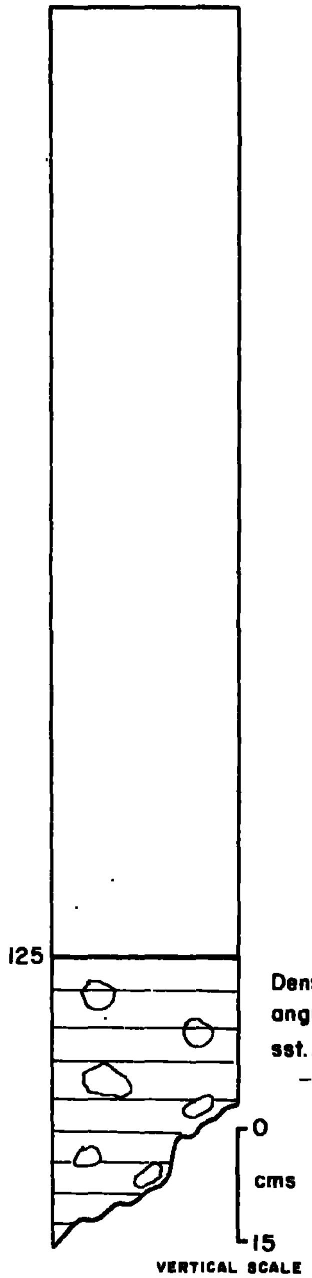
PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
			I (.7486)
			I (.7488)



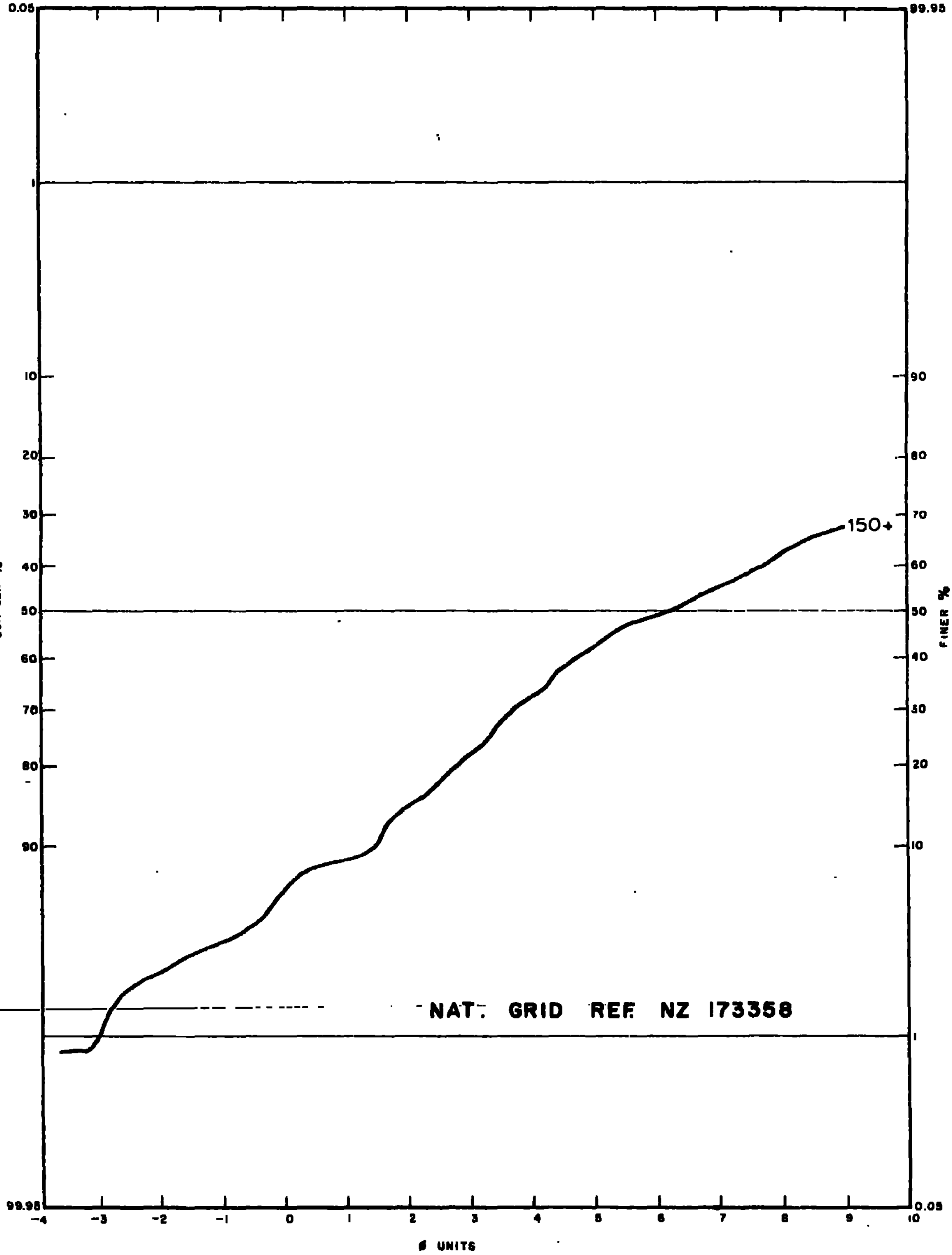


ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ø UNITS
30/50
90/105
NAT. GRID REF. NZ 074345

NAT. GRID REF. NZ 173358

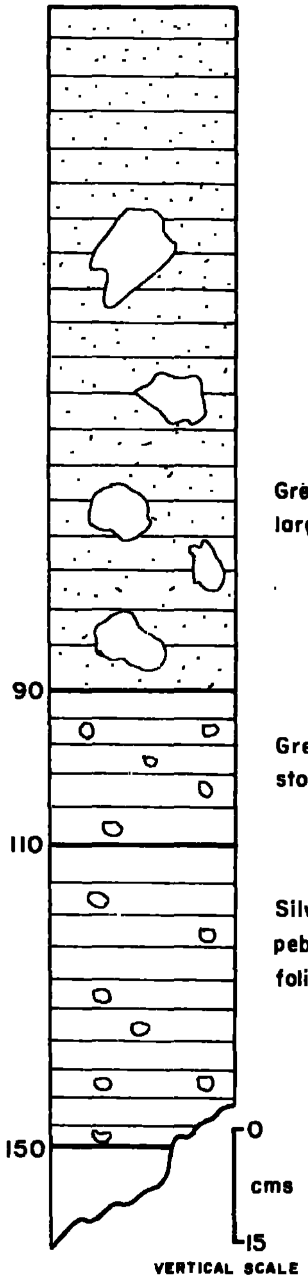
PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
	Dense blue clay with angular fragments of sst., sh., qzite.		1 (.9083)

ARITHMETIC PROBABILITY GRAPH PAPER

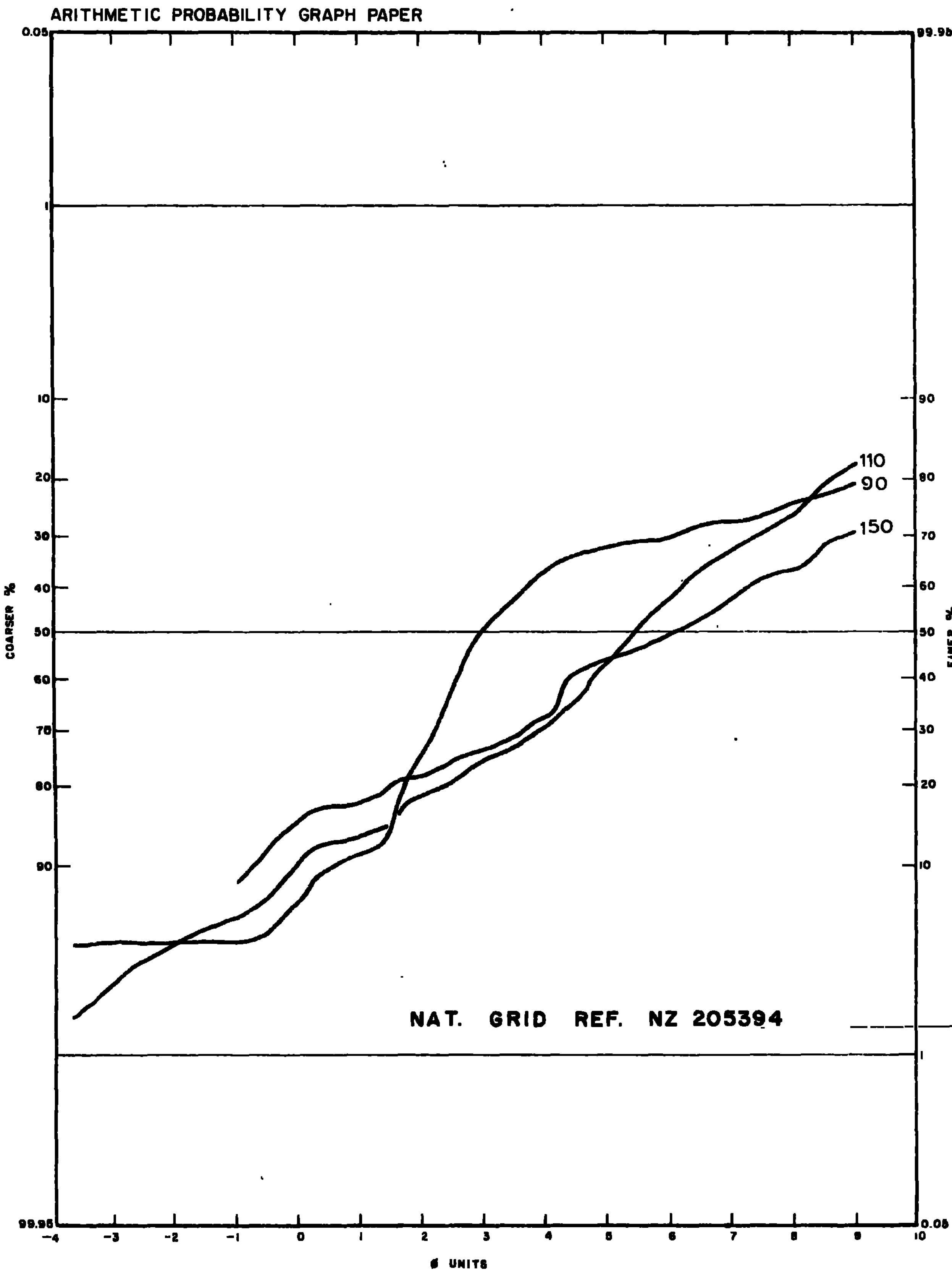


NAT. GRID REF. NZ 205394

PROFILE

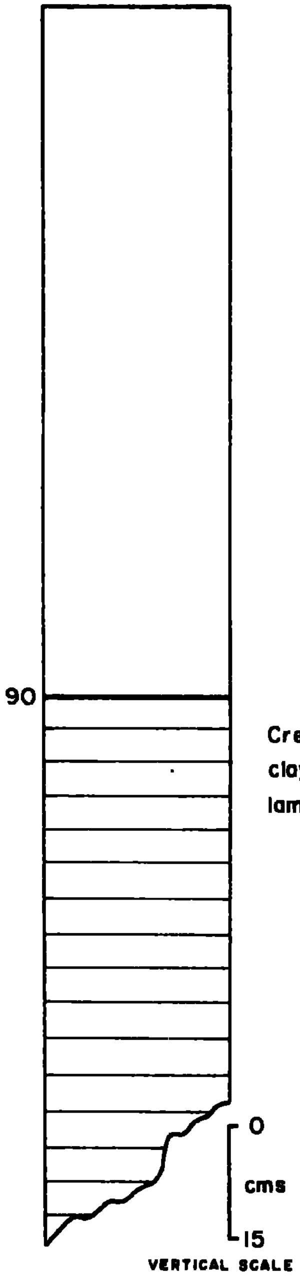


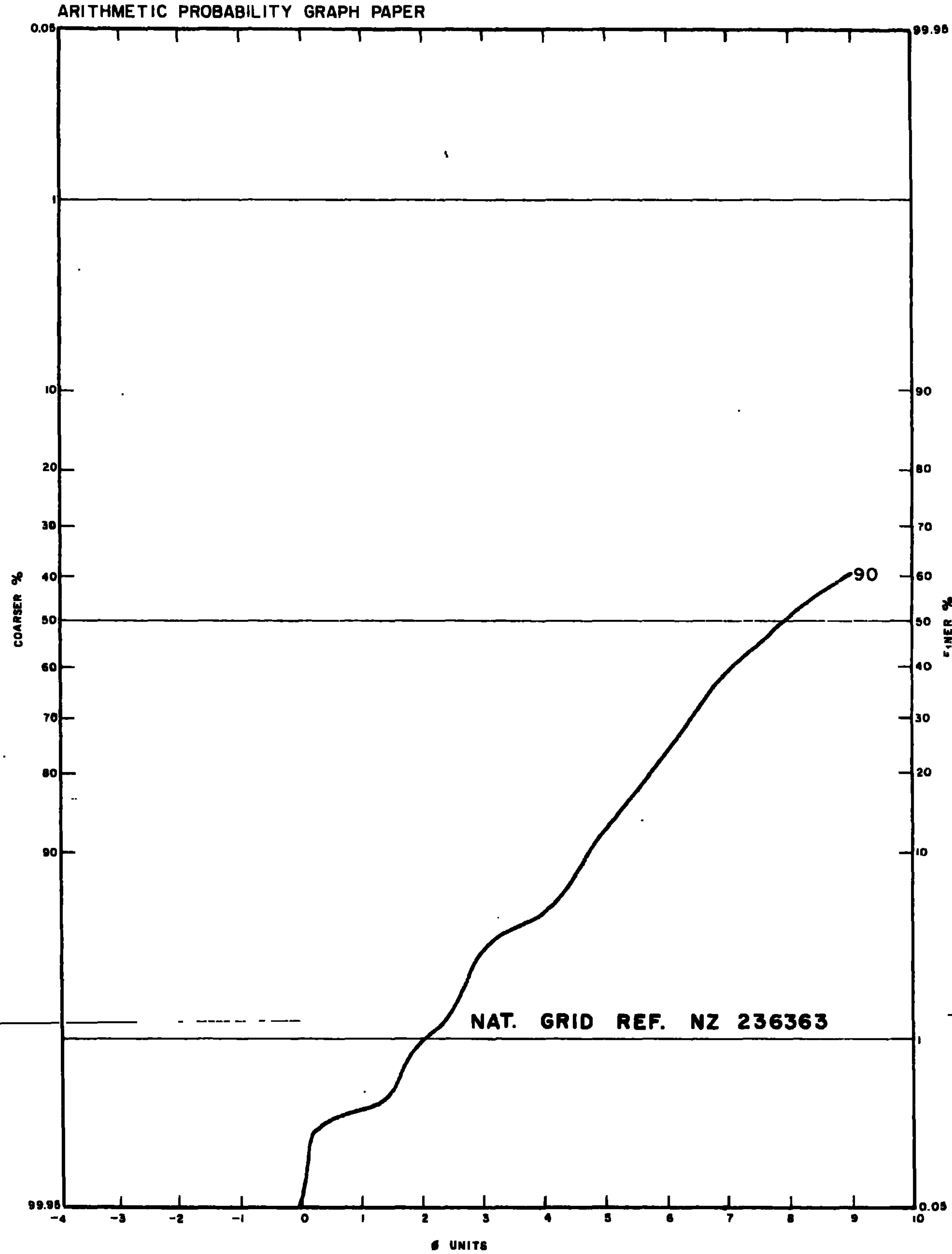
FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
Grey - brown clay with large sst. fragments		3 (.7581)
Grey-brown clay with stones, sst., lst., sh.,		1 (.8688)
Silver grey clay with pebbles – signs of foliation.		1 (.8877)



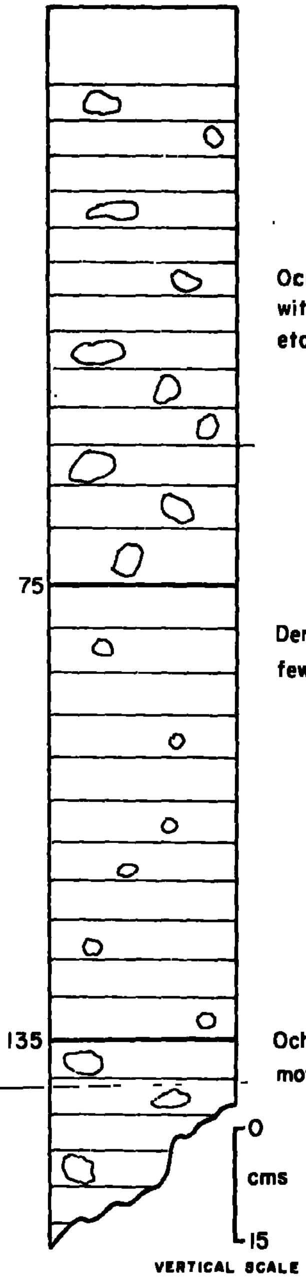
ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ø UNITS
110
90
150
NAT. GRID REF. NZ 205394

NAT. GRID REF. NZ 236363

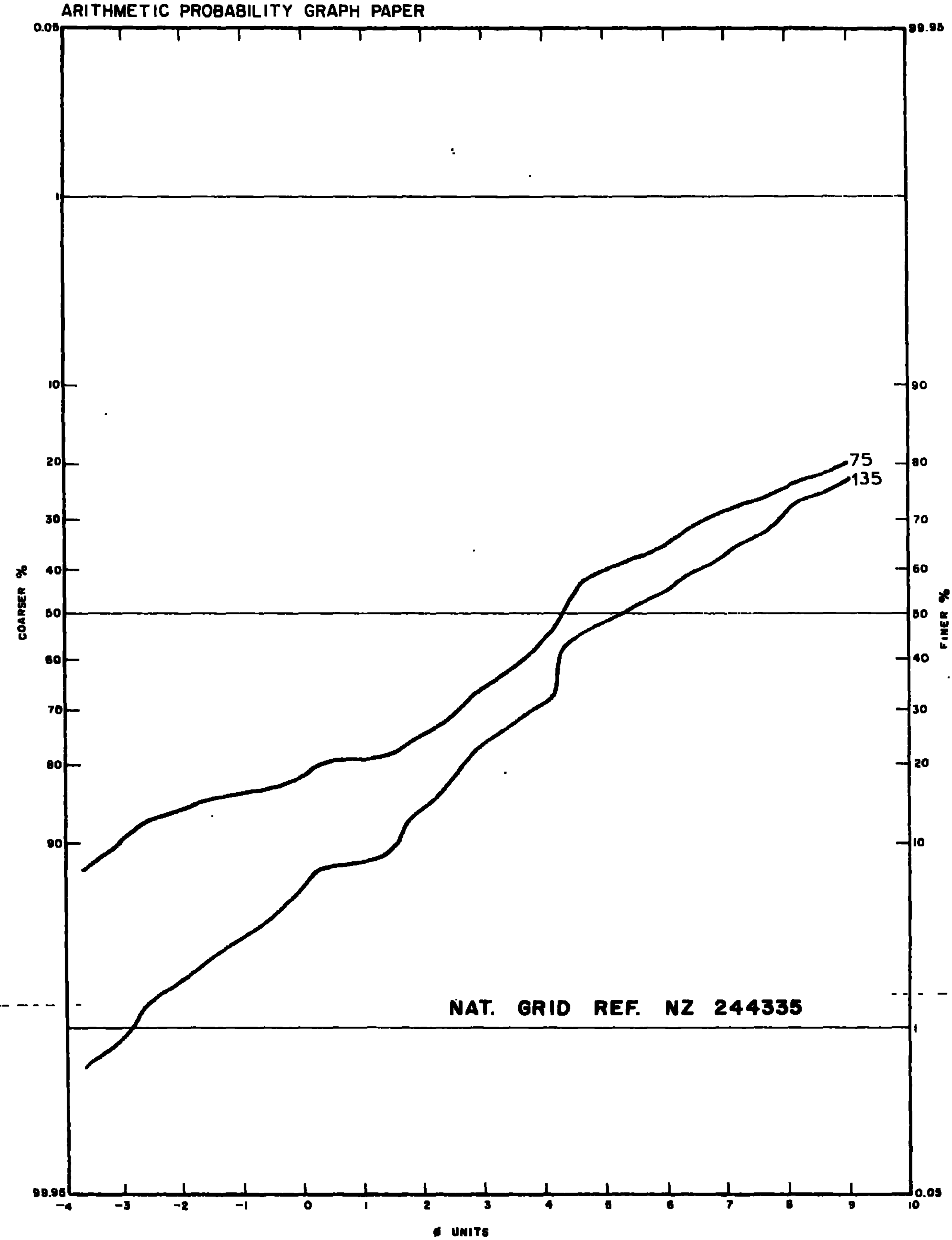
PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
	Cream-grey coloured clay very finely laminated		1 (.9954)


ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ø UNITS
90
NAT. GRID REF. NZ 236363

NAT. GRID REF. NZ 244335



PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
0–75	Ochre-grey clay with mottles, sst fragments etc.		
75–135	Dense ochre-grey clay few sst. fragments		1(.7461)
135–	Ochre grey clay with mottles sst. fragments etc.		1 (.8334)



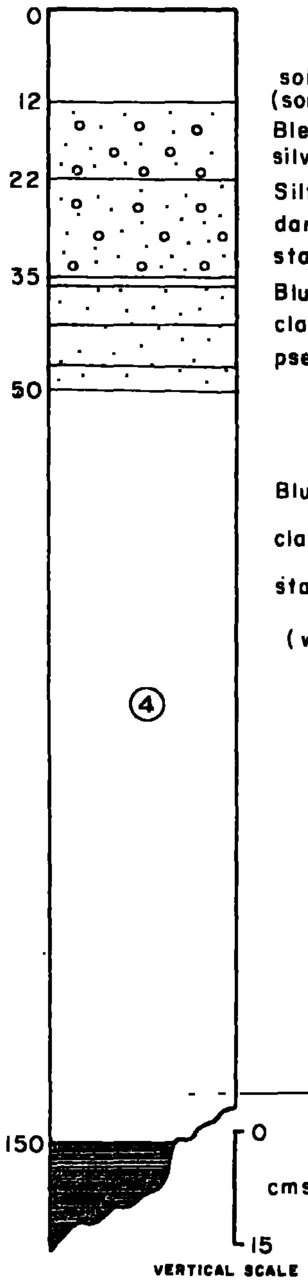
ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
0.05
1
10
20
30
40
50
60
70
80
90
99.95
99.95
90
80
70
60
50
40
30
20
10
1
0.05
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
ø UNITS
75
135
NAT. GRID REF. NZ 244335

APPENDIX II

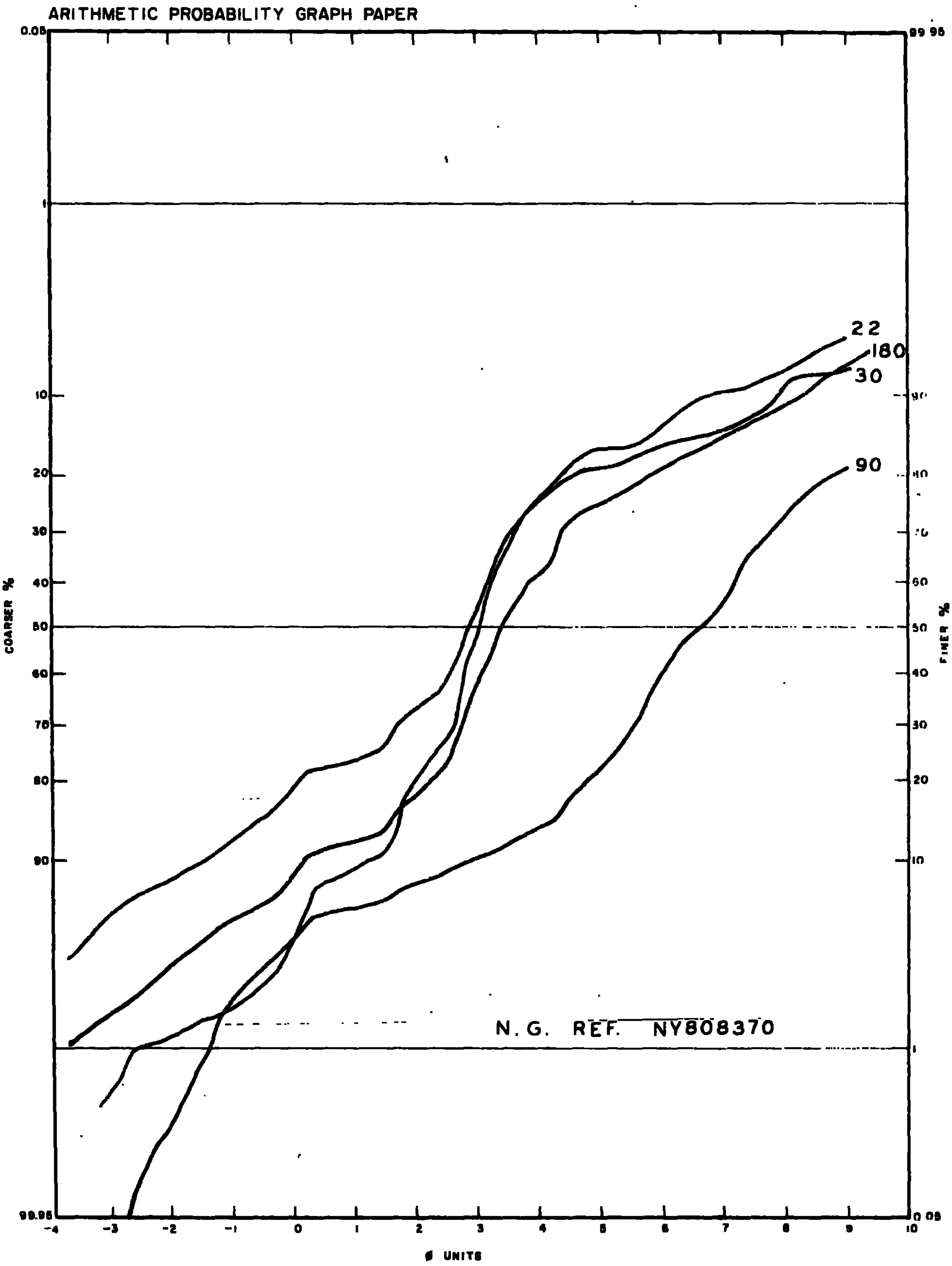
Containing field notes and description of each site sampled together with the particle size curves for each sample analysed.

<u>N.B.</u> The "Laboratory data" have been omitted from this appendix and incorporated into the text as tables of particle-size data.

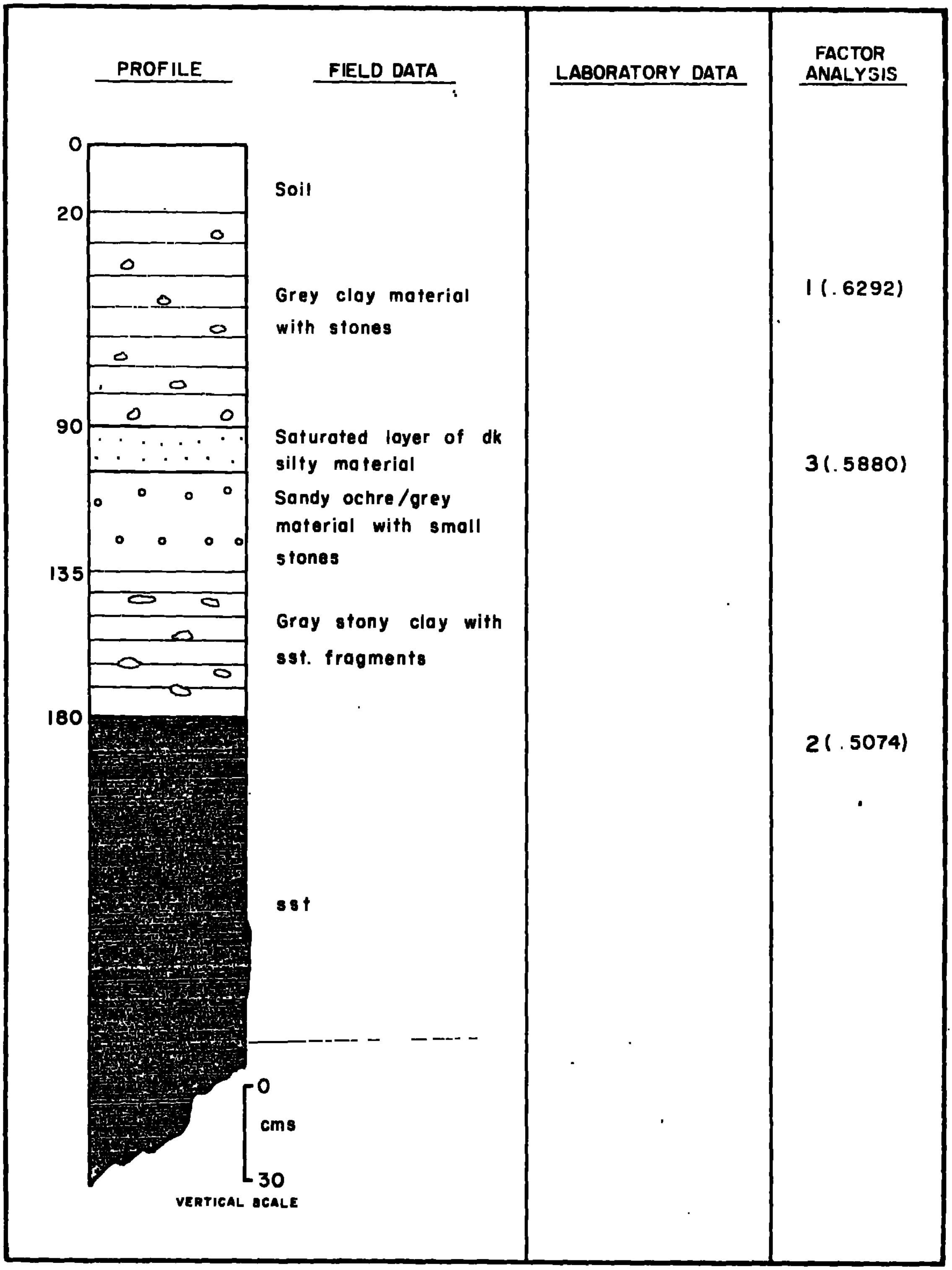
NAT GRID REF. NY808370

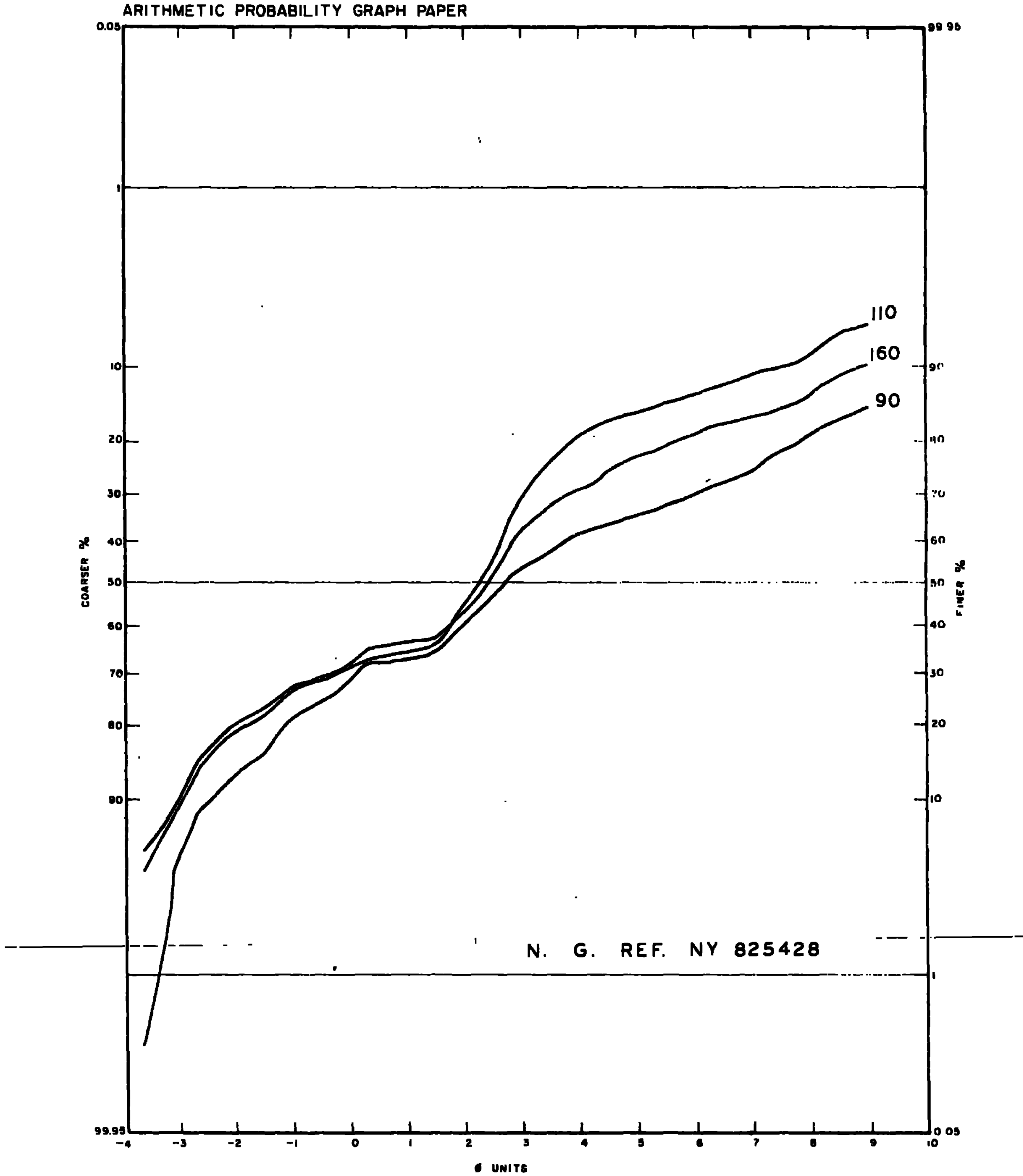


PROFILE (depth)	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
0	soil (some peat)		
12	Bleached sandy material silver grey colour		4 (.7343)
22	Silty sandy material darker grey iron stained nodules		4 (.6532)
35	Blue/grey colour silty clay material compact– pseudo stratification		1 (.9196)
50	Blue grey heavy clay with iron staining. (weathered shale)		4 (.7838)
150	shale		


ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
22
180
30
90
N. G. REF. NY808370
ø UNITS

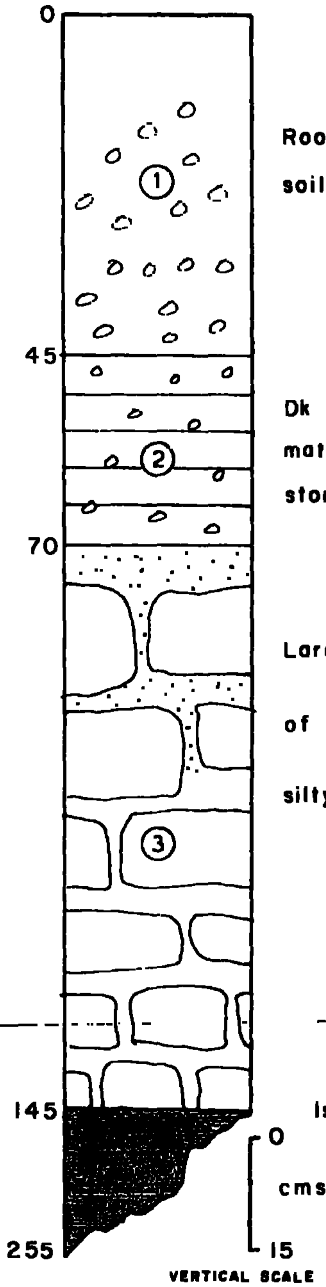
NAT. GRID REF. NY 825428



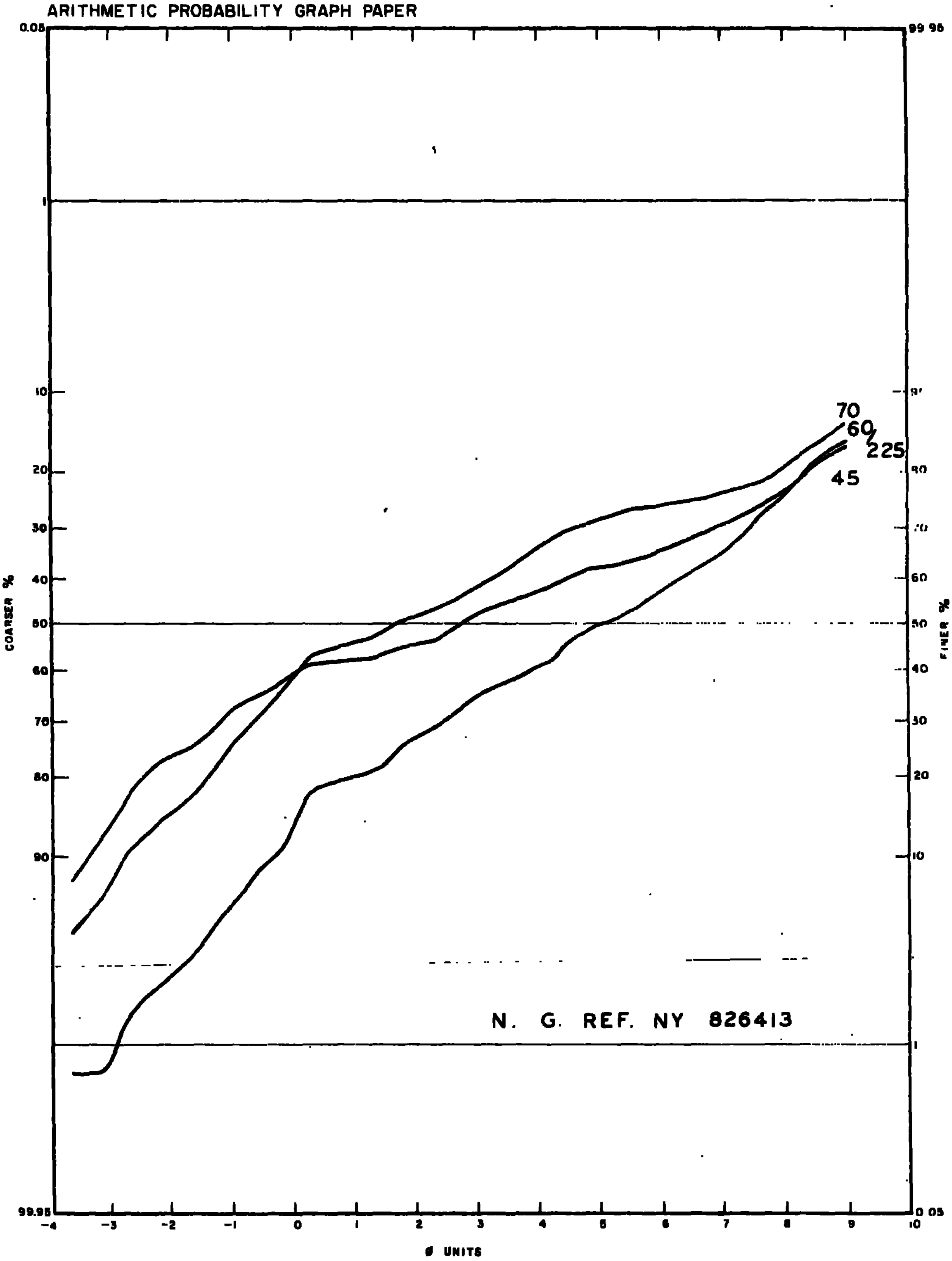

ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ϕ UNITS
110
160
90
N. G. REF. NY 825428

NAT. GRID REF. NY 826413

PROFILE



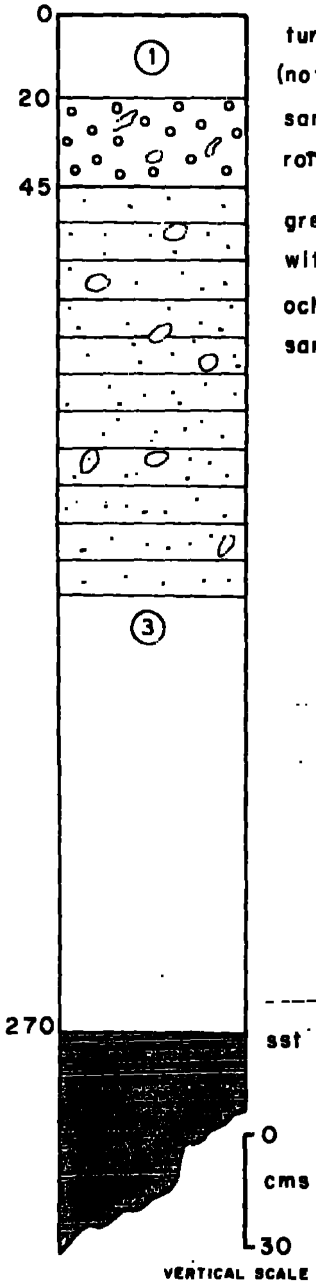
FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
Root layer, silt – clay soil .v. stony		2 (.6766)
Dk bluish clayey material with small stones.		2 (.6673)
Large cubic blocks of lst. in dk silty matrix		1 (.8349)
lst.		



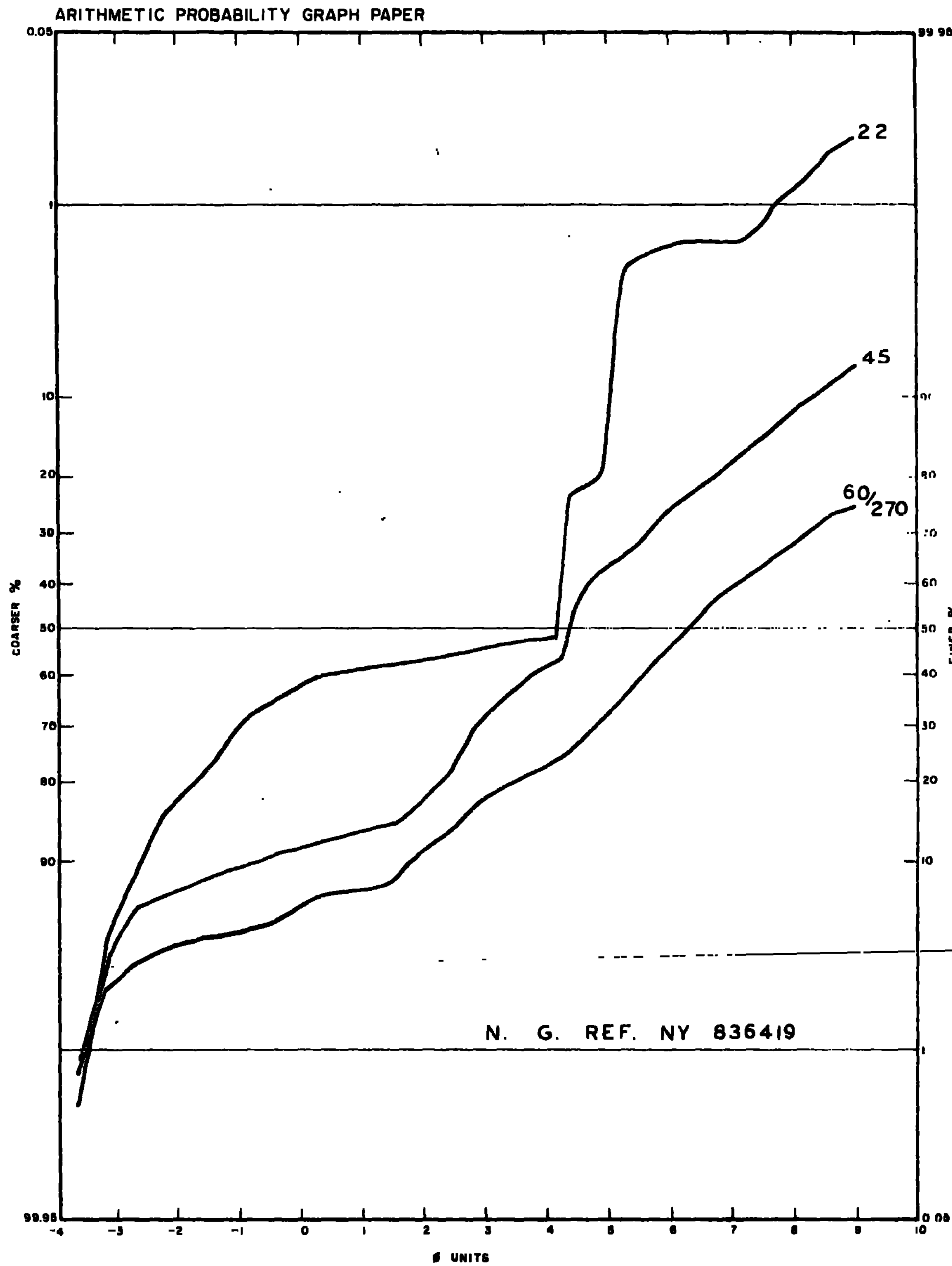
ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ø UNITS
70
60
225
45
N. G. REF. NY 826413

NAT. GRID REF. NY 836419

PROFILE

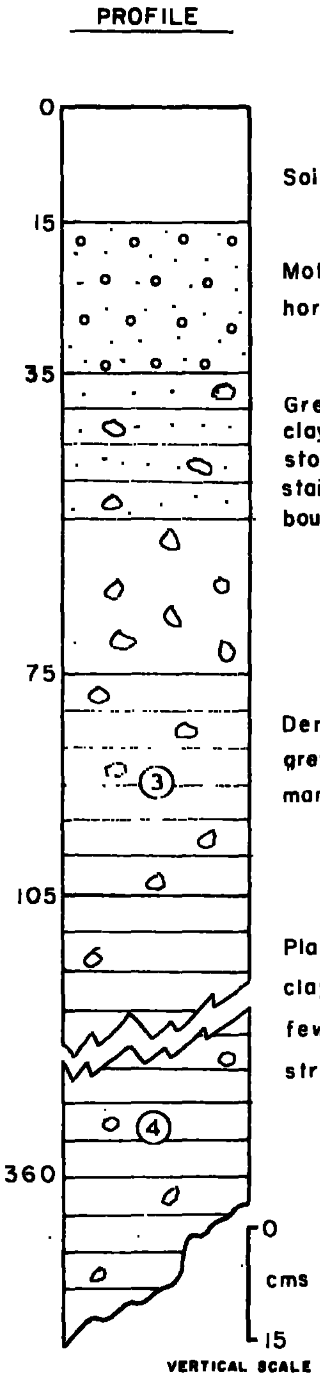


FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
turf + dk material (not humus)		4 (.7235)
sandy material with rotted sandstone		4 (.7222)
grey silty clay with large platy stones ochre markings and sandstone pebbles		
		1 (.9640)
sst		



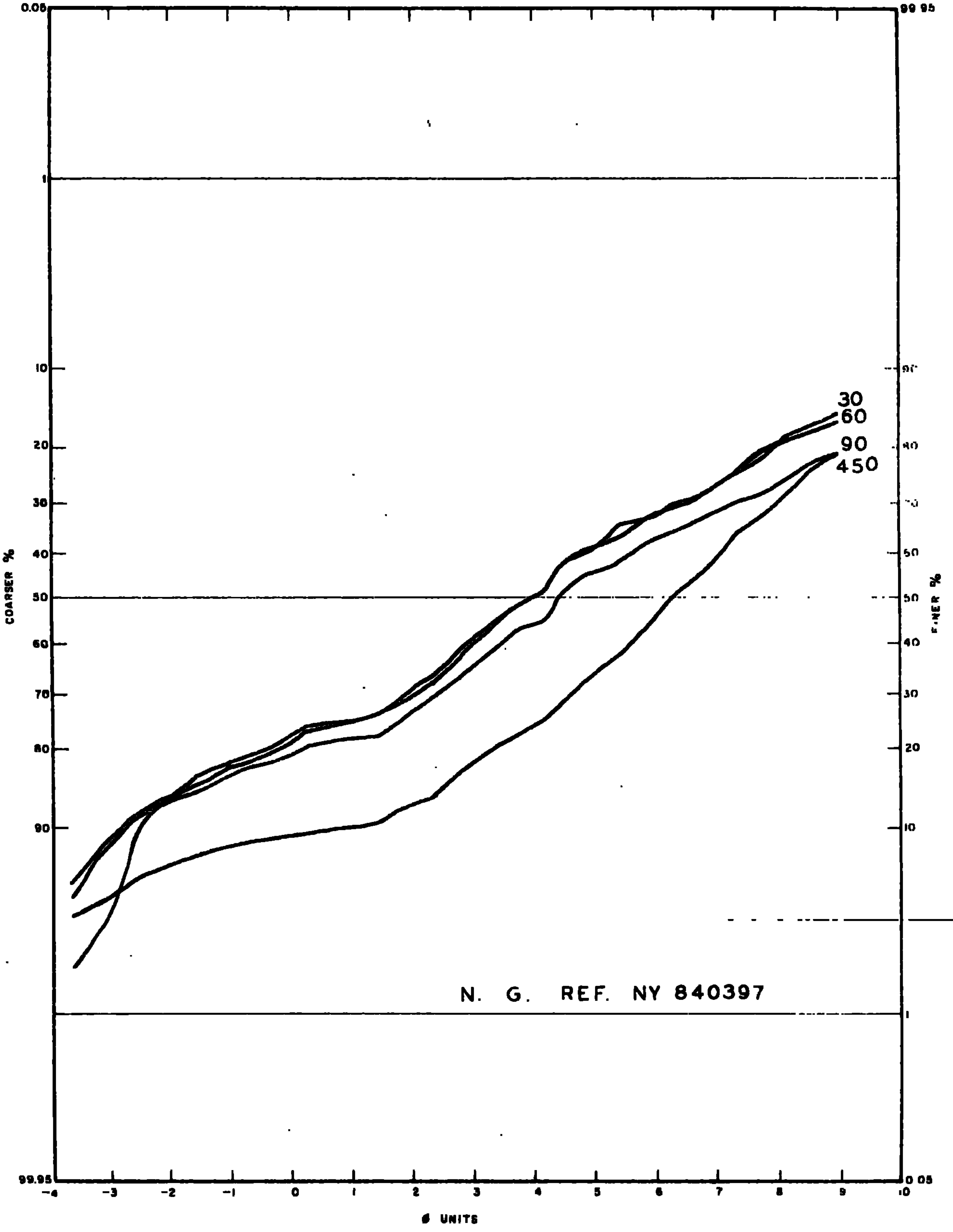
ARITHMETIC PROBABILITY GRAPH PAPER
22
45
60/270
N. G. REF. NY 836419
COARSER %
FINER %
ø UNITS

NAT. GRID REF. NY 840397



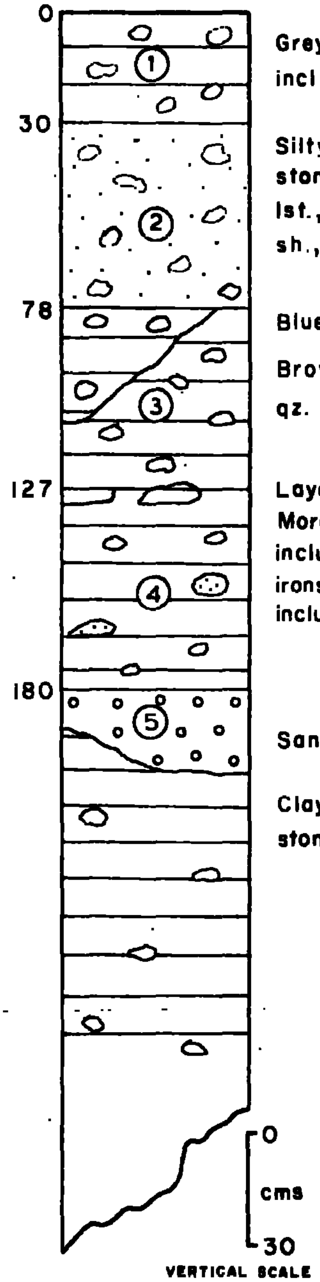
FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
Soil		
Mottled silty sandy horzon. — gleyed		1(.7208)
Grey blue heavy silty clay material with stones some iron staining occ. large boulders up to 9"		1(.7601)
Dense compact blue grey clay with many stones		1(.8164)
Plastic blue — grey clay v. dense with few stones — some striated.		1(.9464)

ARITHMETIC PROBABILITY GRAPH PAPER

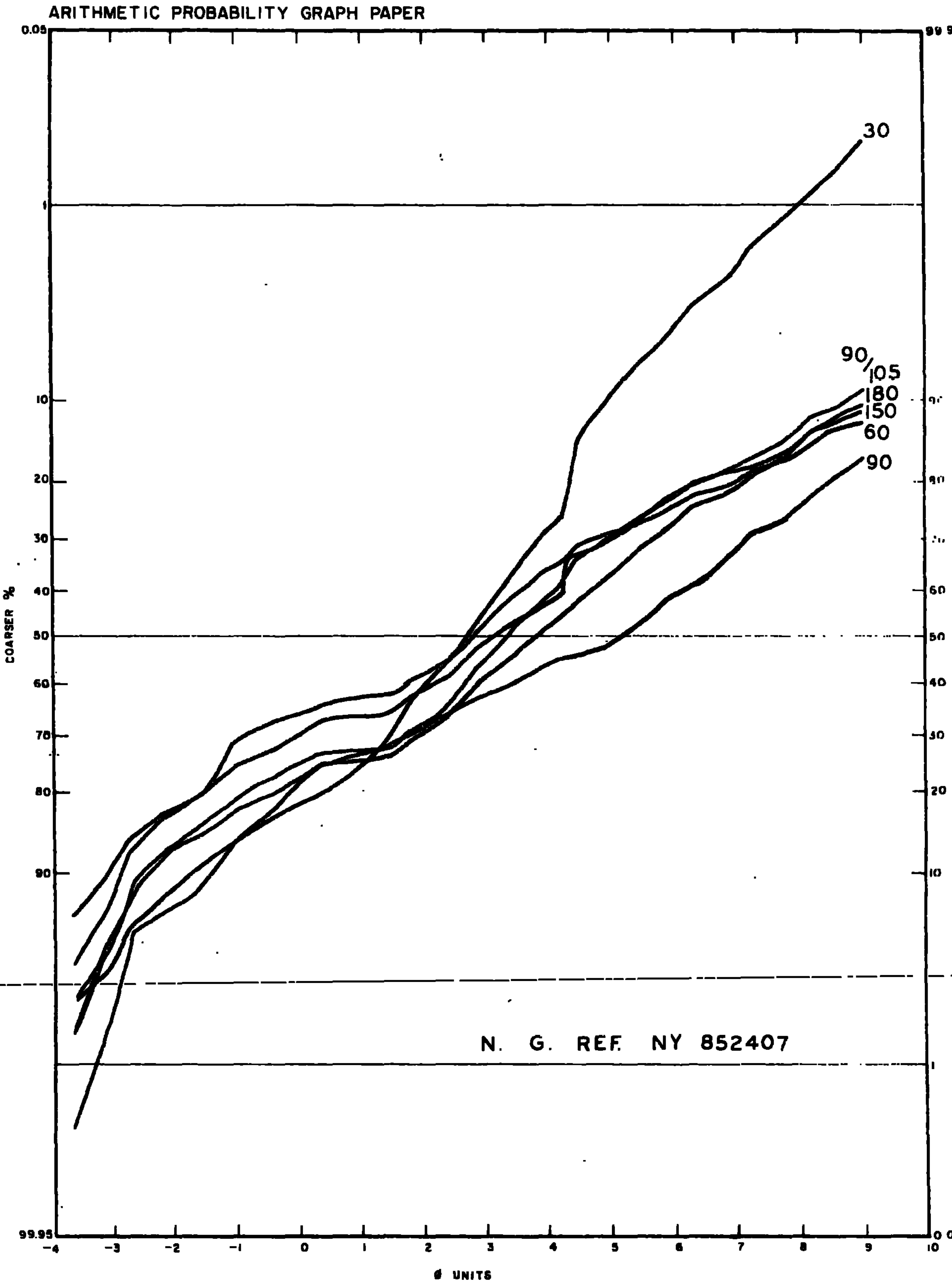


NAT. GRID REF. NY 852407

PROFILE

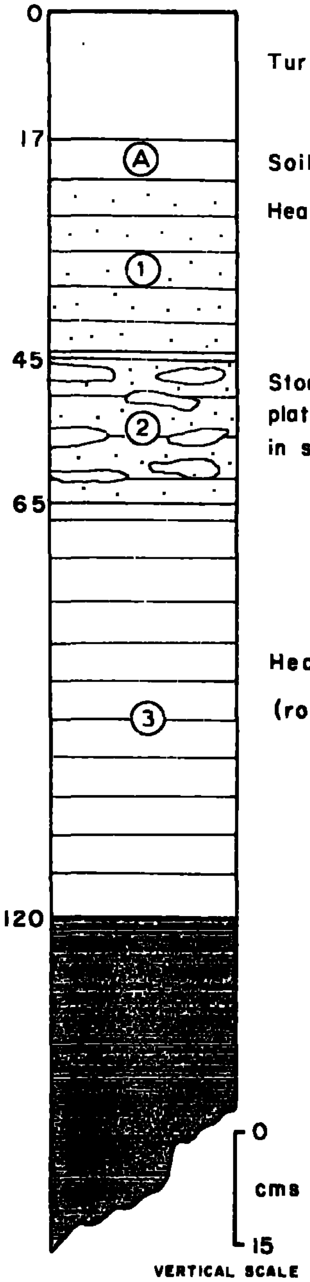


FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
Greyish clay material incl. stones		4(.7718)
Silty brown material stones rel. compacted lst., sst., qz., & sh., ang., & sub ang.		2(.5828)
Blue shaly material Brown clay with sst. qz. & lst.		1(.8359) 1(.5795)
Layer of platy stones More compact material including sh., sst., lst. ironstone nodules + sandy inclusions		1(.6831)
Sandy lens		4(.6201)
Clay material with stones		1(.6881)

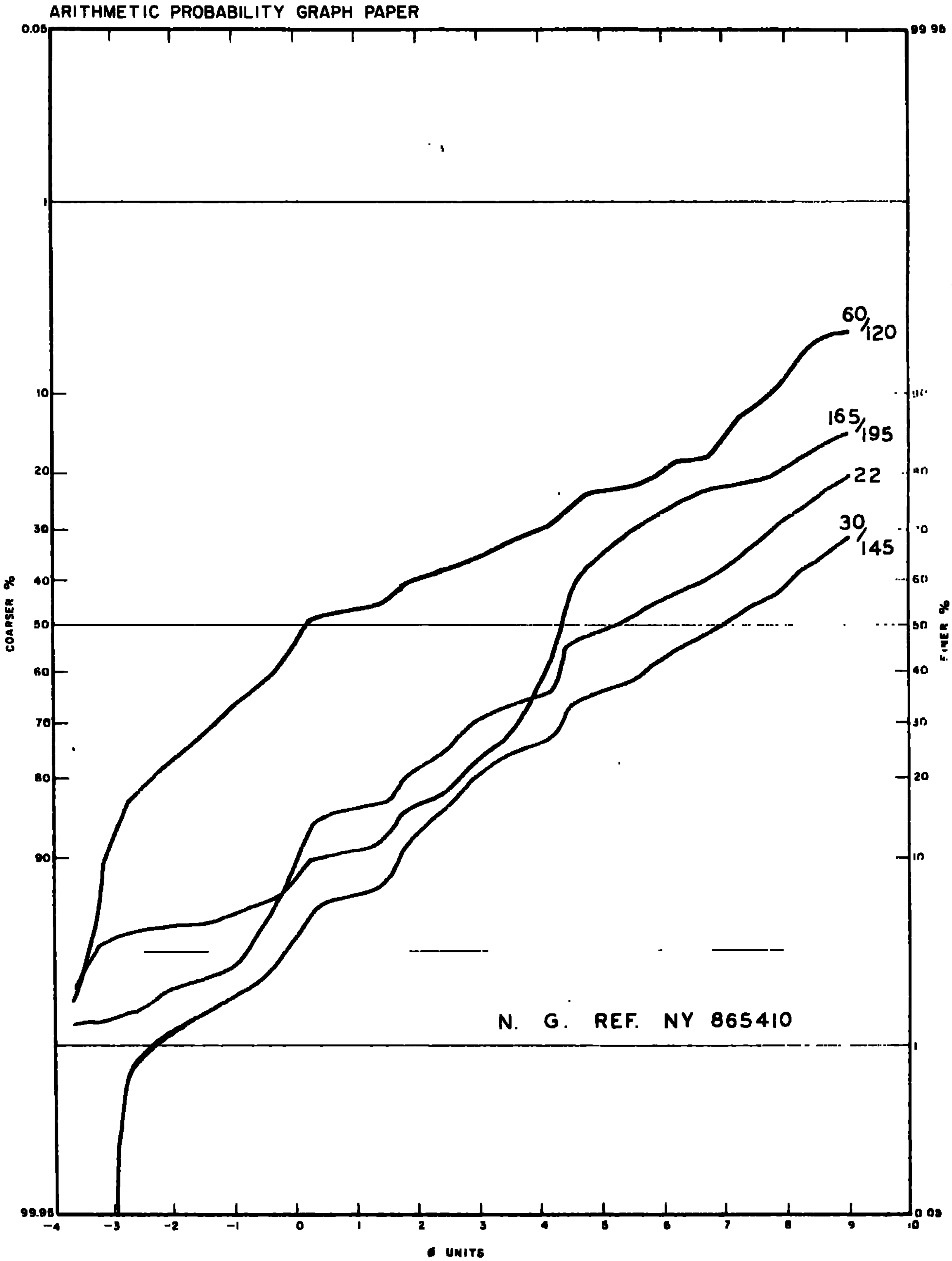


ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
30
90/105
180
150
60
90
N. G. REF. NY 852407
ø UNITS

NAT. GRID REF. NY 865410

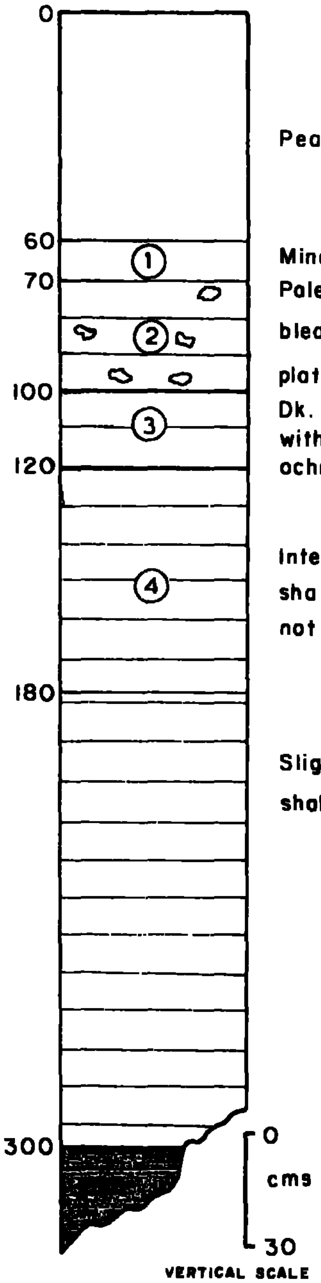


PROFILE (depth)	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
0–17	Turf		
17 (A)	Soil 'B'		1(.8624)
17–45 (1)	Heavy gleyed silty clay		
45–65 (2)	Stone layer – large platy sst. 2' x 3" x 2" in silty gray clay		1(.9377)
65–120 (3)	Heavy blue clay (rotted shale)		2(.8088)
120–	195		4(.7204)

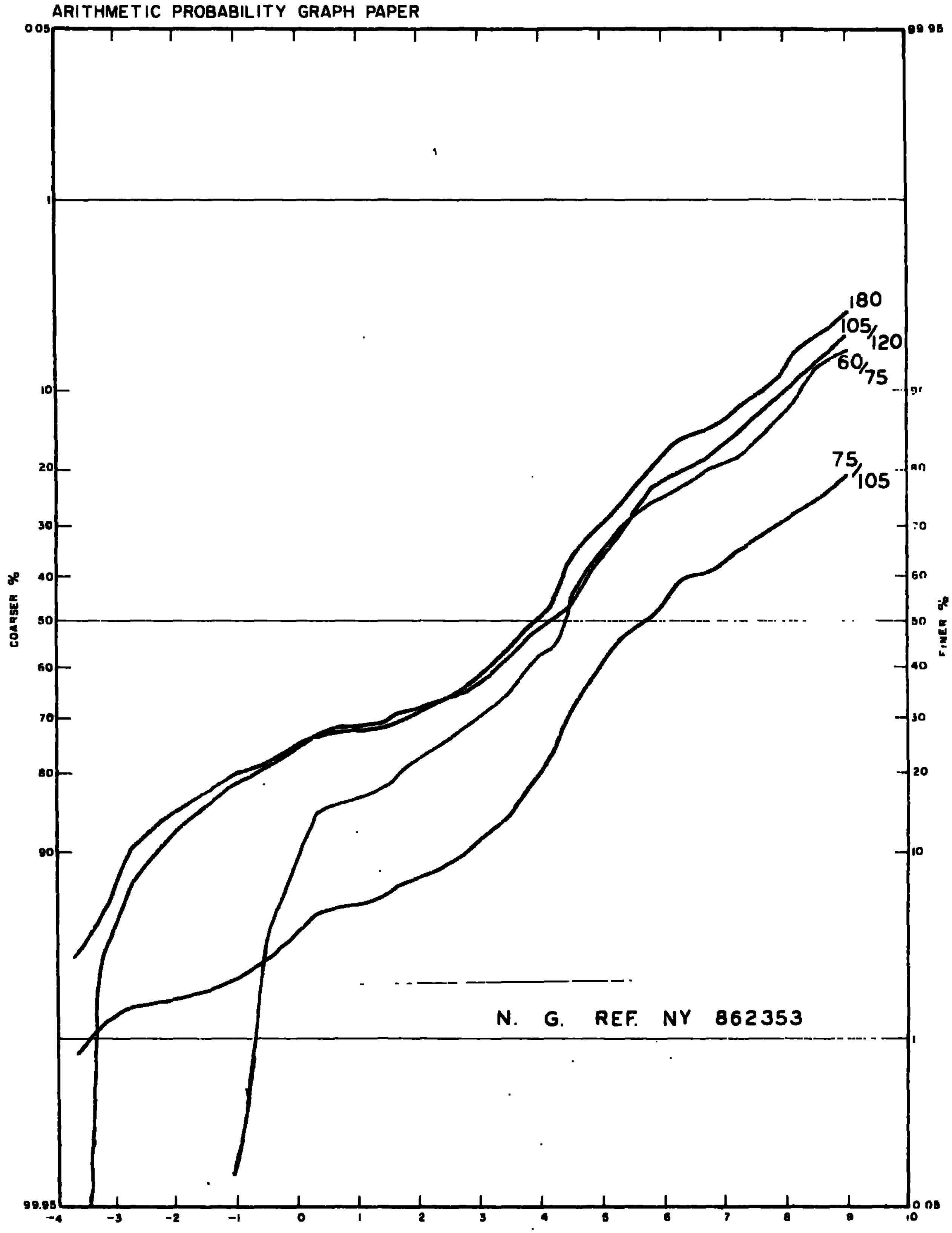


ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ø UNITS
60/120
165/195
22
30/145
N. G. REF. NY 865410

NAT. GRID REF. NY 862353

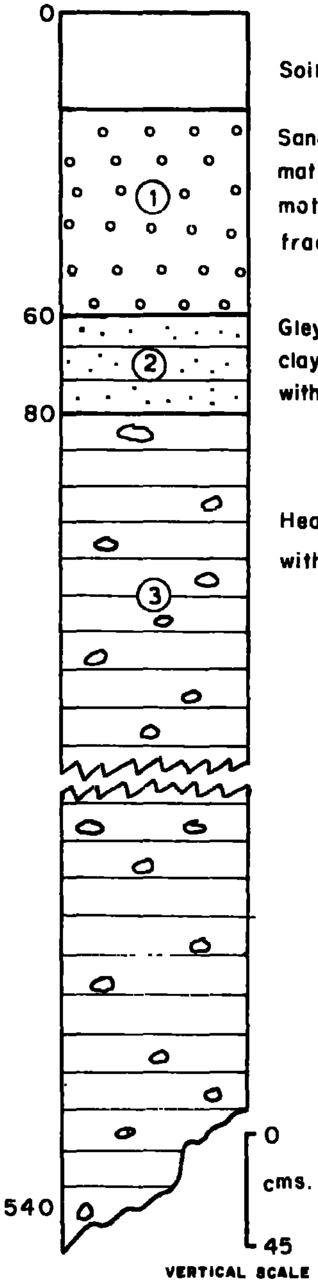


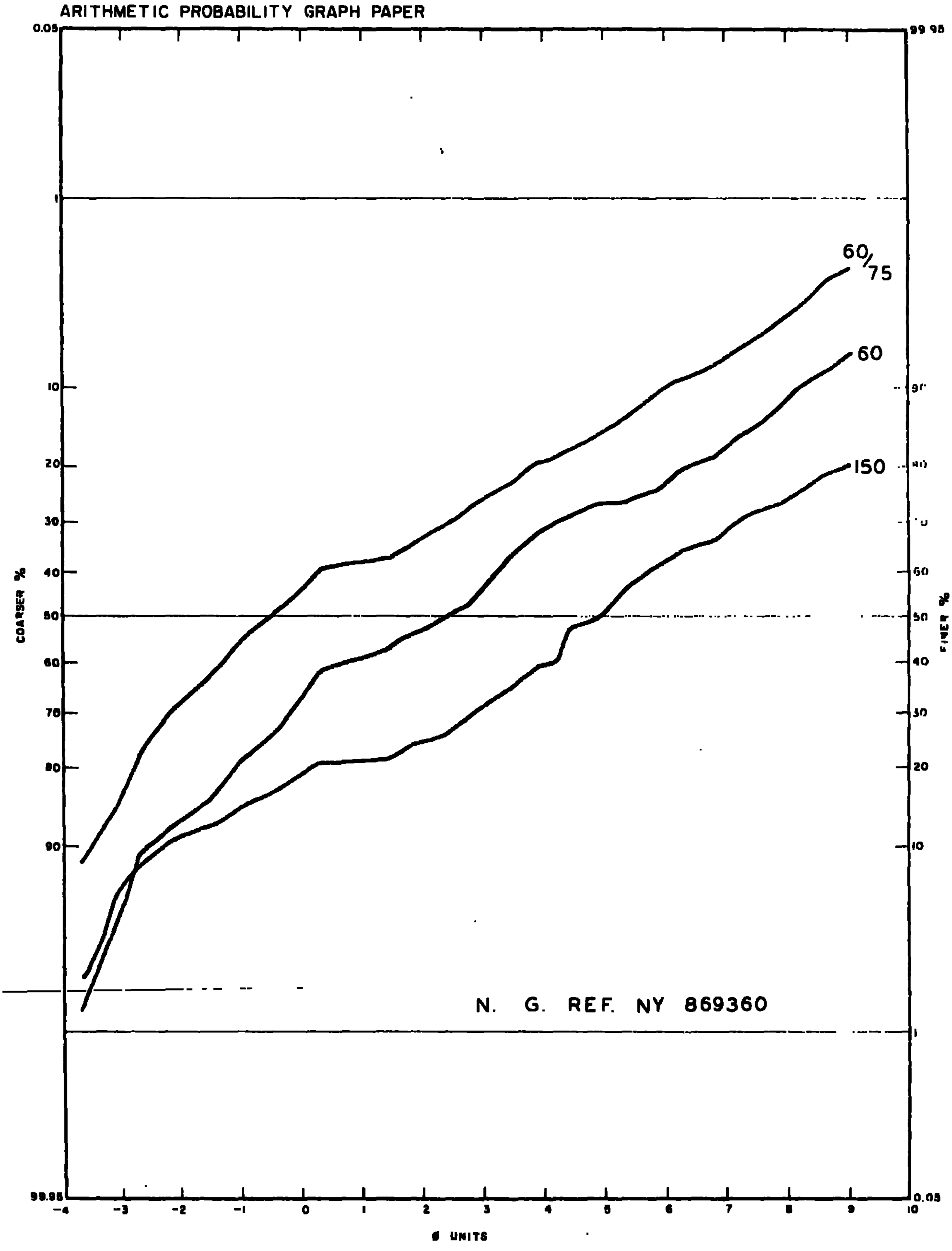
PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
0	Peat		
60 ①	Mineral soil		4 (.6635)
70 ②	Pale grey clay with bleached sst particles & platy sst up to 8"		1(.8866)
100 ③	Dk. blue clay material with root channels ochre/brown staining		1(.6130)
120 ④	Intensely weathered shale – foliation not shown.		4(.7233)
180	Slightly weathered shale		
300			



ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ø UNITS
180
105/120
60/75
75/105
N. G. REF. NY 862353

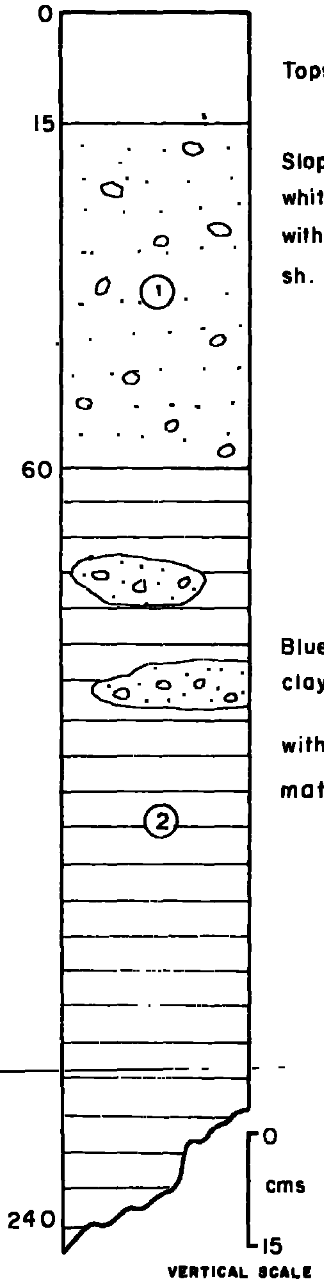
NAT. GRID REF. NY 869360

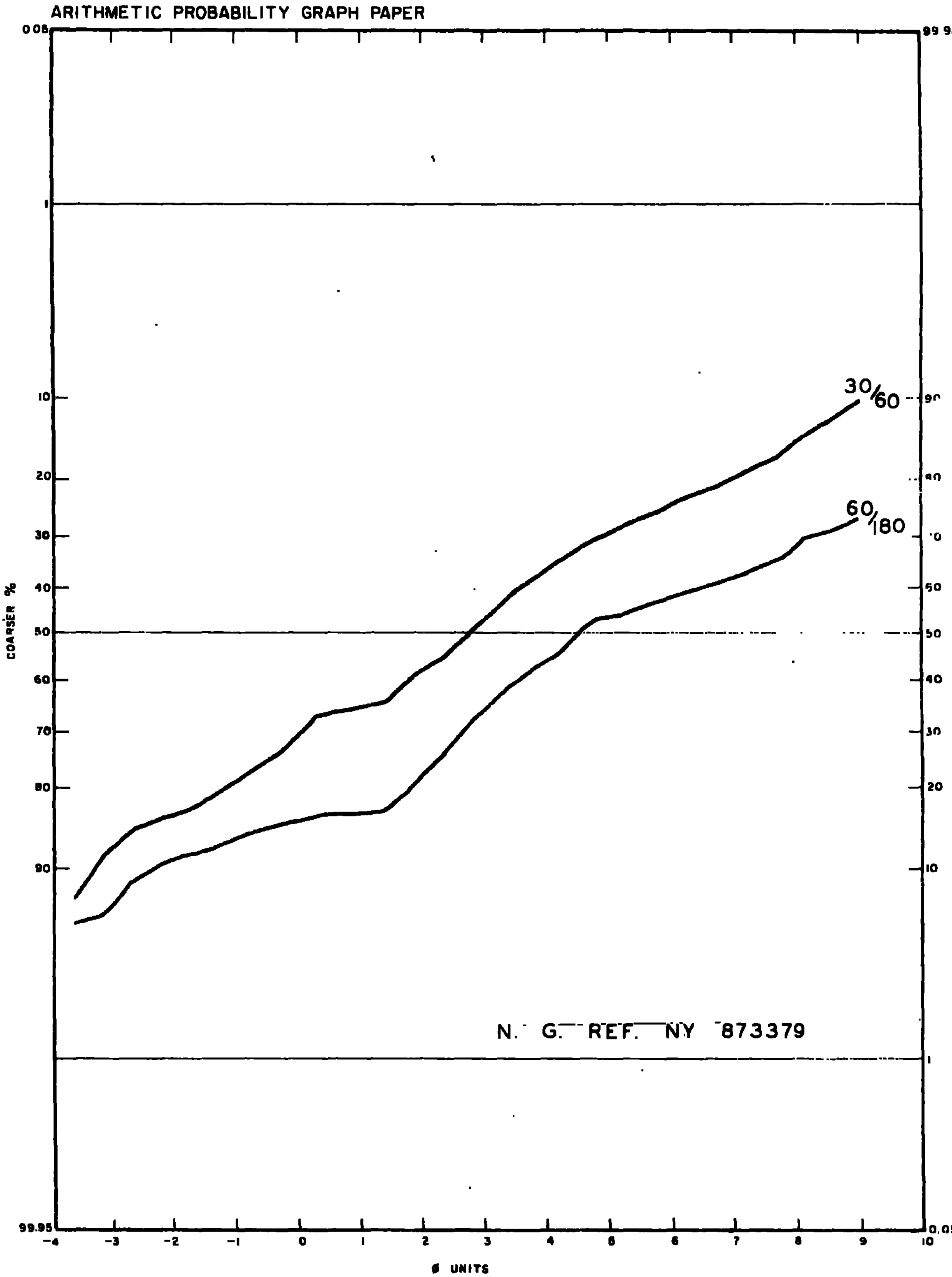
PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
	Soil		
	Sandy deposit light grey material with ochre mottles & platy sst fragments		2(.5825)
	Gley material silty clay darker than above with brown/ochre mottles		2(.9193)
	Heavy bluish clay with stones sh. sst		1(.8503)
	Deposit appears homogeneous		



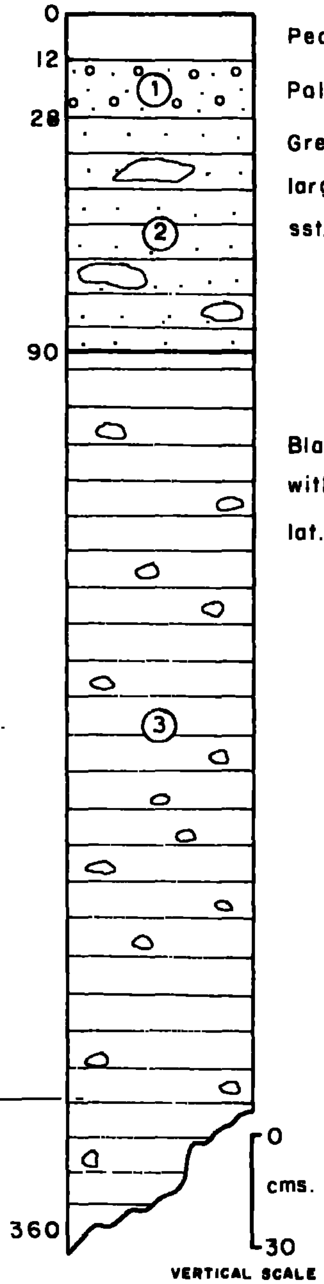
ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ø UNITS
60/75
60
150
N. G. REF. NY 869360

NAT. GRID REF. NY 873379

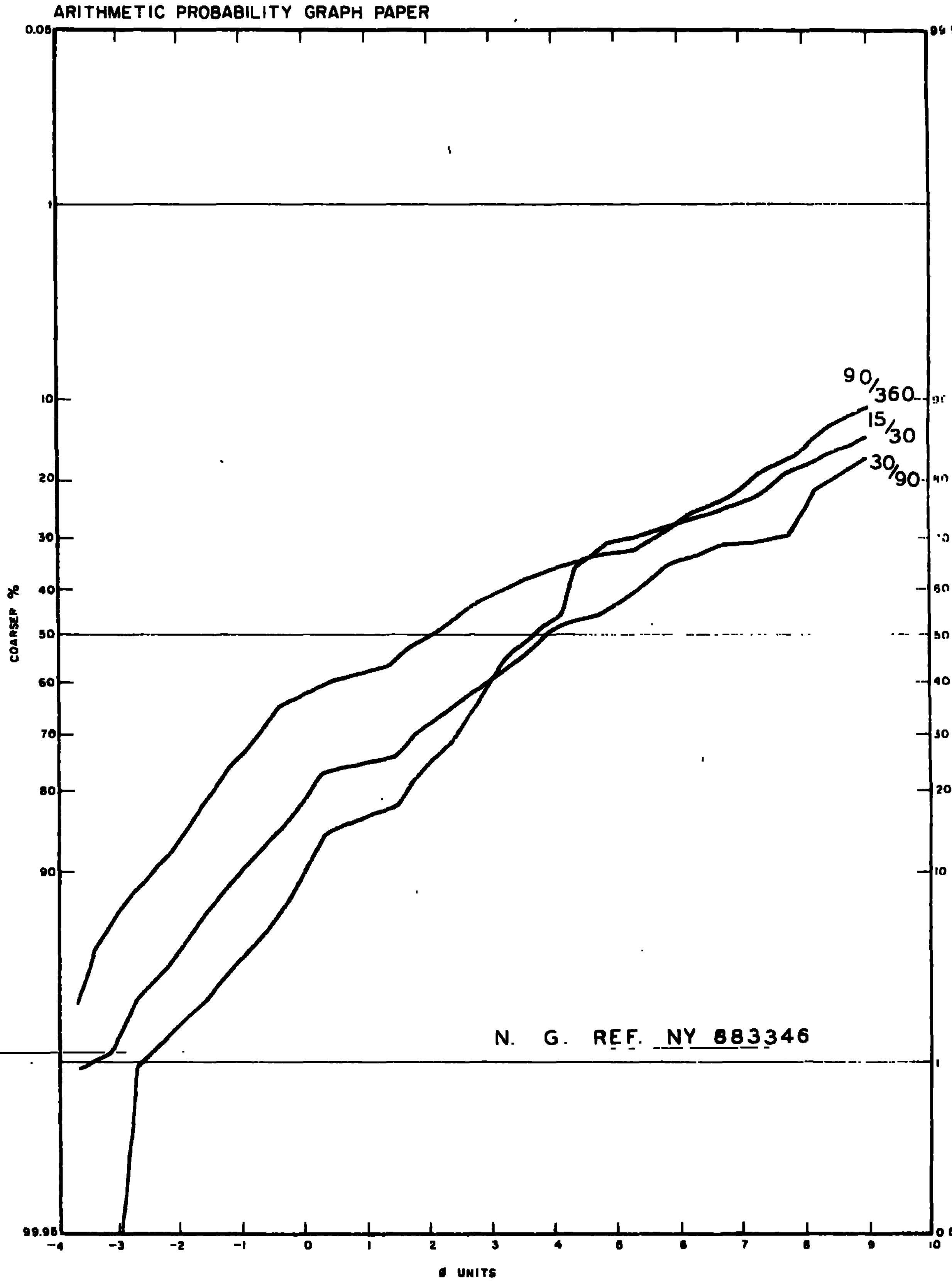
PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
	Topsoil & turf		
	Slope. deposit white/grey silty material with fragments of sst. sh. lat.		1(.5660)
	Blue boulder clay with lenses of above material enclosed		1(.8209)


ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
30/60
60/180
N. G. REF. NY 873379
ø UNITS

NAT. GRID REF. NY 883346



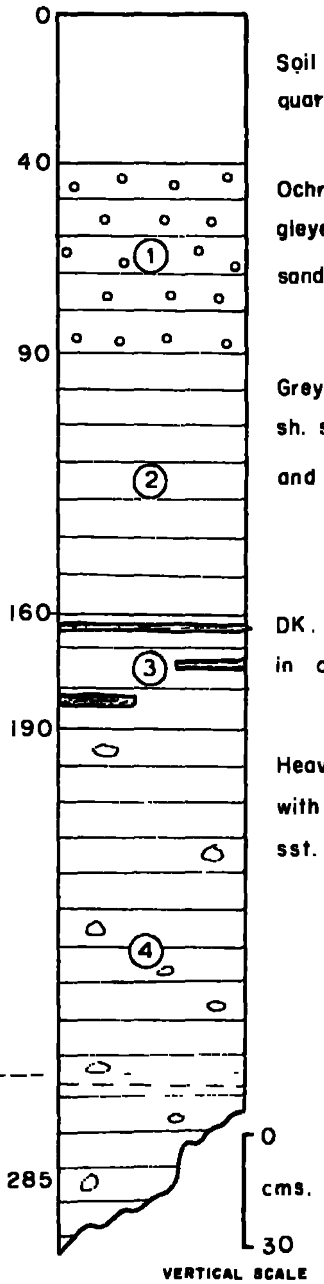
PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
0–12	Peaty turf		
12–28 (1)	Pale grey sandy silt		4 (.6068)
28–90 (2)	Grey silty clay with large sub-angular sst. blocks		1 (.7467)
90–360 (3)	Black-brown clay with stones inc., sst., lat., sh.		2 (.6656)



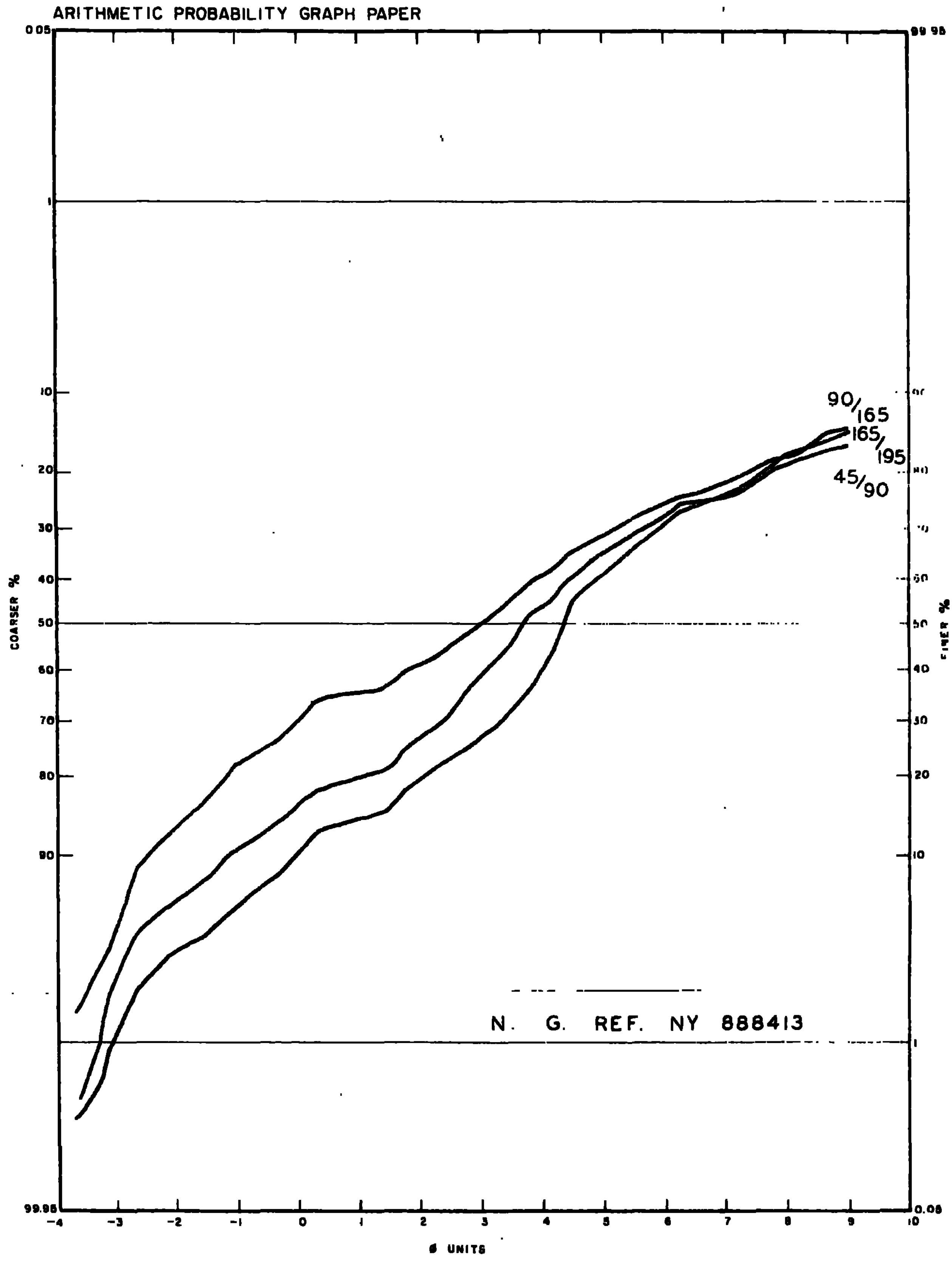
ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ϕ UNITS
90/360
15/30
30/90
N. G. REF. NY 883346

NAT. GRID REF. NY 888413

PROFILE

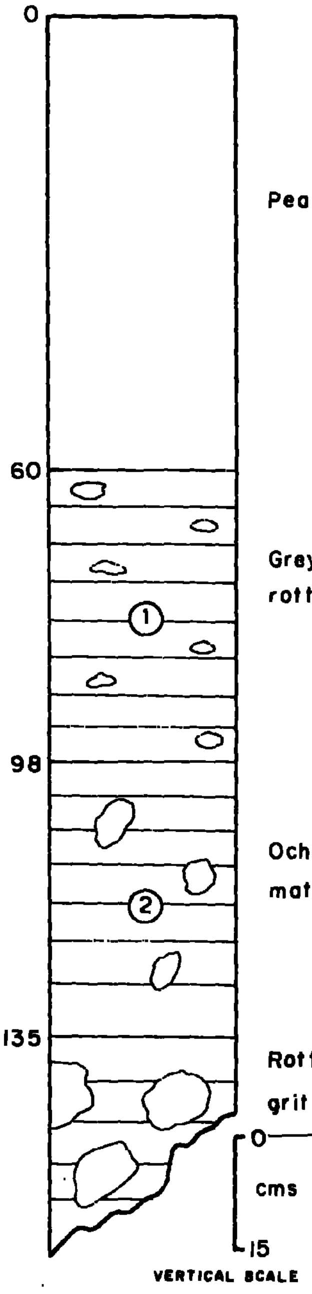


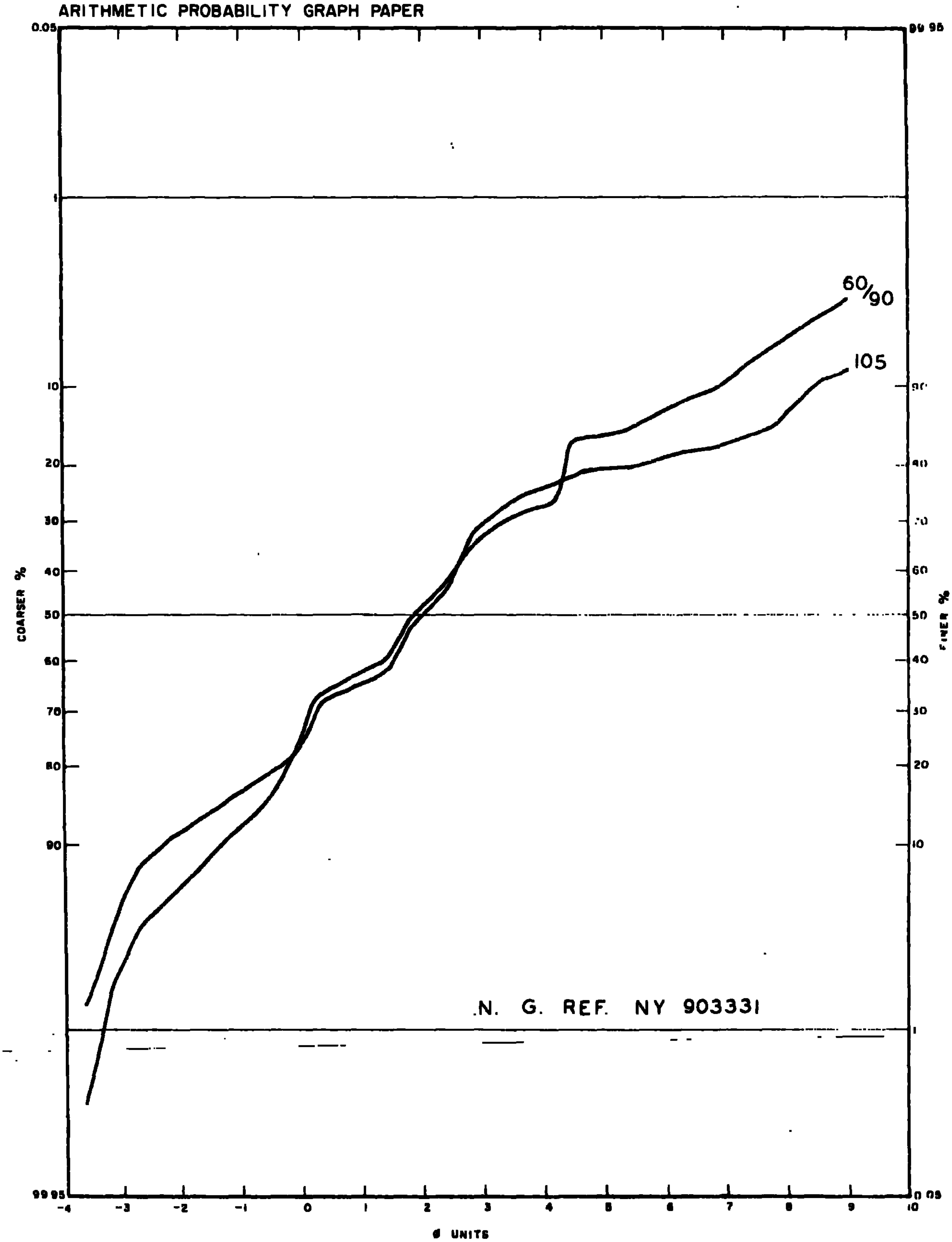
FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
Soil with large quartzite boulders		
Ochre/silver grey gleyed clay material sandy with boulders		
Grey flaky clay with sh. sst. coal flakes and large qzite stones		1 (.6869)
DK. bands of material in dk. grey deposit.		1 (.6366)
Heavy clay material with pebbles — sst. sh. qzite		1 (.6891)



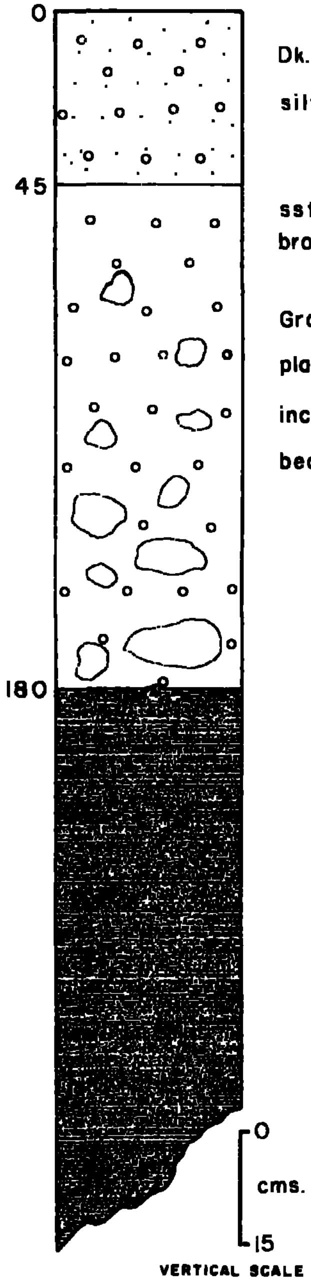
ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
Ø UNITS
90/165
165/195
45/90
N. G. REF. NY 888413

NAT. GRID REF. NY 903331

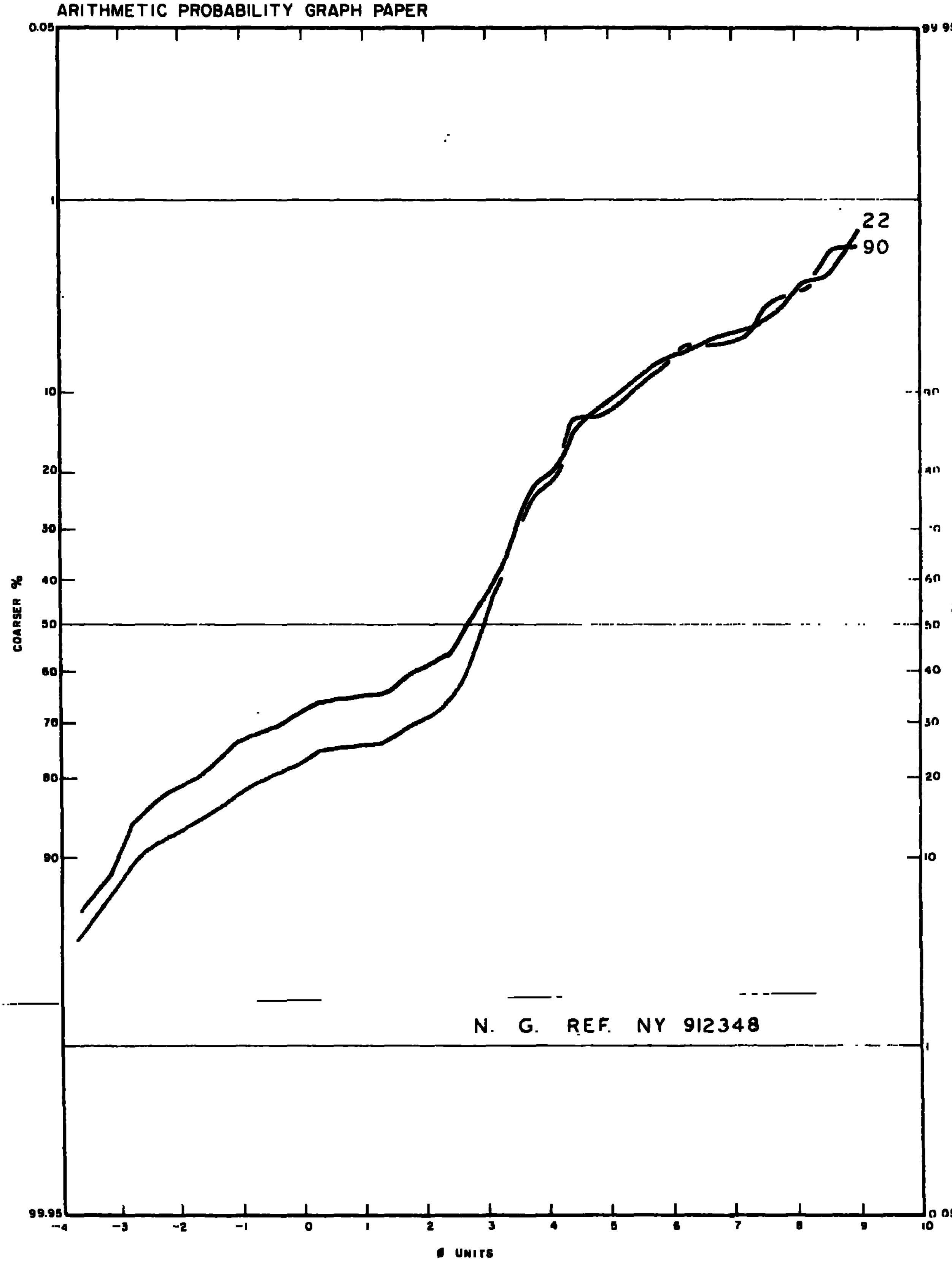
PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
			
	Peat		
	Grey clay with rotted sst.		3 (.7334)
	Ochre & grey sst. in matrix of clay		3 (.7484)
	Rotted millstone grit with clay		———


ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ϕ UNITS
60/90
105
N. G. REF. NY 903331

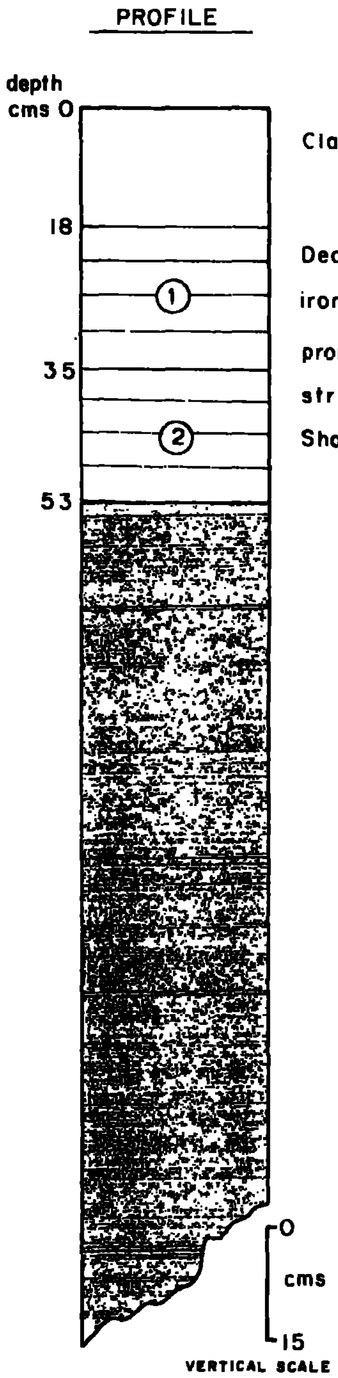
NAT. GRID REF. NY 912348



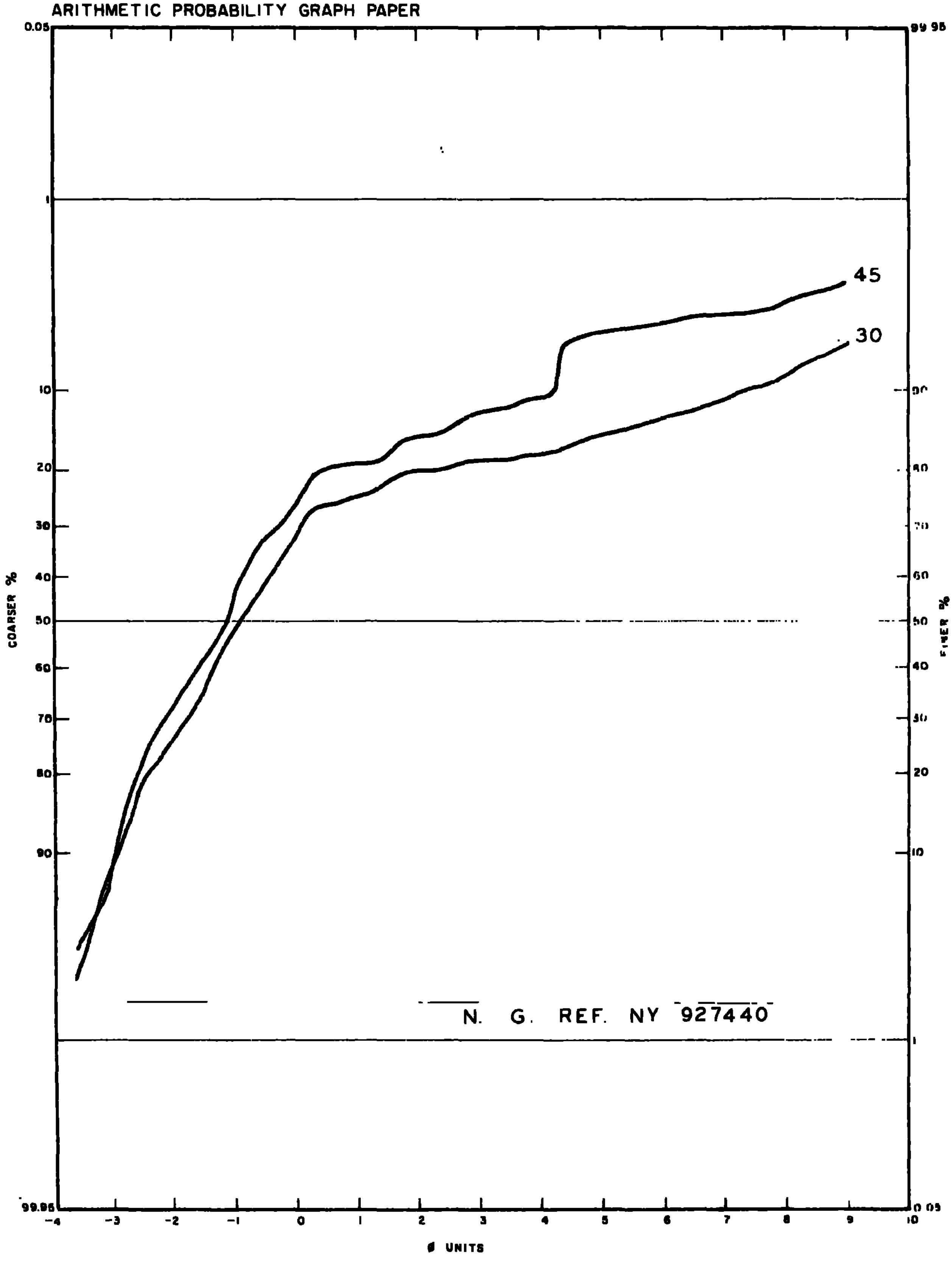
PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
0–45	Dk. brown sandy silty soil		4 (.7749)
45–180	sst. fragments in dk. brown sandy matnx Grading into large platy zone of sst. increasing in size as bedrock is reached		4 (.7898)


ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ø UNITS
22
90
N. G. REF. NY 912348

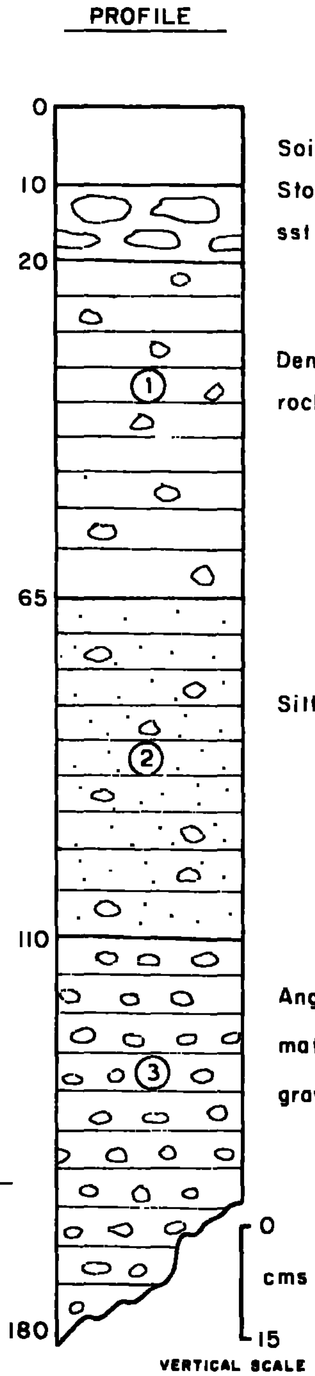
NAT. GRID REF. NY 927440



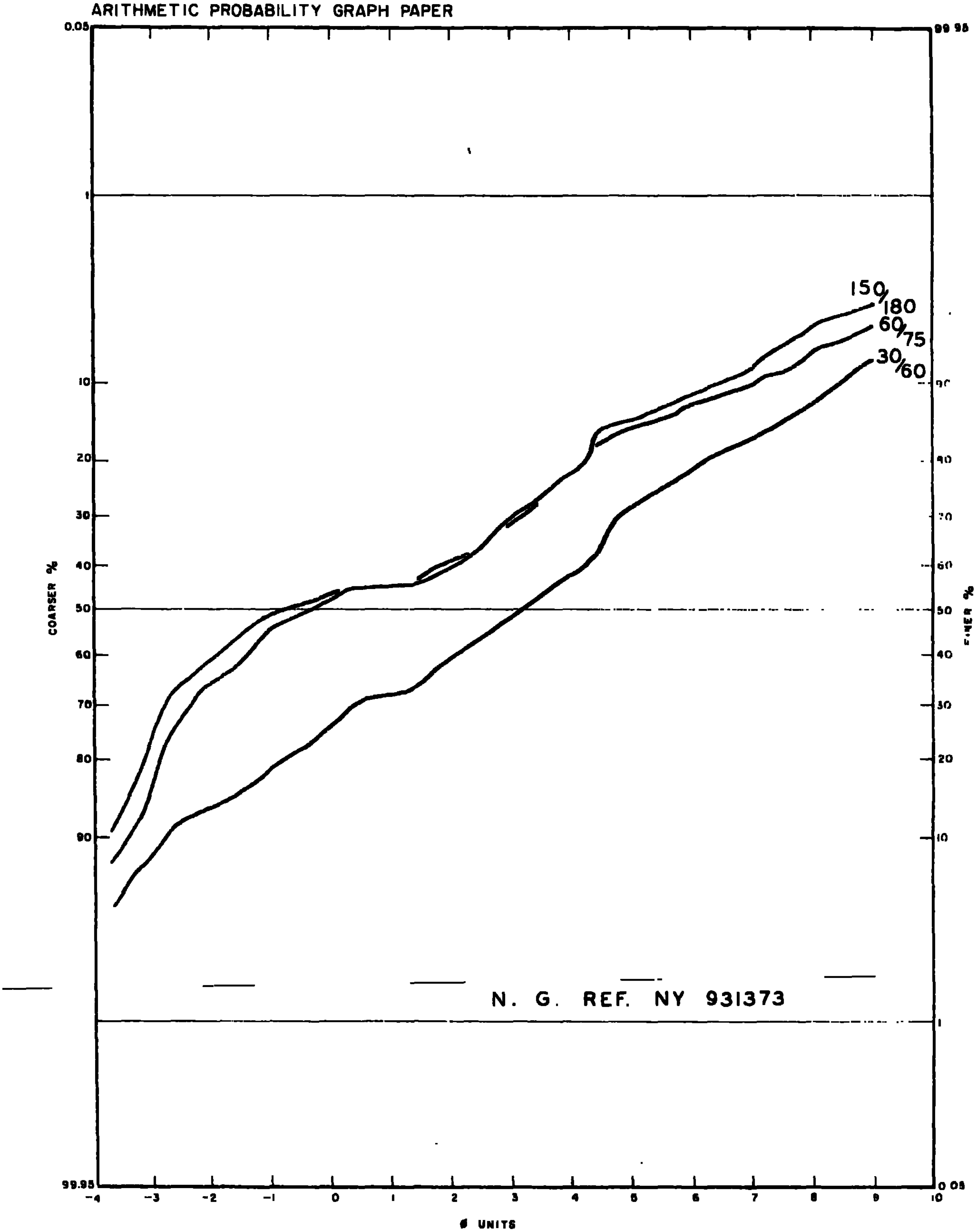
FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
Clay — soil		
Decomposed shale incl. iron-staining and pronounced crumb-structure		2 (.9116)
Shale slightly-weathered		2 (.9252)


ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ø UNITS
45
30
N. G. REF. NY 927440

NAT. GRID REF. NY 931373

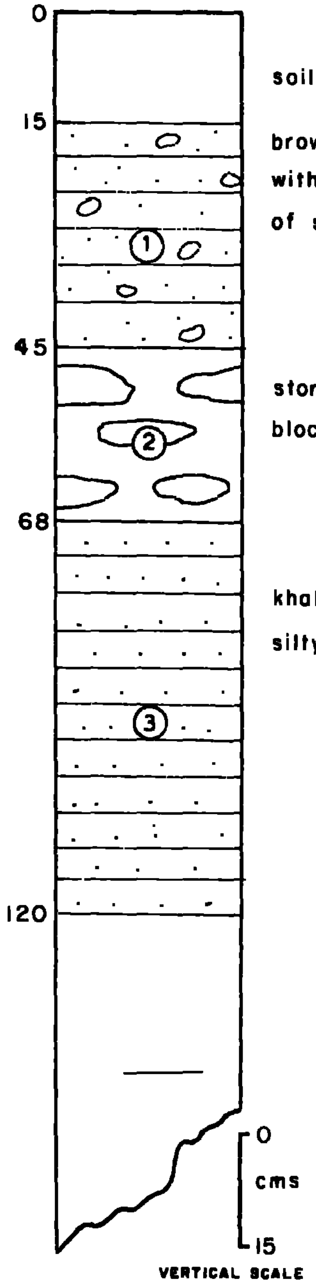


FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
Soil		
Stone layer — rounded ssl up to 7"		
Dense clay with rotted rock fragment.		1 (.5796)
Silty clay with stones		2 (.7875)
Angular gravels in a matrix of finer gravel & clay		2 (.8086)

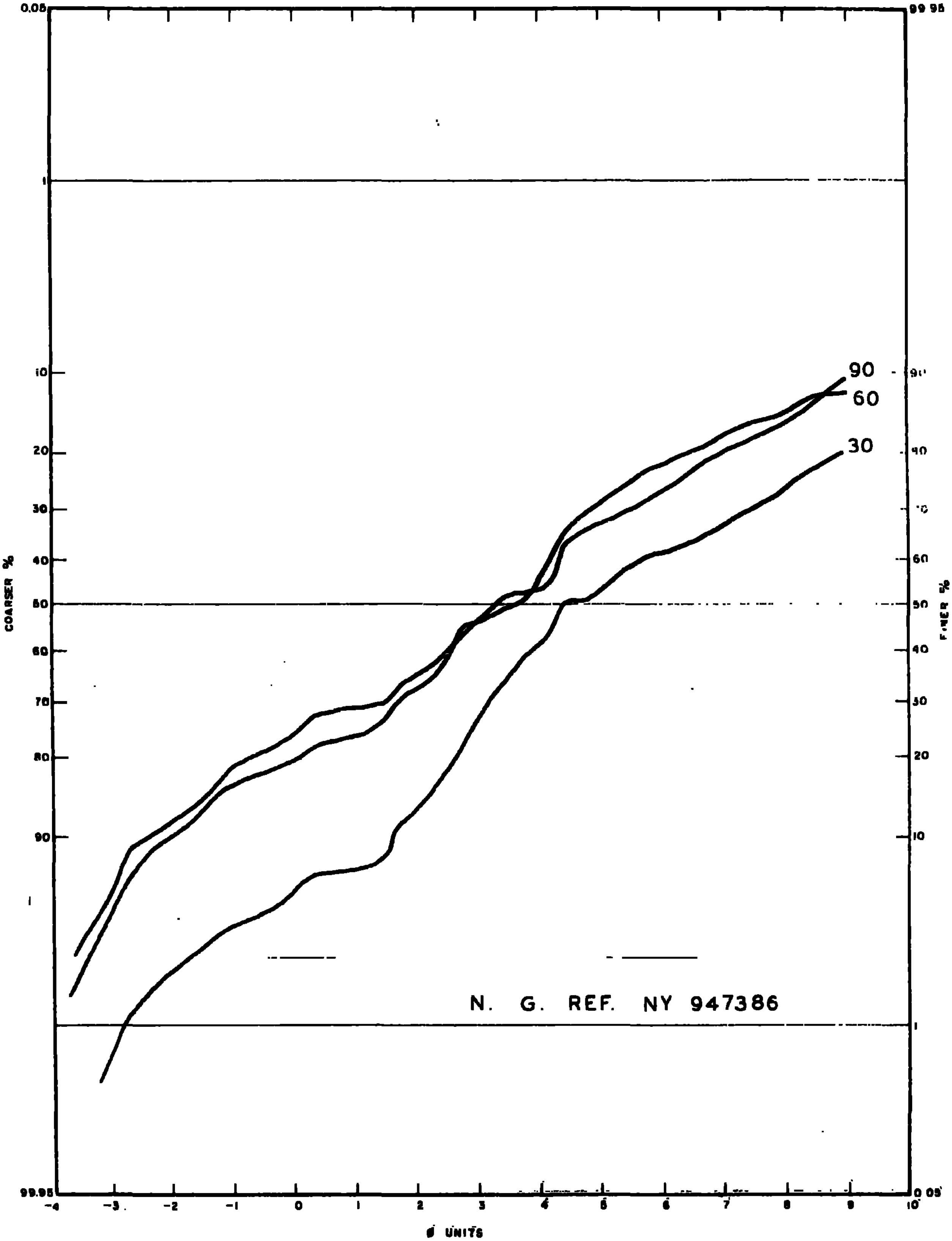


ARITHMETIC PROBABILITY GRAPH PAPER
150/180
60/75
30/60
COARSER %
FINER %
N. G. REF. NY 931373
ø UNITS

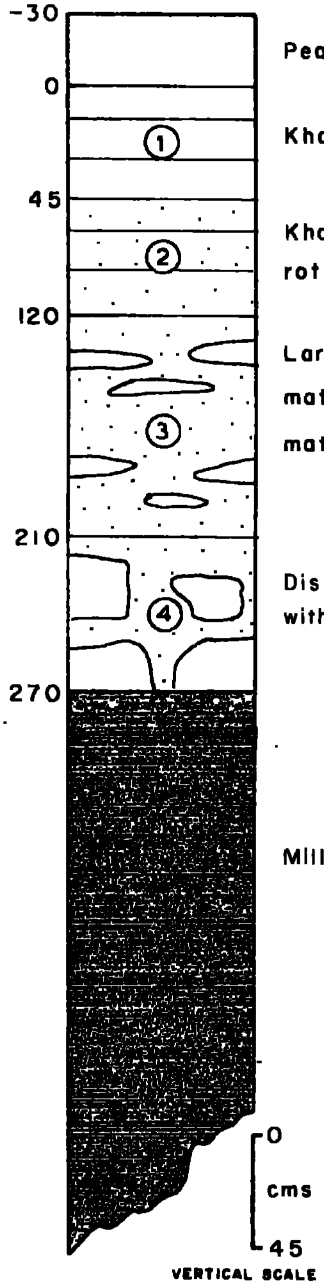
NAT. GRID REF. NY 947386

PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
			
	soil		
	brown silty clay with angular pebbles of sst, coal, sh.		1 (.7658)
	stony layer blocks of sst up to 1"		4 (.6035)
	khaki coloured silty clay material		1 (.6232)

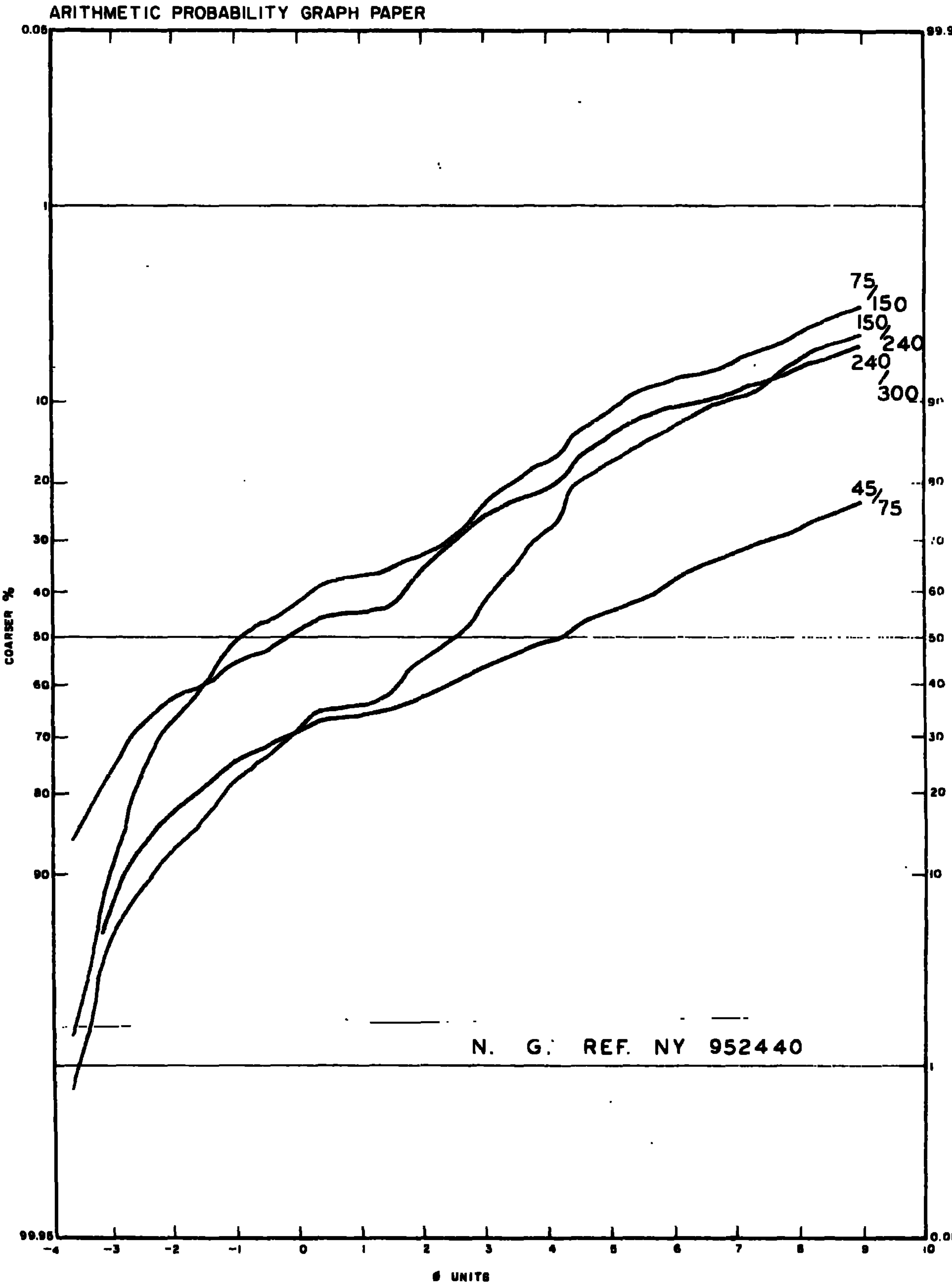
ARITHMETIC PROBABILITY GRAPH PAPER



NAT. GRID REF. NY 952440

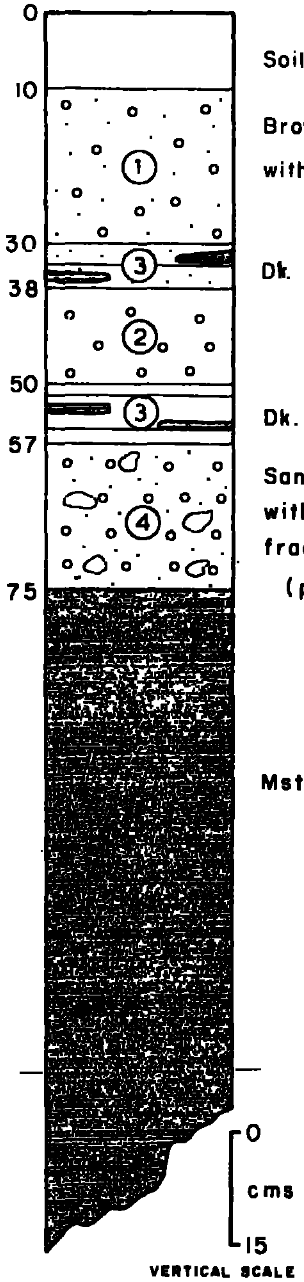


PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
	Peat		
1	Khaki clay		1(.7792)
2	Khaki coloured rotted shale		2(.8727)
3	Large platy sst in matrix of silty material.		4(.6381)
4	Disturbed bedrock with silty material		2(.7524)
	Millstone grit		

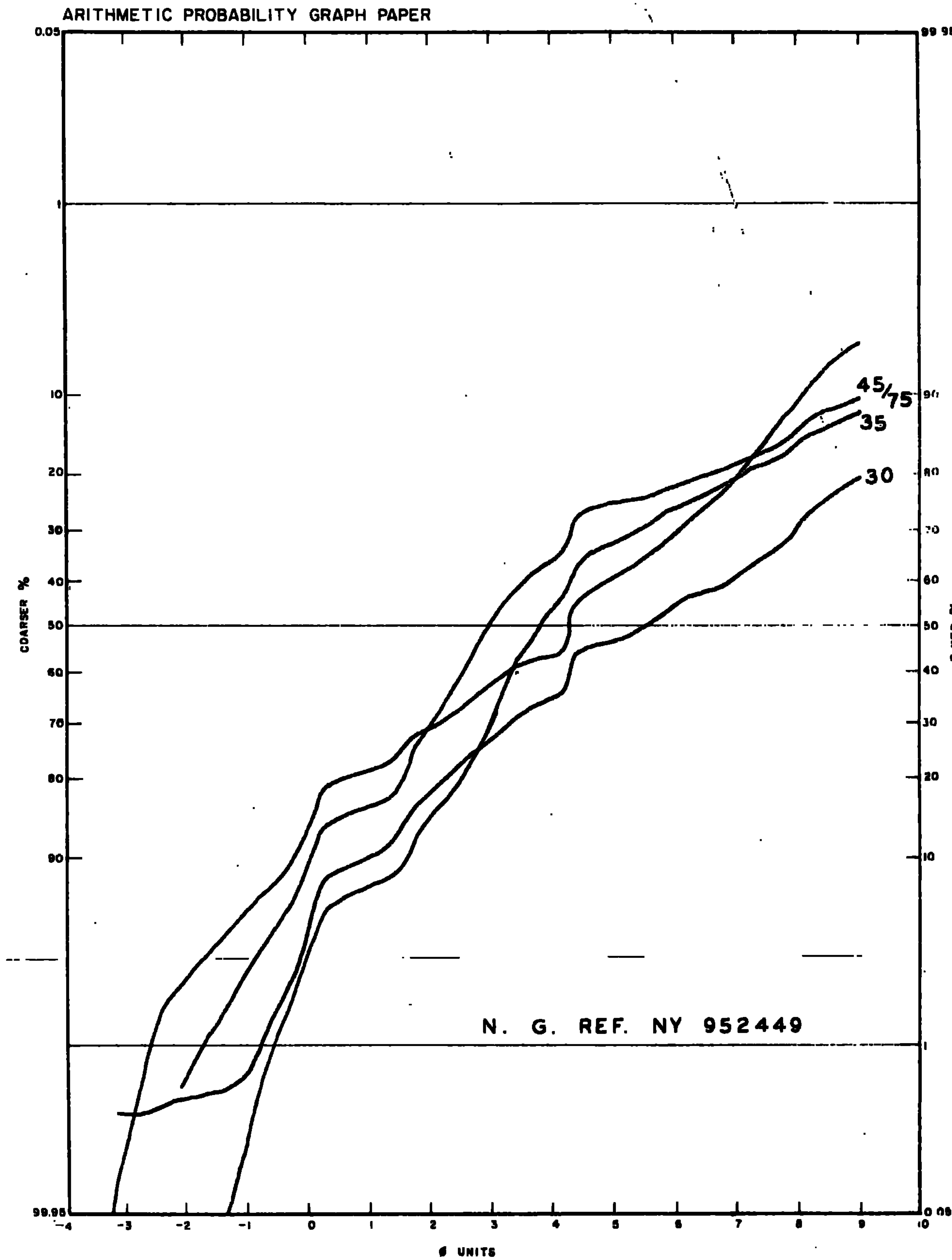

ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
Ø UNITS
75/150
150/240
240/300
45/75
N. G. REF. NY 952440

NAT. GRID REF. NY 952449

PROFILE

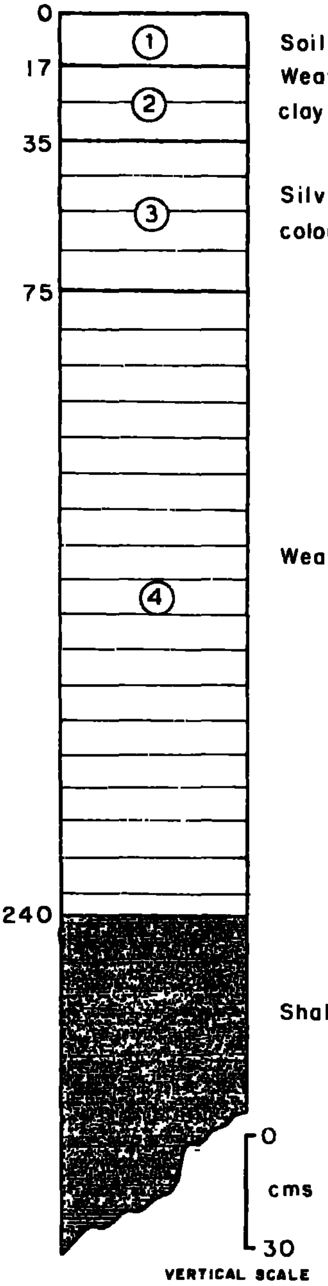


FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
Soil		
Brown sandy – silt with ochre		1(.8606)
Dk. band black (organic)		1(.6399)
		4(.7285)
Dk. band clay material		1(.6399)
Sandy silty material with assorted rock fragments (pudding stone)		3(.6522)
Mst grit		

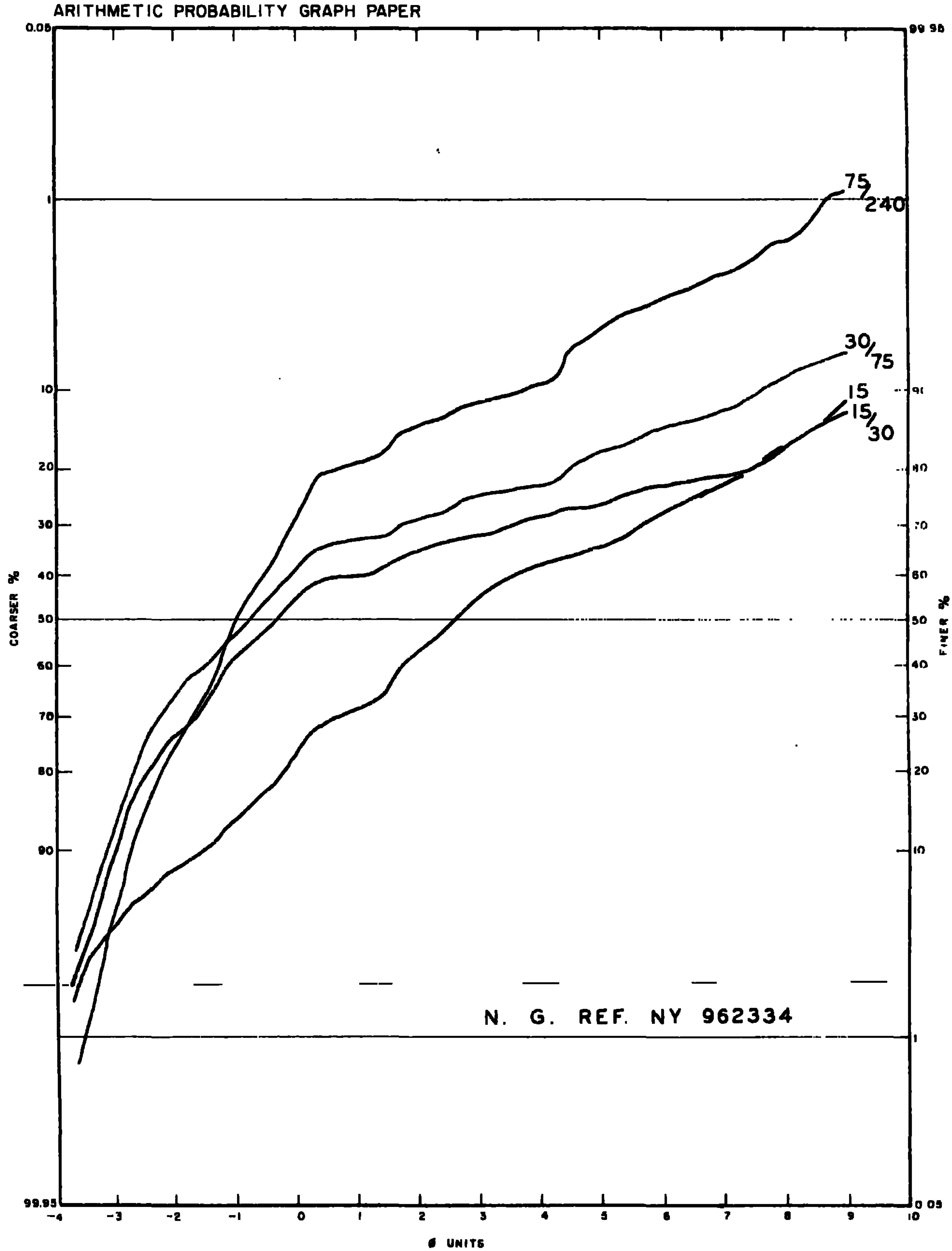

ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ø UNITS
45/75
35
30
N. G. REF. NY 952449

NAT. GRID REF. NY 962334

PROFILE

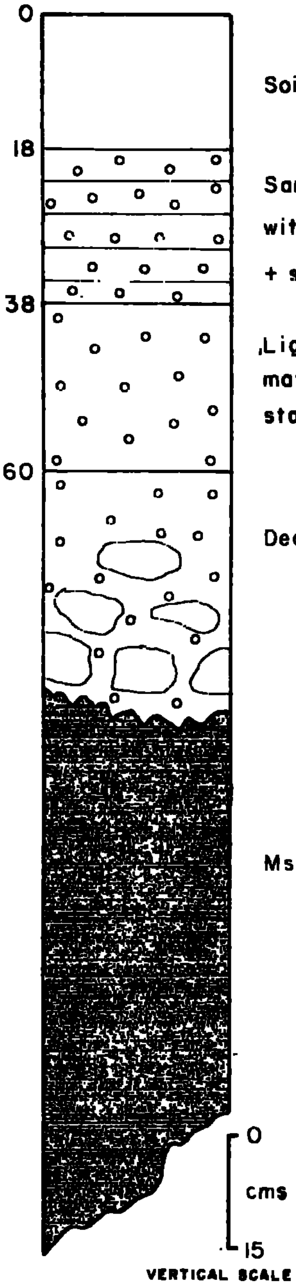


FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
Soil		3(.6381)
Weathered laminated clay khaki colour		2(.8709)
Silver grey/khaki coloured clay		2(.9270)
Weathered grey shale		2(.8740)
Shale		

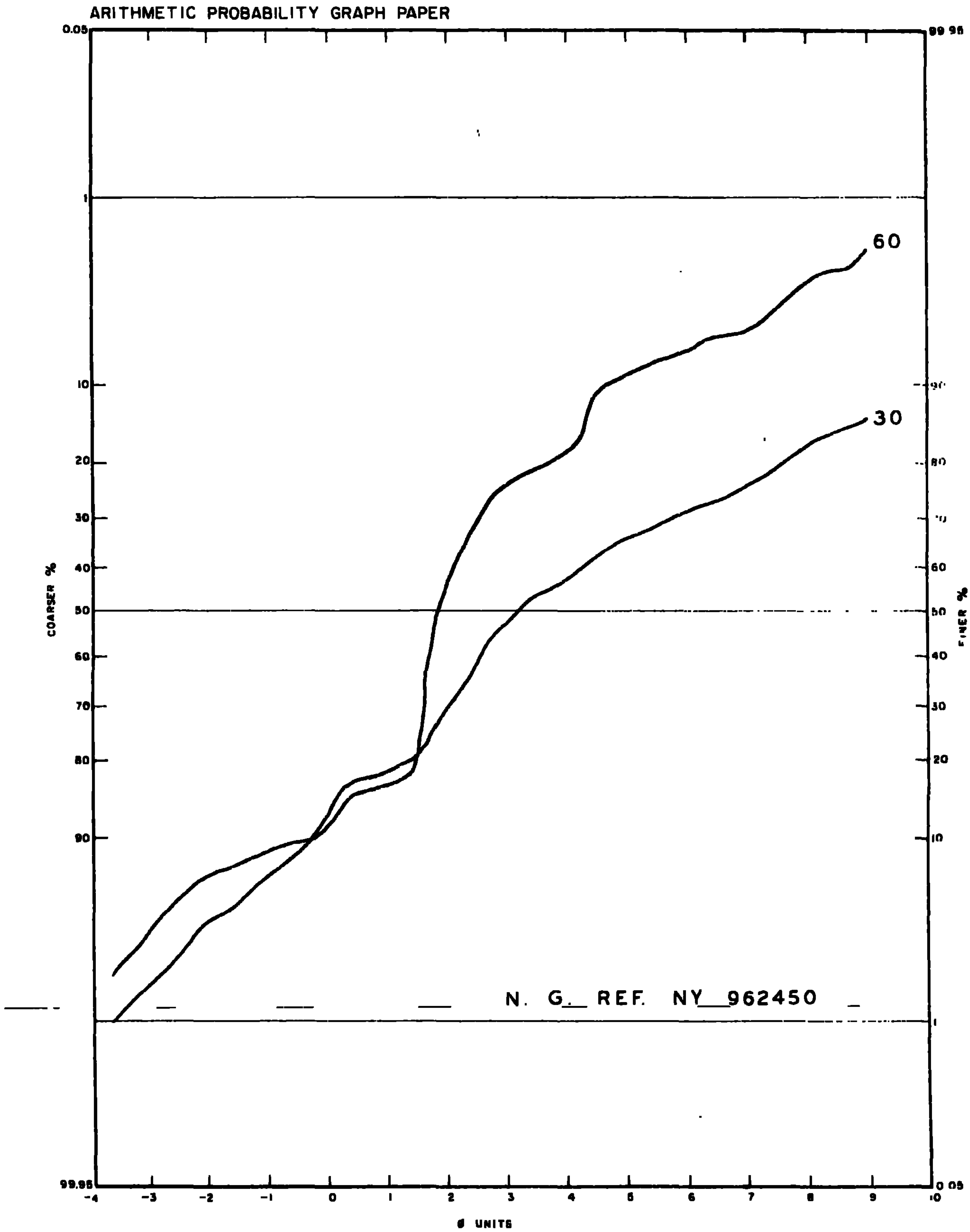

ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
Ø UNITS
75/240
30/75
15
15/30
N. G. REF. NY 962334

NAT. GRID REF. NY 962450

PROFILE



PROFILE (depth)	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
0–18	Soil		
18–38	Sandy clay light grey with ochre mottles + sst.		1(.6022)
38–60	Light grey sandy material with ochre stains.		3(.7326)
60–	Decomposing mst grit		
	Mst grit		


ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
0.05
1
10
20
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50
60
70
80
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99.95
99.95
90
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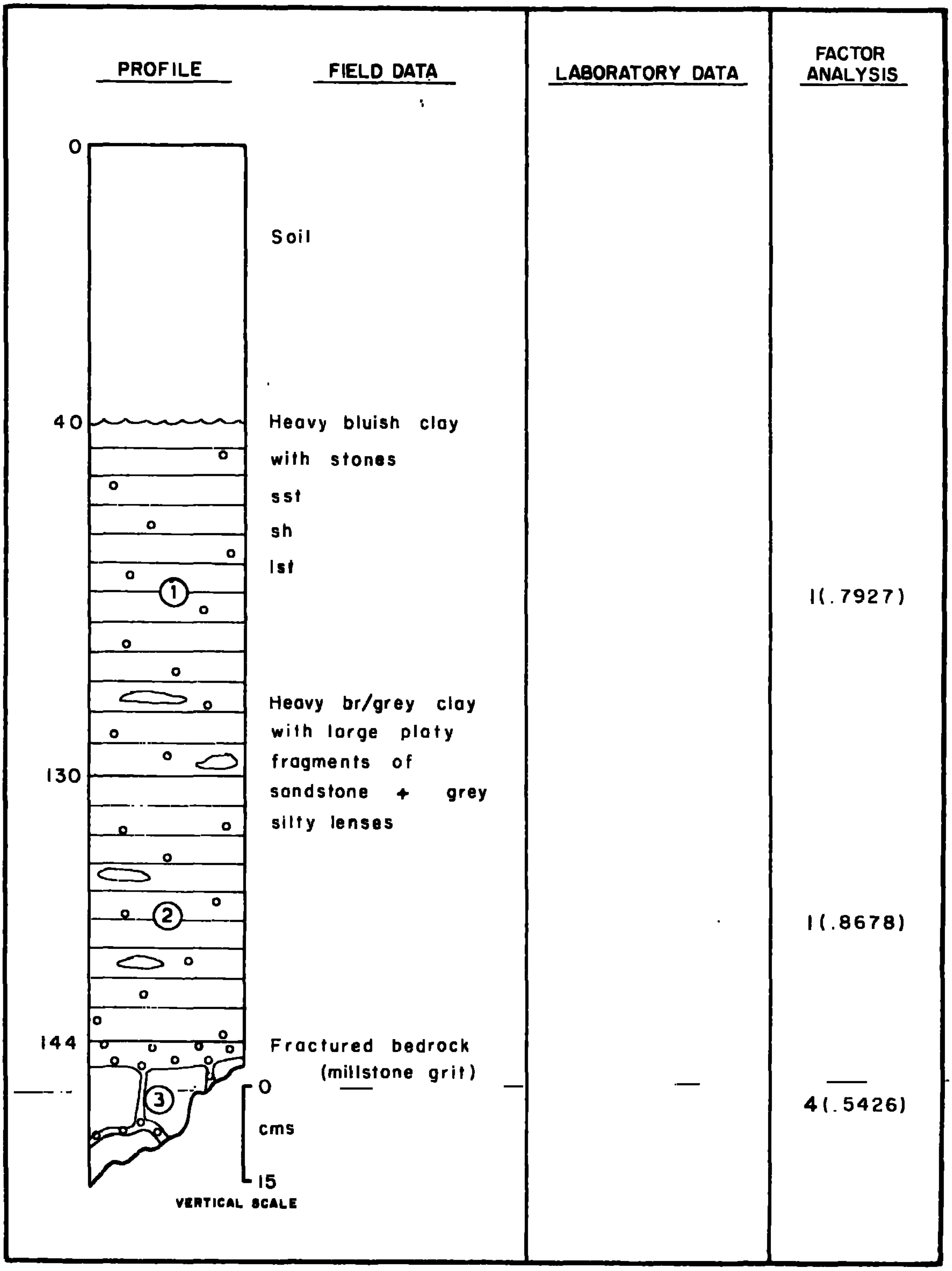
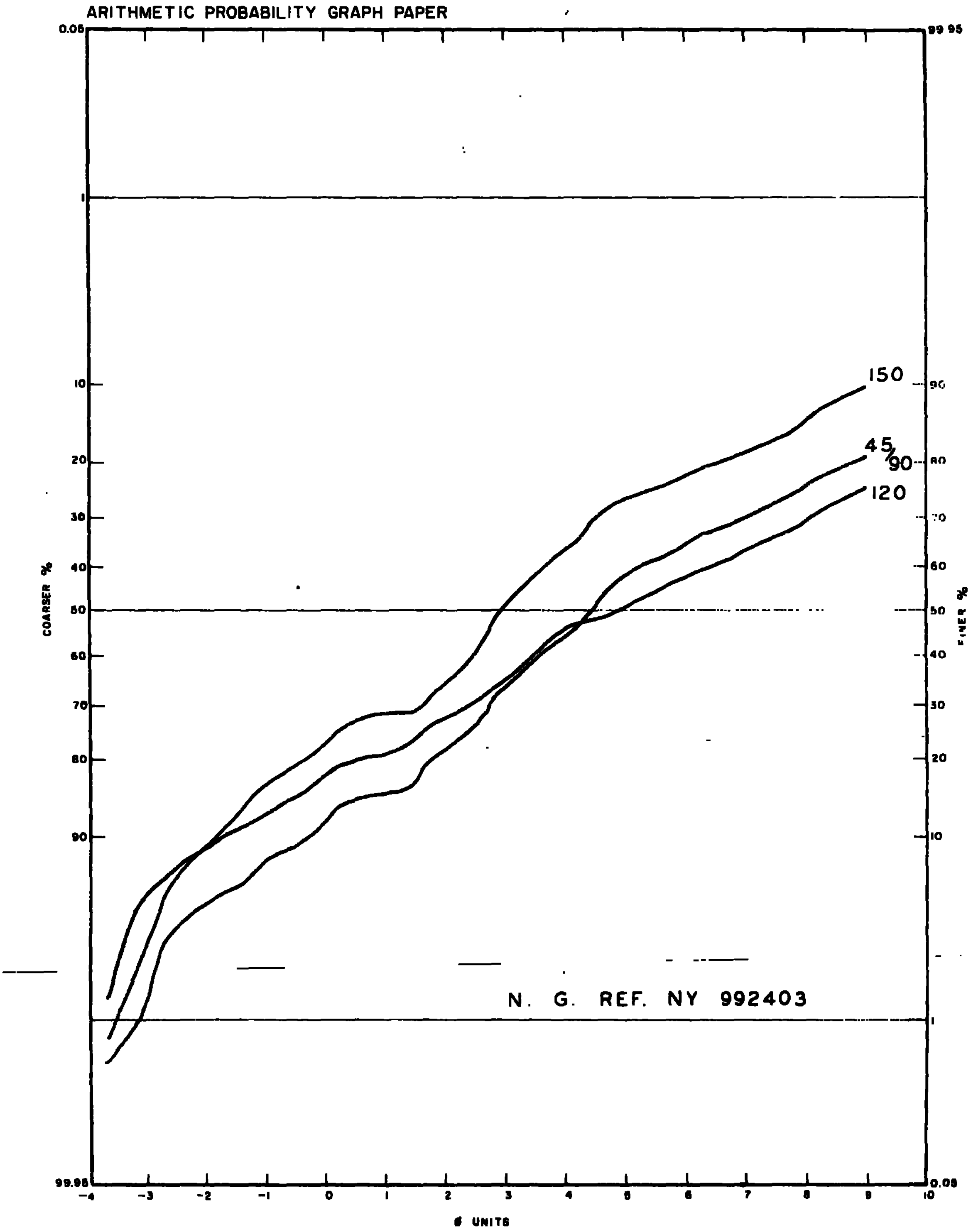
0.05
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
ø UNITS
60
30
N. G. REF. NY 962450

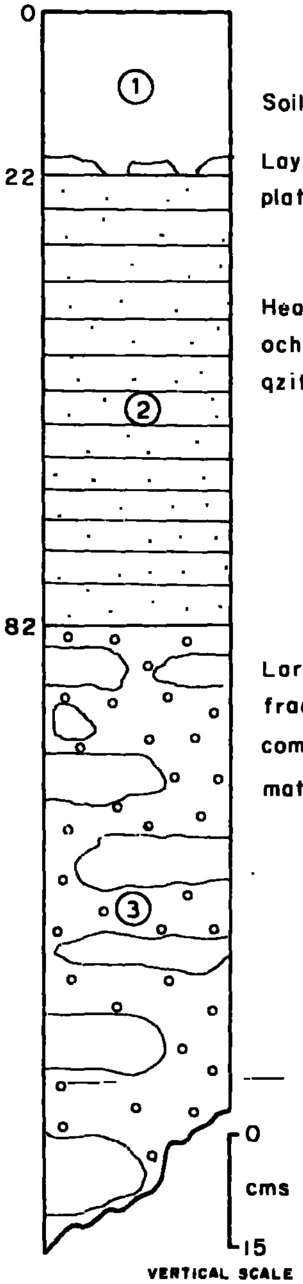
NAT. GRID REF. NY 992403




ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ø UNITS
150
45/90
120
N. G. REF. NY 992403

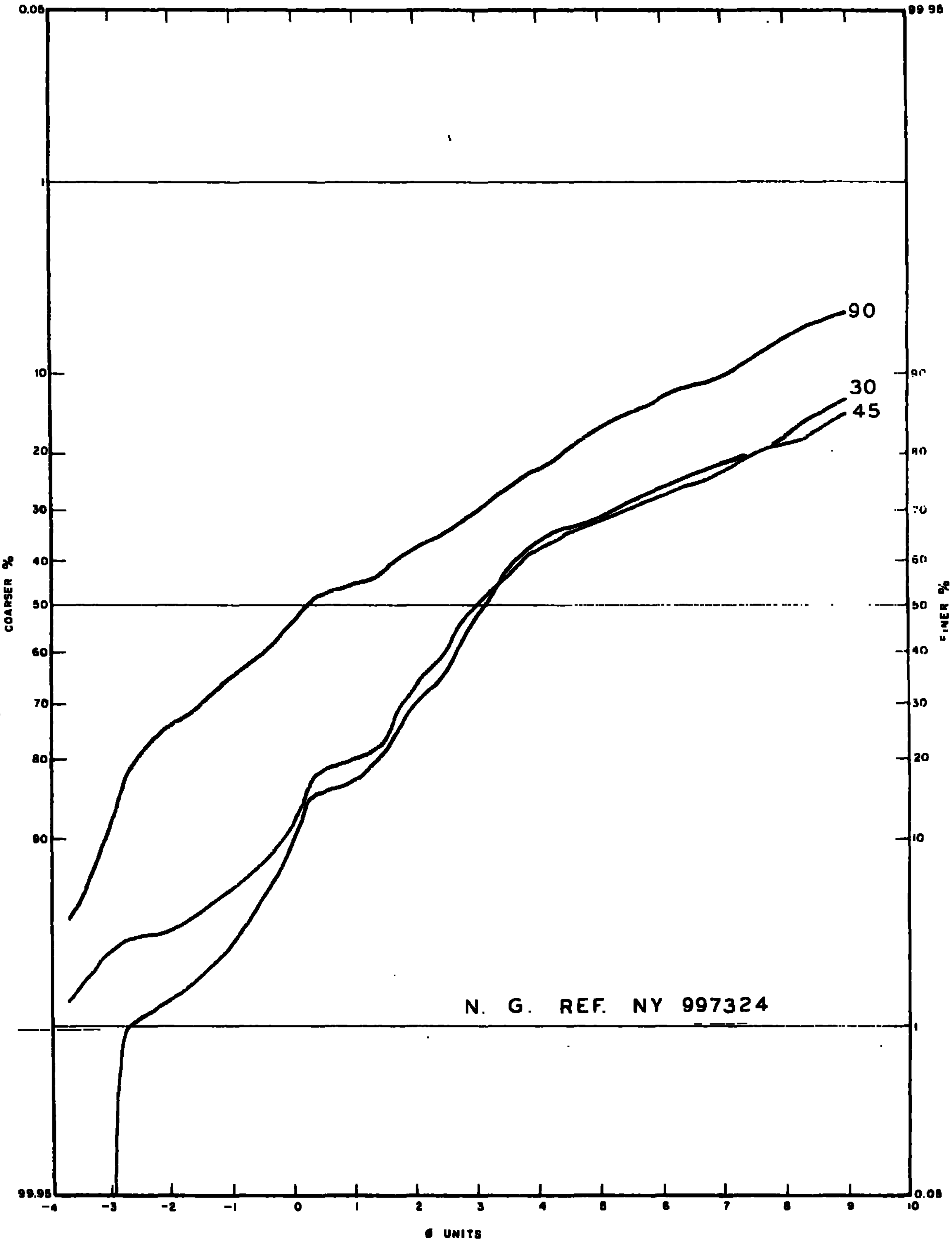
NAT. GRID REF. NY 997342

PROFILE

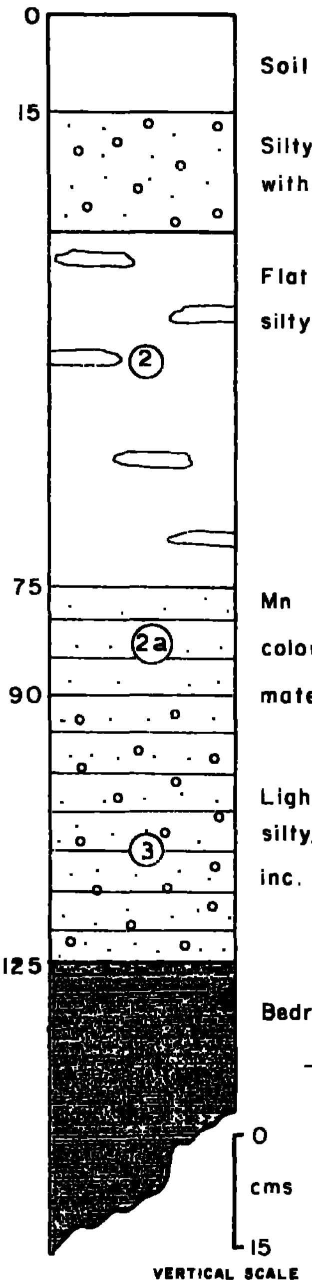


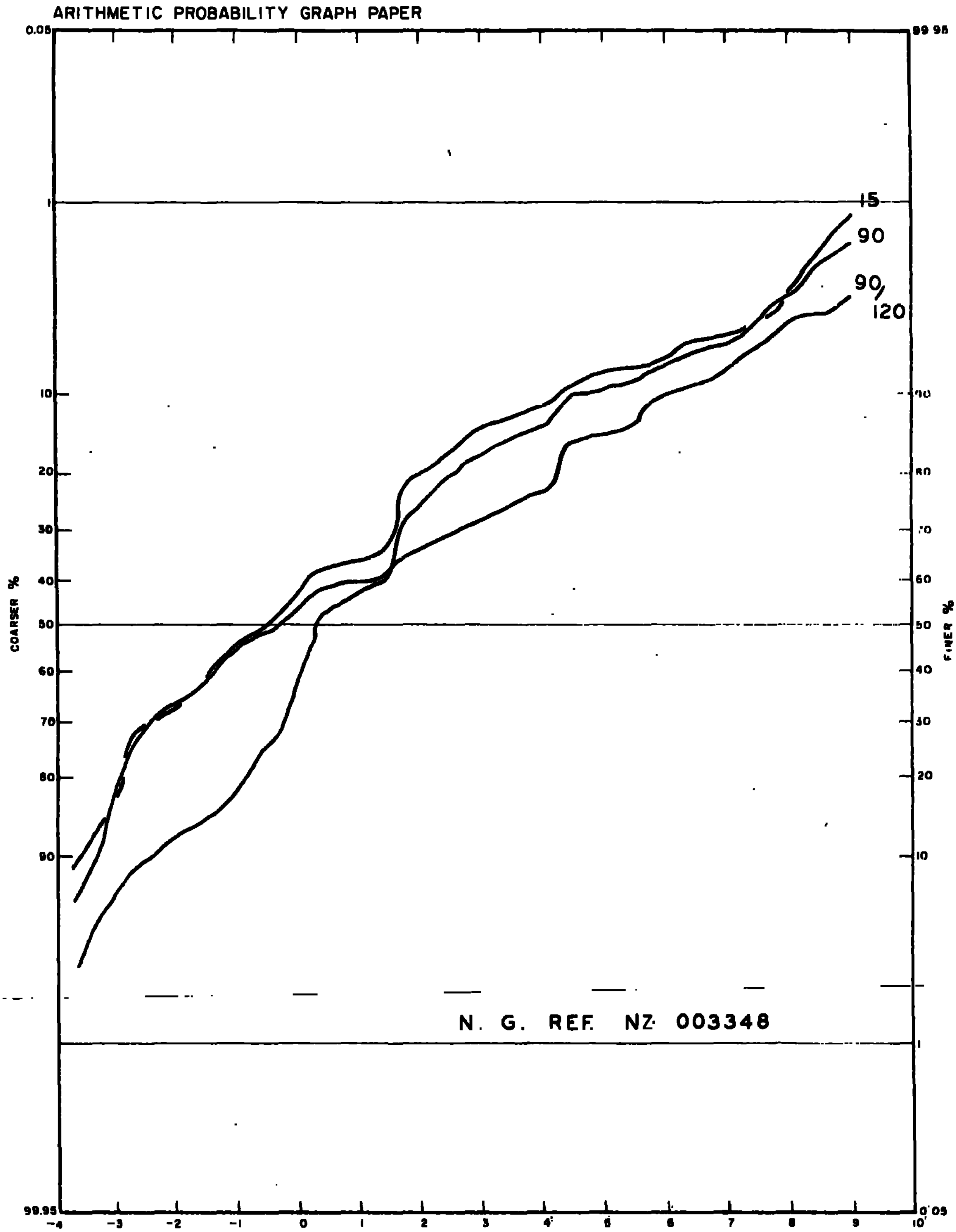
FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
Soil		
Layer of stones - large platy sst material		3(.6343)
Heavy silty clay silver/ ochre colour with sst. qzites.		3(.6350)
Large platy sst fragments in compact pebbly matrix.		2(.7749)

ARITHMETIC PROBABILITY GRAPH PAPER

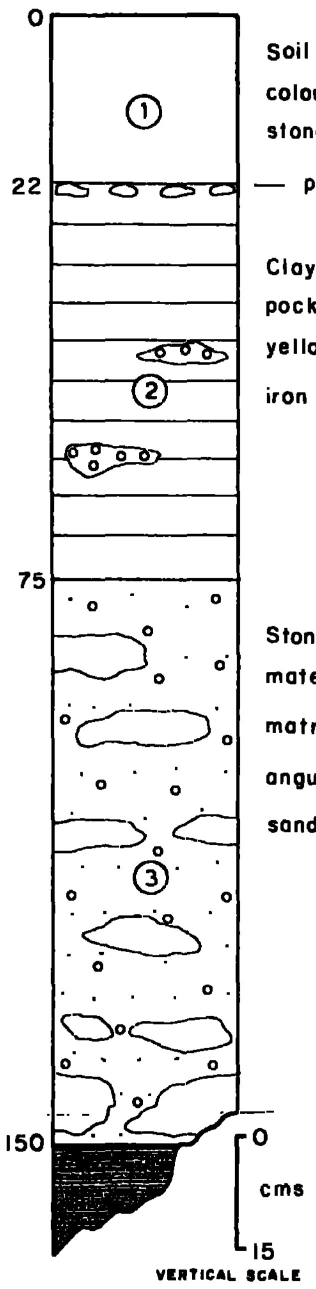


NAT. GRID REF. NZ 003348

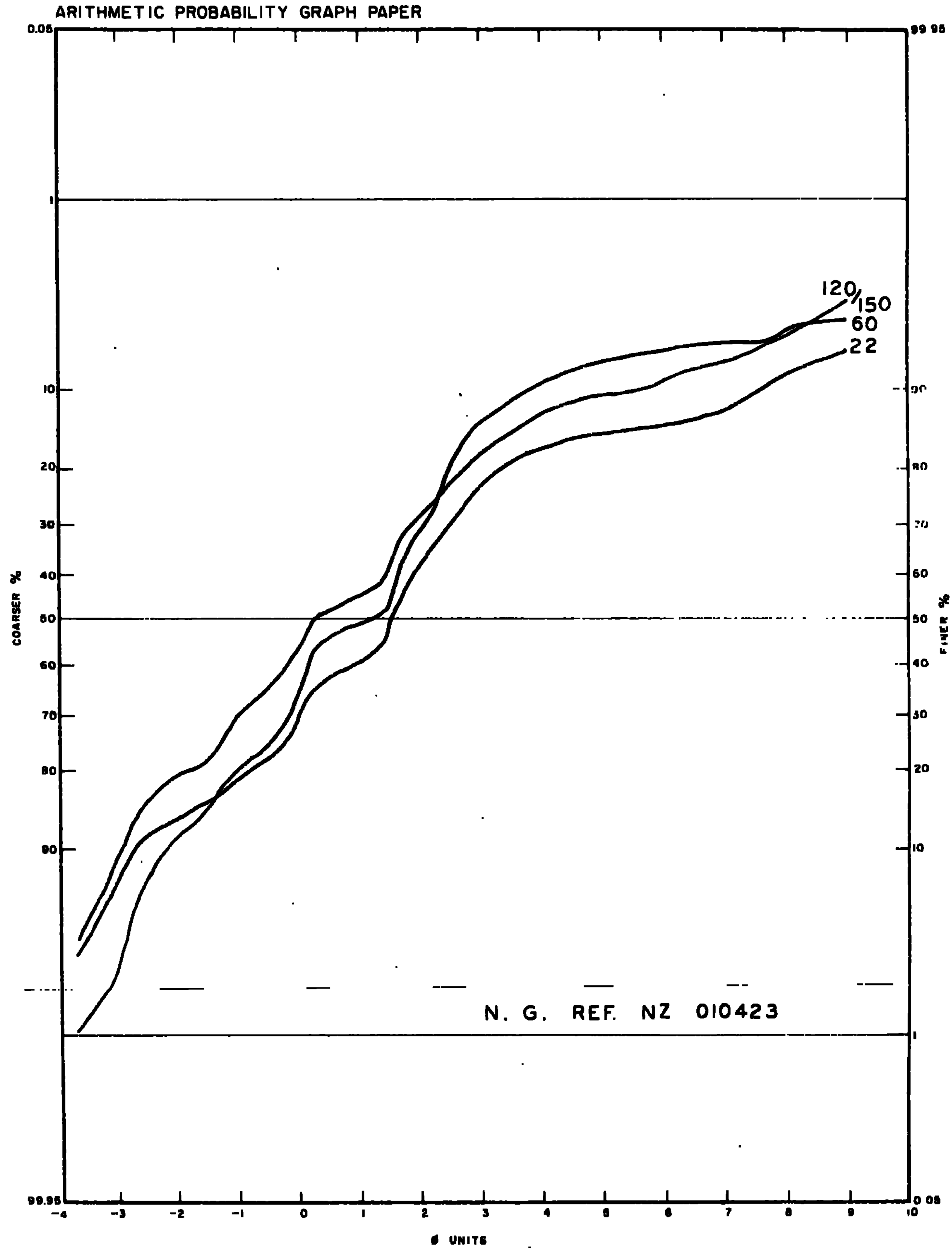
PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
	Soil		
	Silty material grey with sst fragments		2(.8433)
	Flat platy sst with silty detritus		3(.7759)
	Mn stained khaki coloured silty-clay material		3(.7759)
	Light grey coloured silty/clay material inc. pebbles		2(.8569)
	Bedrock		


ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
15
90
90/120
N. G. REF NZ 003348
ø UNITS

NAT. GRID REF. NZ 010423



PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
0–22 (1)	Soil bleached grey colour with angular stones		3(.7913)
22	— pebbly layer		
22–75 (2)	Clay material with pockets of sand yellow/white veins of iron staining		3(.8197)
75–150 (3)	Stony debris coarse material in sandy-silt matrix with large angular platy blocks sandstone		3(.7069)
150	bedrock millstone grit		



ARITHMETIC PROBABILITY GRAPH PAPER
0.05
1
10
20
30
40
50
60
70
80
90
99.95
COARSER %
99 95
90
80
70
60
50
40
30
20
10
1
0 05
FINER %
120/150
60
22
N. G. REF. NZ 010423
-4
-3
-2
-1
0
1
2
3
4
5
6
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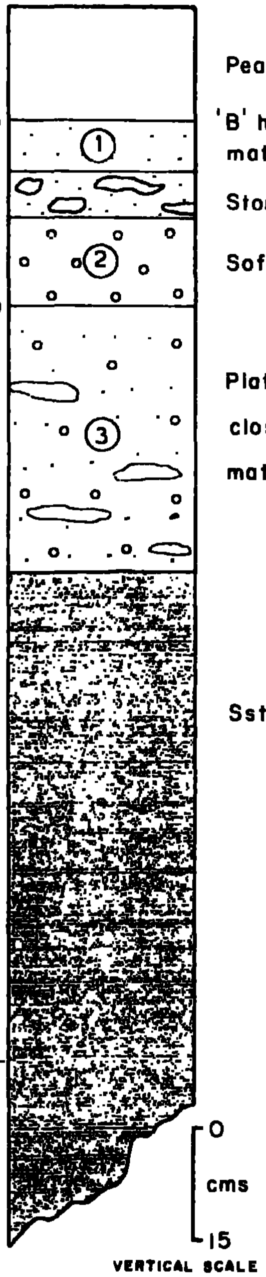
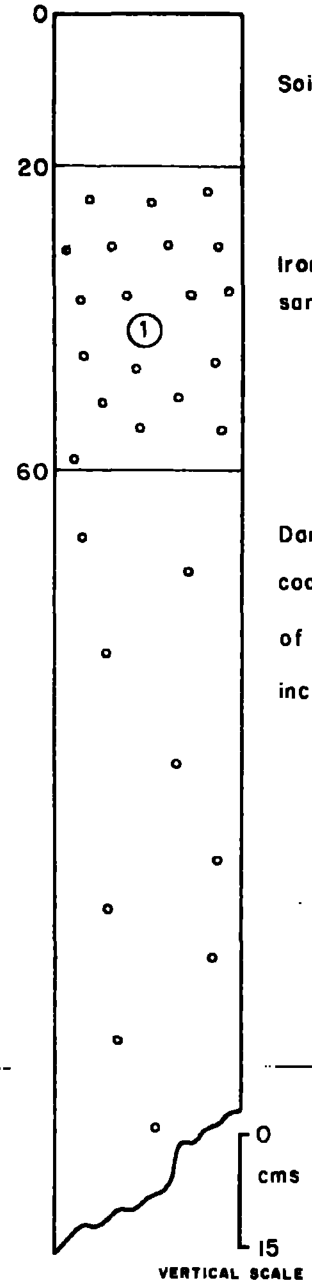
8
9
10
ø UNITS

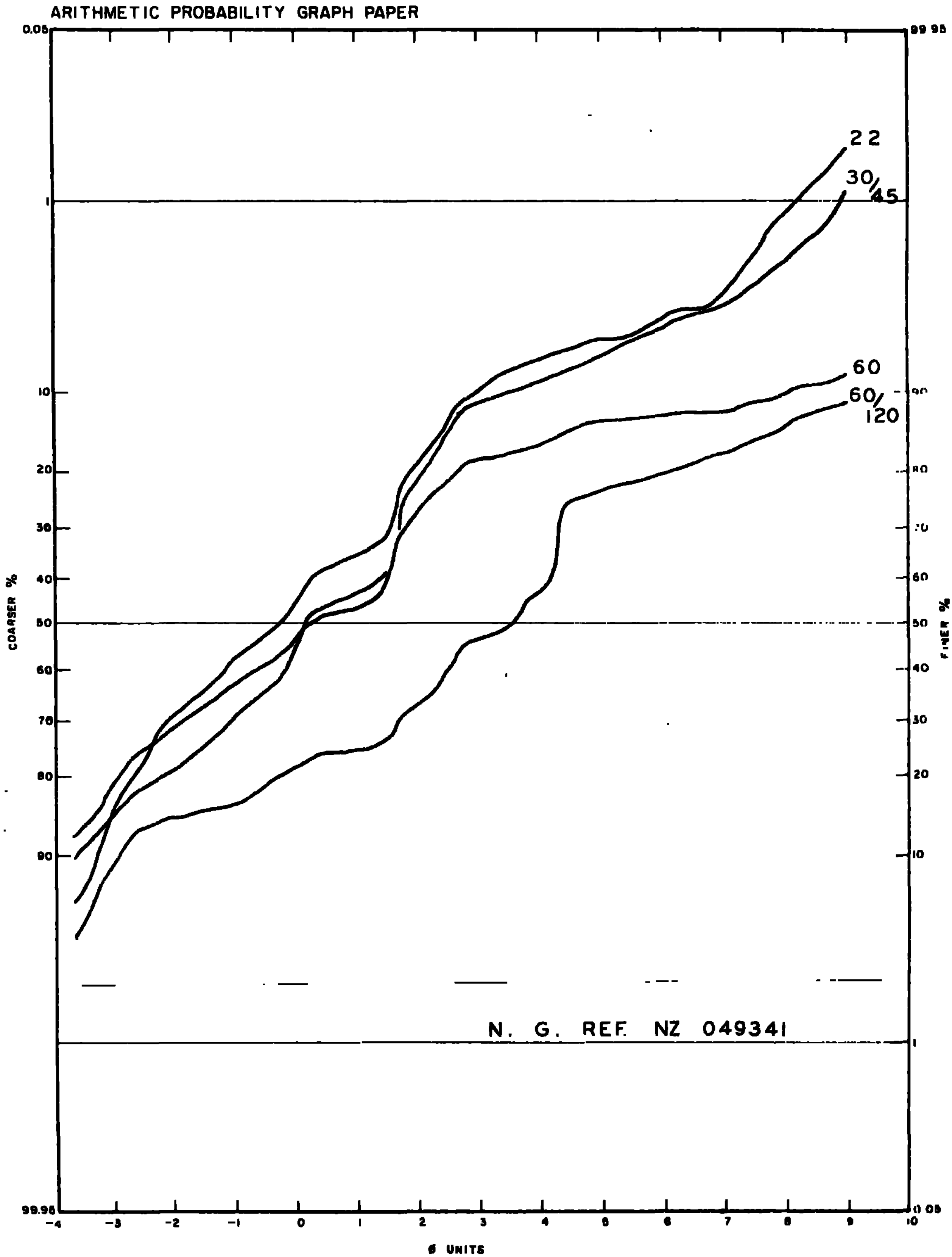
NAT. GRID REF. NZ 049341



PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
0–15	Peaty soil		
15–22 (1)	'B' horzon. silty brown material		2(.8536)
22–28	Stone layer		
28–40 (2)	Soft rotted sst		2(.6924)
40–75 (3)	Platy sst. fragments close packed in a matrix of silty sand		4(.6986)
75–	Sst		

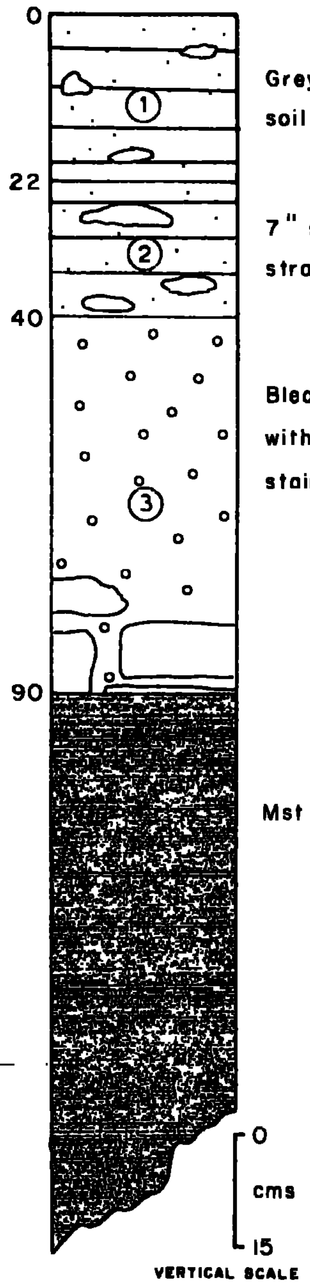
NAT. GRID REF. NZ 049341

PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
	Soil Iron – stained ochre sand material Darker material coarser, with bands of black and grey including mica flakes		3 (.7034)

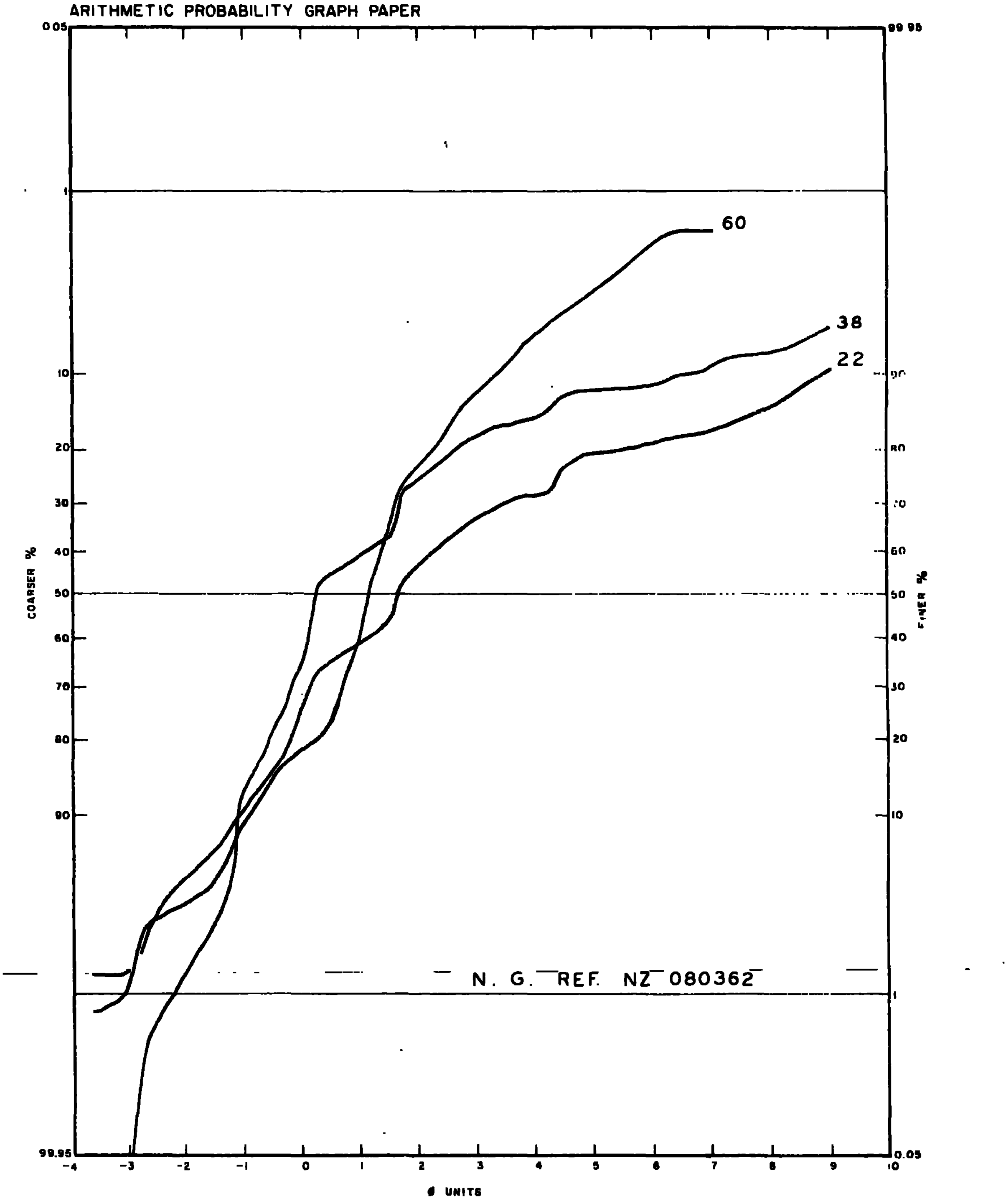


ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ø UNITS
22
30/45
60
60/120
N. G. REF. NZ 049341

NAT. GRID REF. NZ 080362

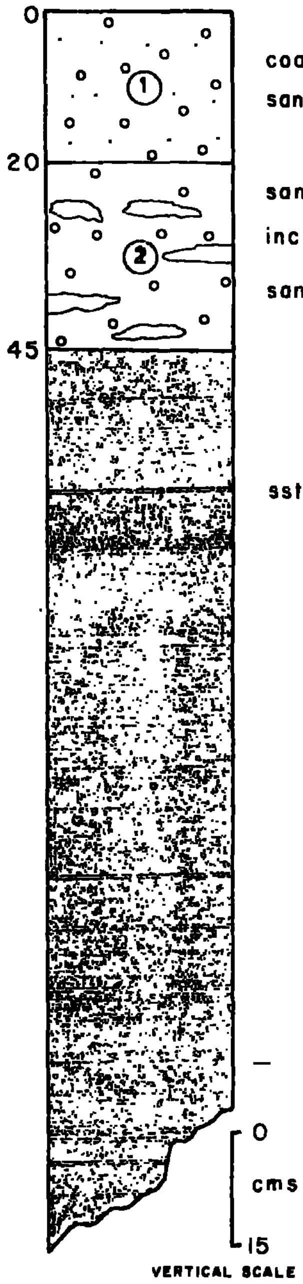


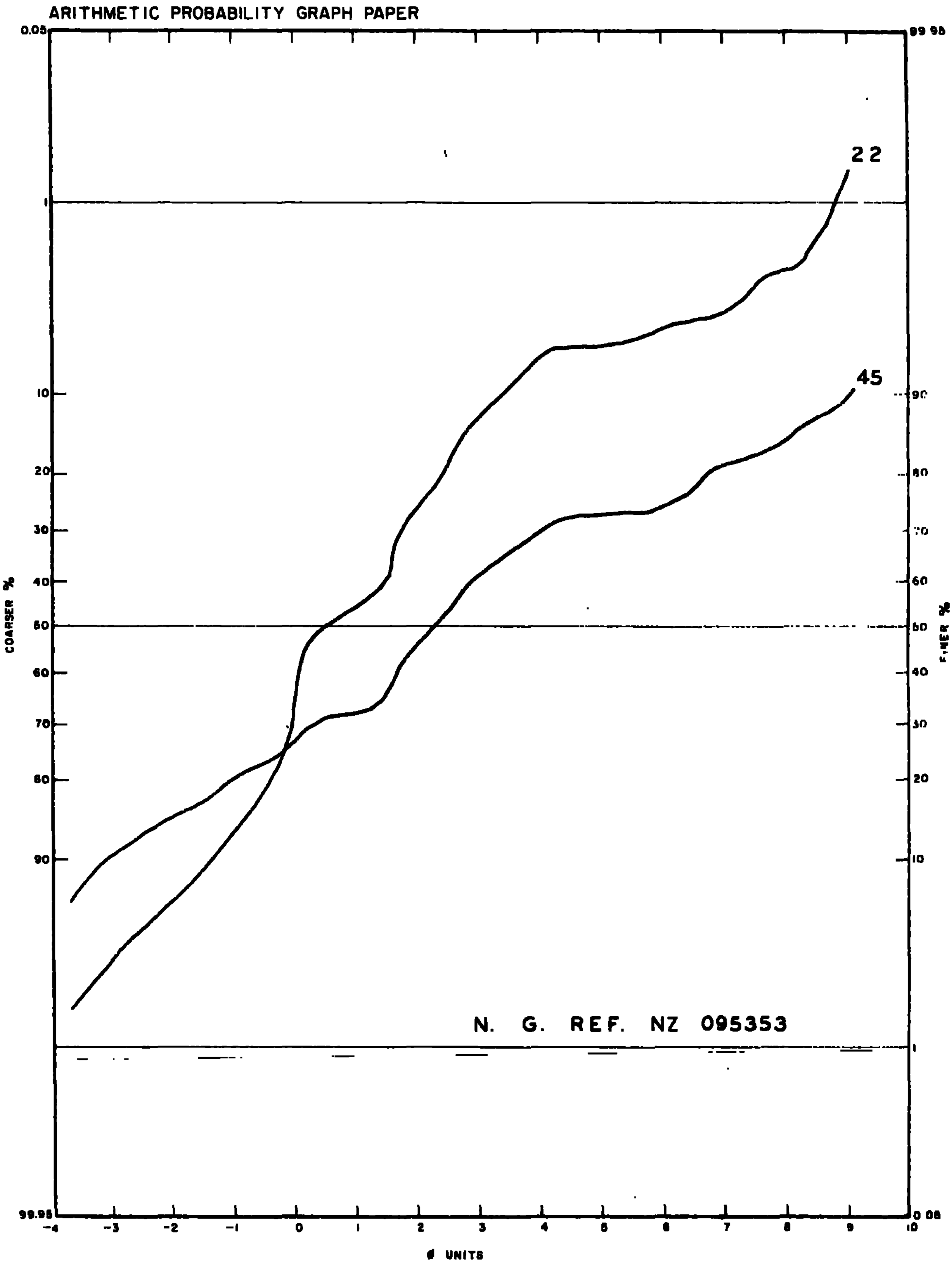
PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
1	Grey material soil with sst fragments		3 (.7690)
2	7" sst & soil pseudo stratification		3 (.8142)
3	Bleached rotted sst with some iron staining		3 (.8067)
	Mst grit		



ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ø UNITS
60
38
22
N. G. REF. NZ 080362

NAT. GRID REF NZ 095353

PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
			
	coarse dark soil sandy-silt		3 (.8334)
	sandy material including large angular sandstone fragments		1 (.6119)
	sst		



ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
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99.95
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0.05
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-2
-1
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1
2
3
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6
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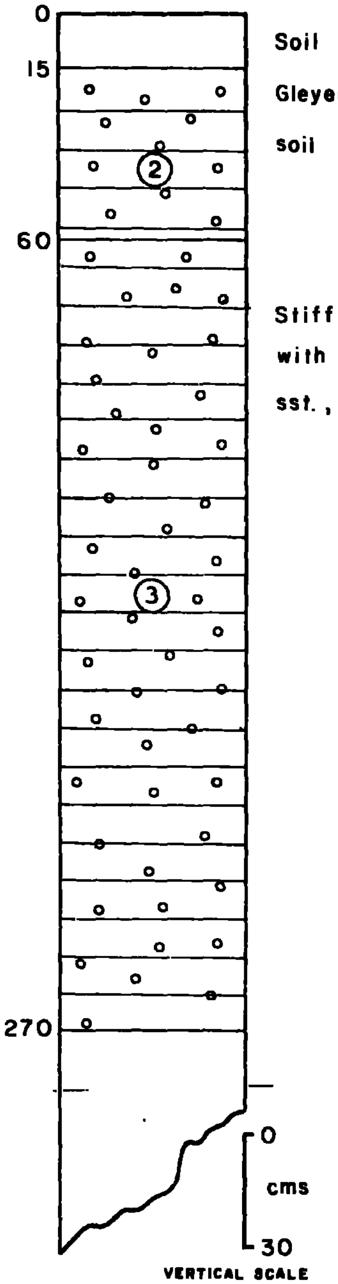
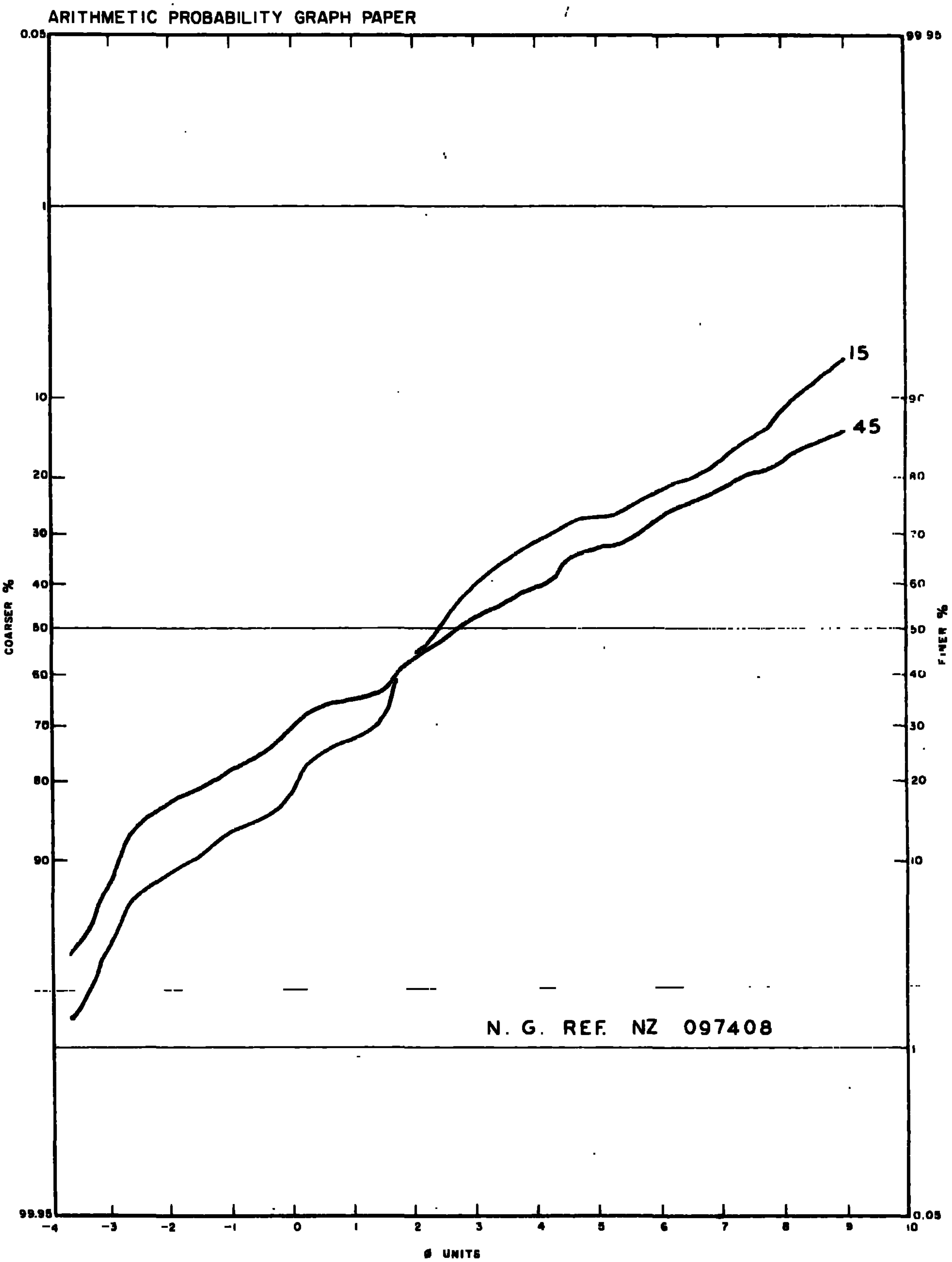
9
10
ø UNITS
22
45
N. G. REF. NZ 095353

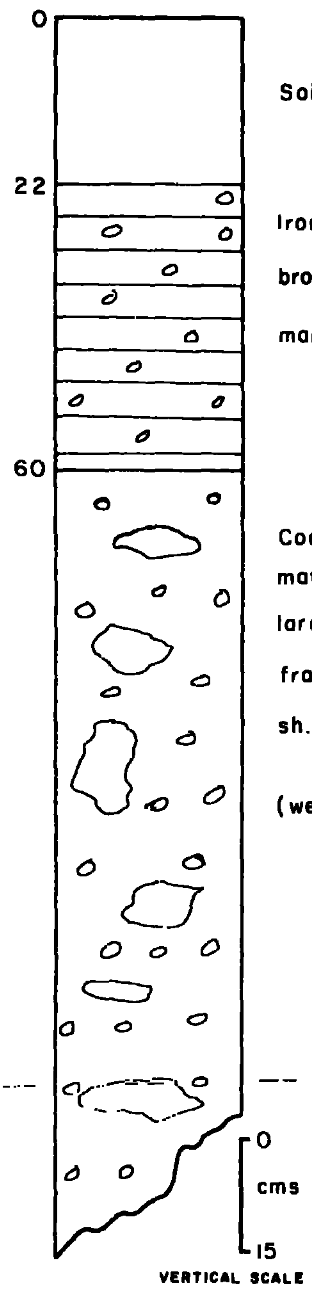
NAT. GRID REF. NZ 097408

PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
	Soil Gleyed stony clay soil Stiff brown clay with stones sst., sh., lst.,(b-c?)		3 (.6897) 1 (.6379)

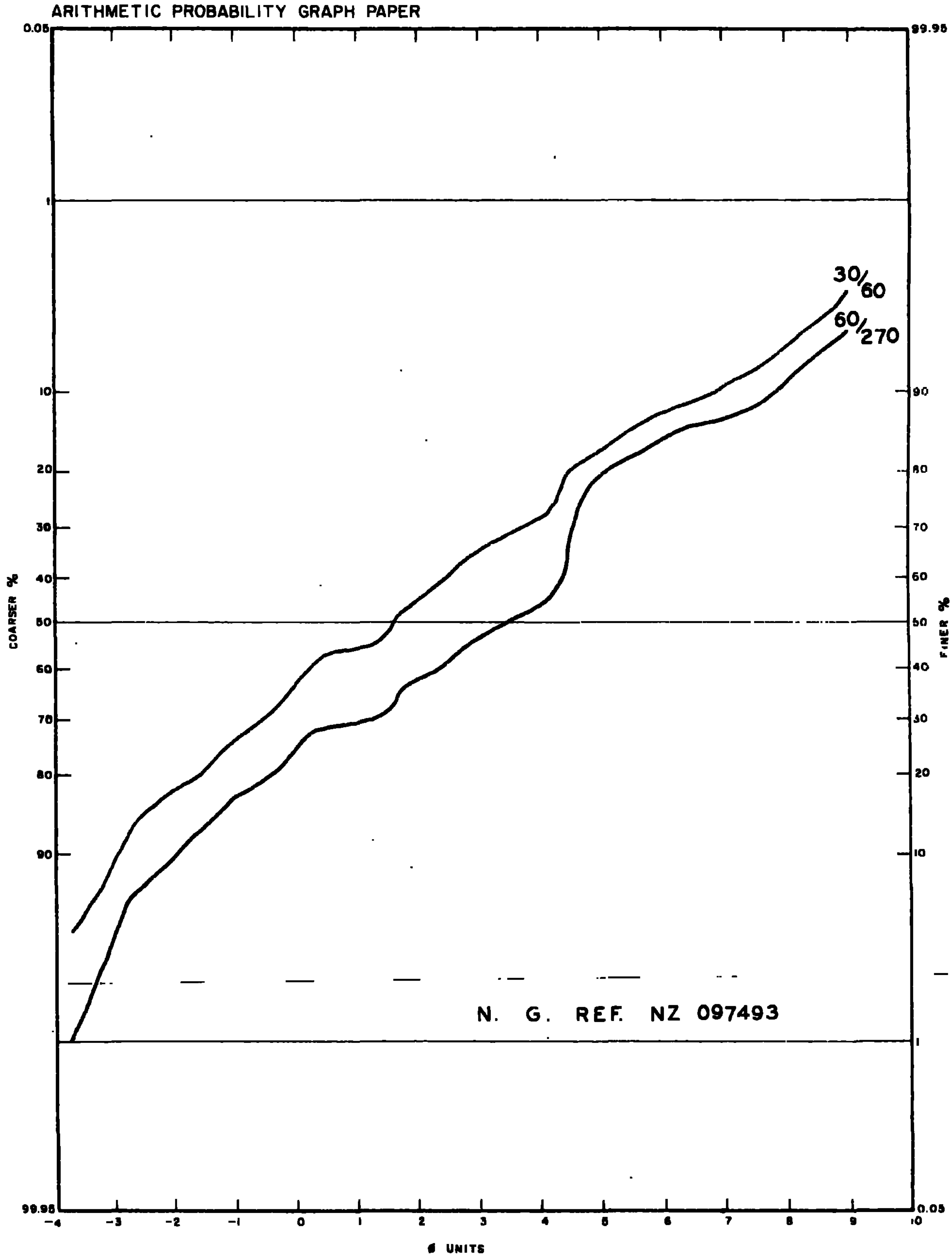


ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ø UNITS
15
45
N. G. REF. NZ 097408

NAT. GRID REF. NZ 097493



PROFILE	FIELD DATA	LABORATORY DATA	FACTOR ANALYSIS
0–22	Soil		
22–60	Iron stained clay layer brown colour with many small pebbles.		1(.6169)
60–	Coarse gravelly material including large angular sst fragments gannister sh., coal (weathered gannister)		4(.7106)



ARITHMETIC PROBABILITY GRAPH PAPER
COARSER %
FINER %
ø UNITS
30/60
60/270
N. G. REF. NZ 097493

APPENDIX III

Containing the significance tests and trend surface maps of

(i) Gravel Content of Surface Layer
(ii) Sand Content of Surface Layer
(iii) Silt Content of Surface Layer
(iv) Clay Content of Surface Layer
(v) Maximum Factor 1 loading at each site
(vi) Maximum Factor 2 loading at each site
(vii) Maximum Factor 3 loading at each site
(viii) Maximum Factor 4 loading at each site
(ix) Maximum Factor 5 loading at each site

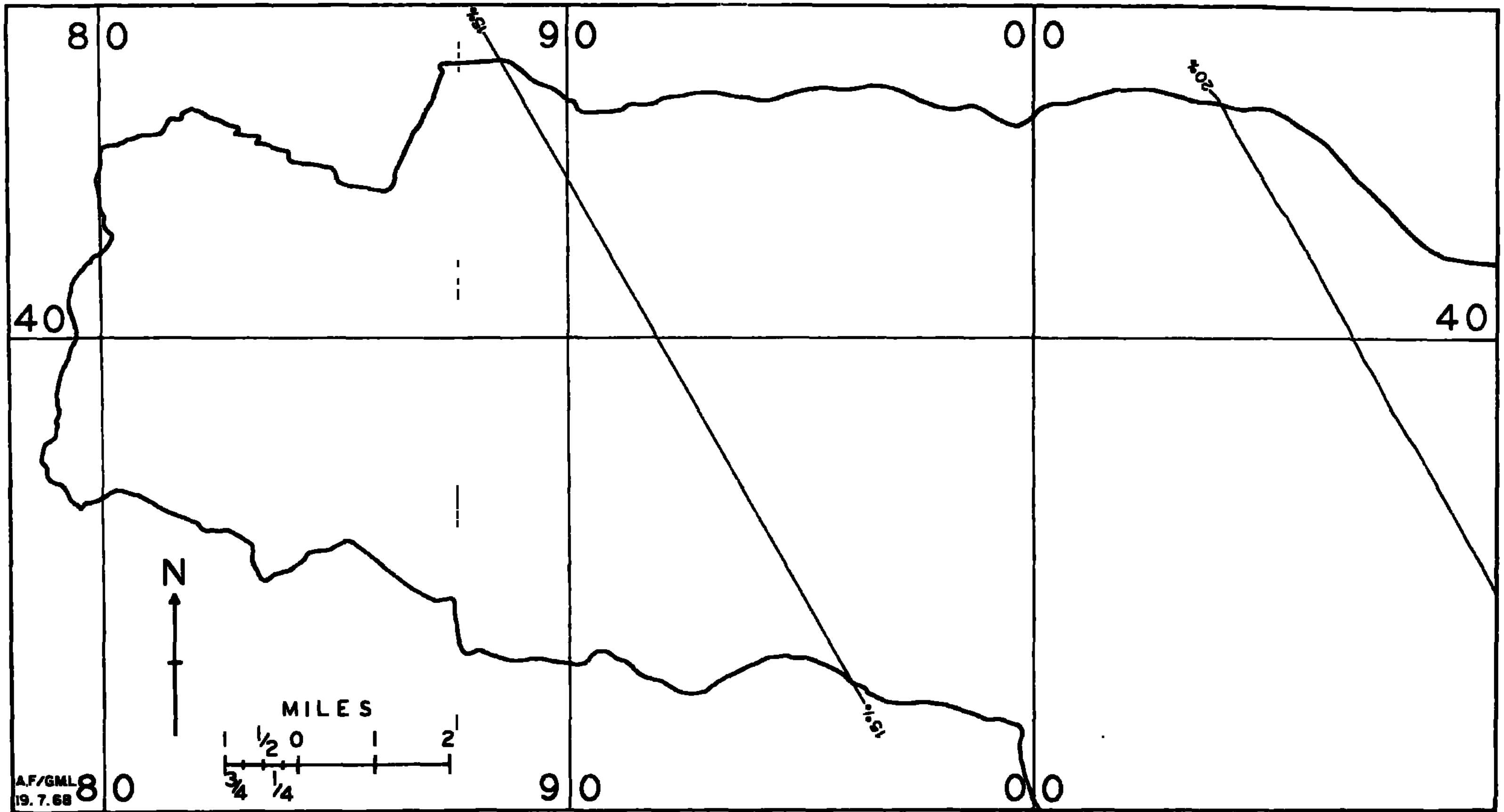
MAPS OF % GRAVEL CONTENT OF SURFACE LAYER

TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT
OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

source	sum of squares	degrees of freedom	mean square	F	%confidence
linear surface deviations from above	396 7281	2 42	198.00 173.35	1.14	50+
quadratic surface deviations from quadratic	55 7225	3 39	18.33 185.25	0.09	2.5+
cubic surface deviations from cubic	235 6990	4 35	58.75 199.71	0.29	10+
quartic surface deviations from quartic	1799 5191	5 30	359.80 173.03	2.07	90+
quintic surface deviations from quintic	1344 3946	6 24	224.00 164.41	1.36	50+

TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

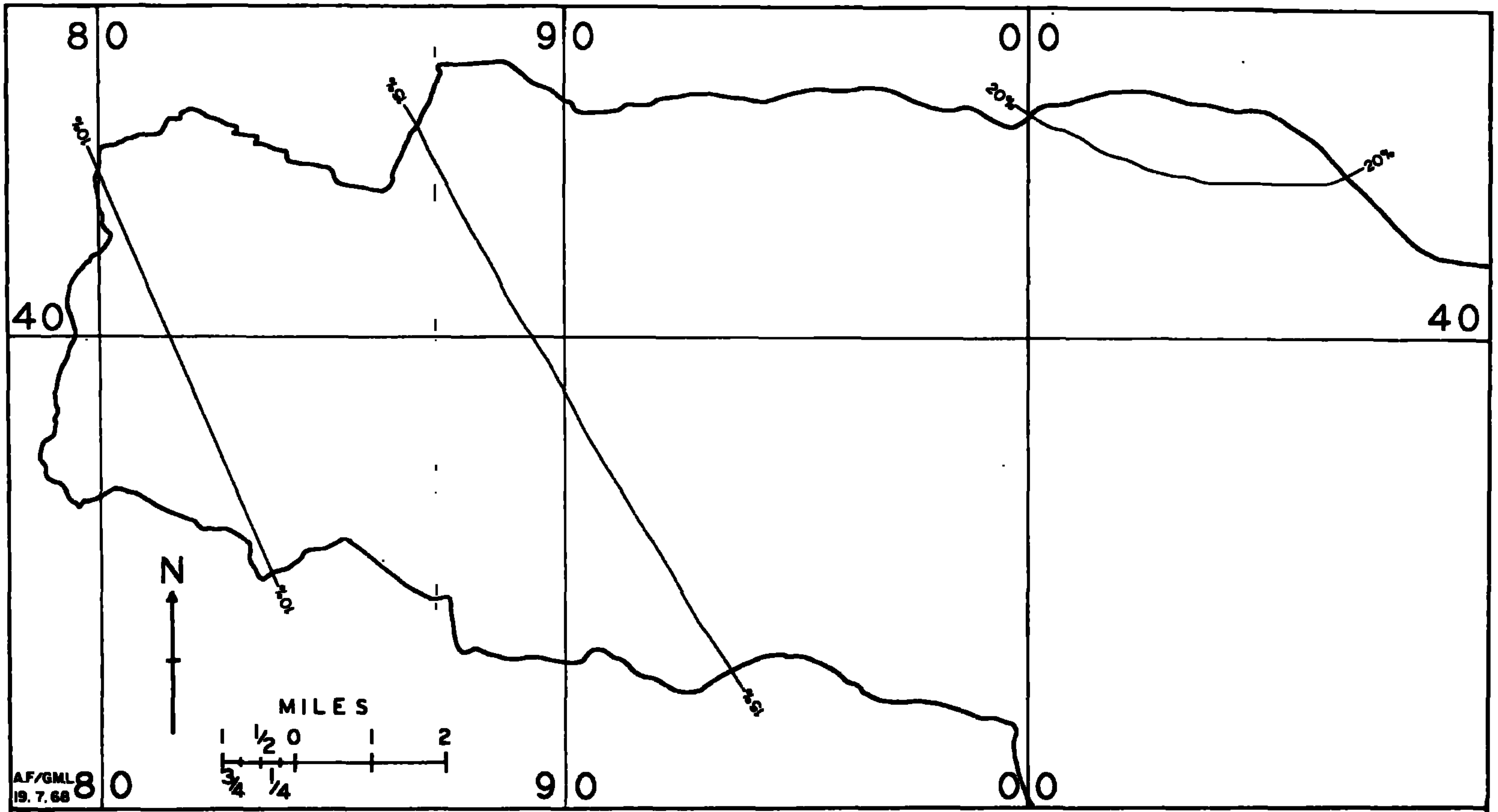
source	sum of squares	degrees of freedom	mean square	F	%confidence
first order surface deviations from first order	396 7281	2 42	198.00 173.35	1.14	50+
second order surface deviations from second order	451 7225	5 39	90.20 185.25	0.48	10+
third order surface deviations from third order	686 6990	9 35	76.22 199.71	0.38	5+
fourth order surface deviations from fourth order	2485 5191	14 30	177.50 173.03	1.03	50+
fifth order surface deviations from fifth order	3729 3946	20 24	186.45 164.41	1.13	50
source	sum of squares	degrees of freedom	mean square	F	%confidence



UPPER WEARDALE

MAP OF GRAVEL CONTENT OF SURFACE LAYER

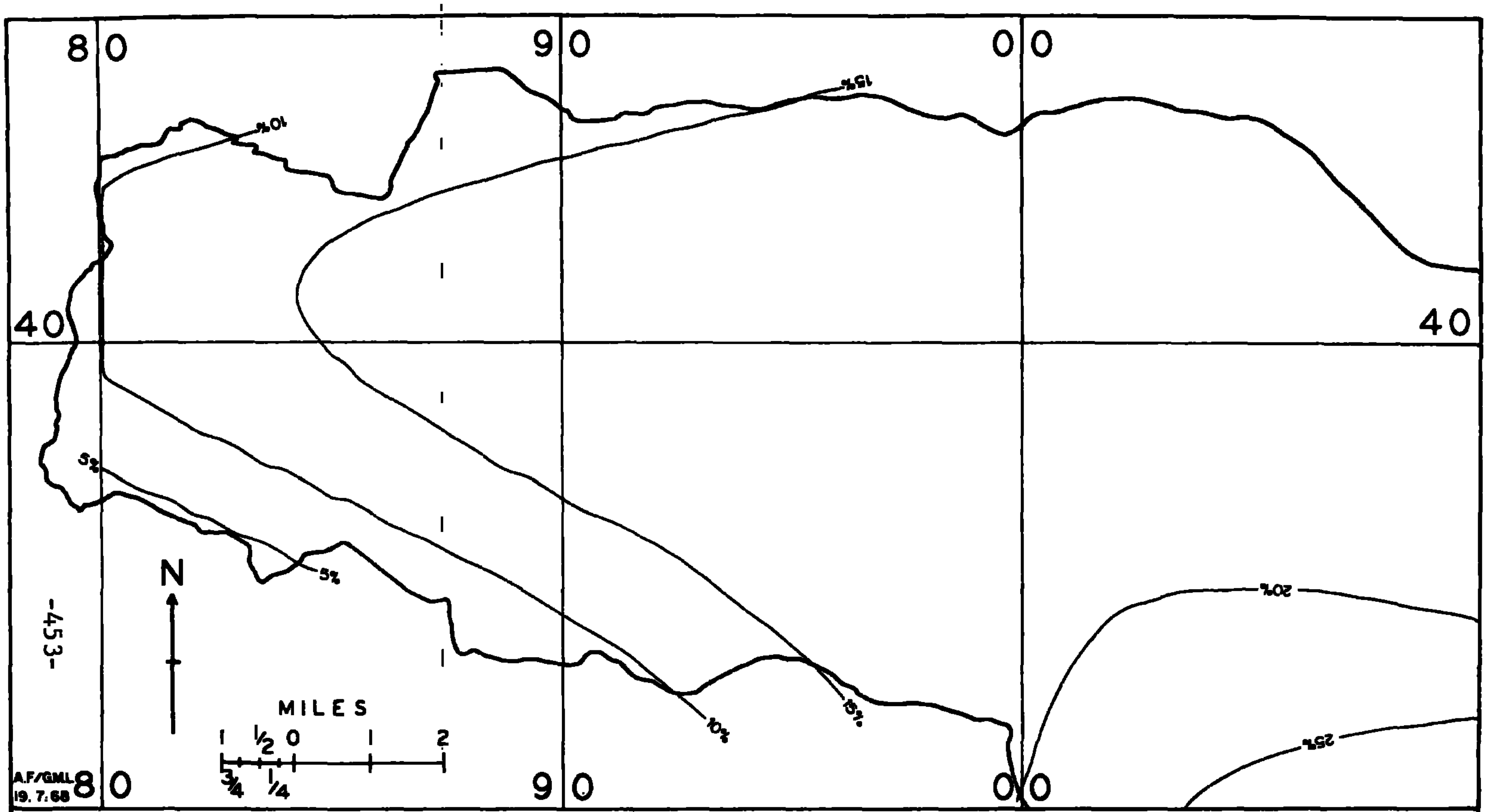
CONTOURED FIRST DEGREE SURFACE



UPPER WEARDALE

MAP OF GRAVEL CONTENT OF SURFACE LAYER

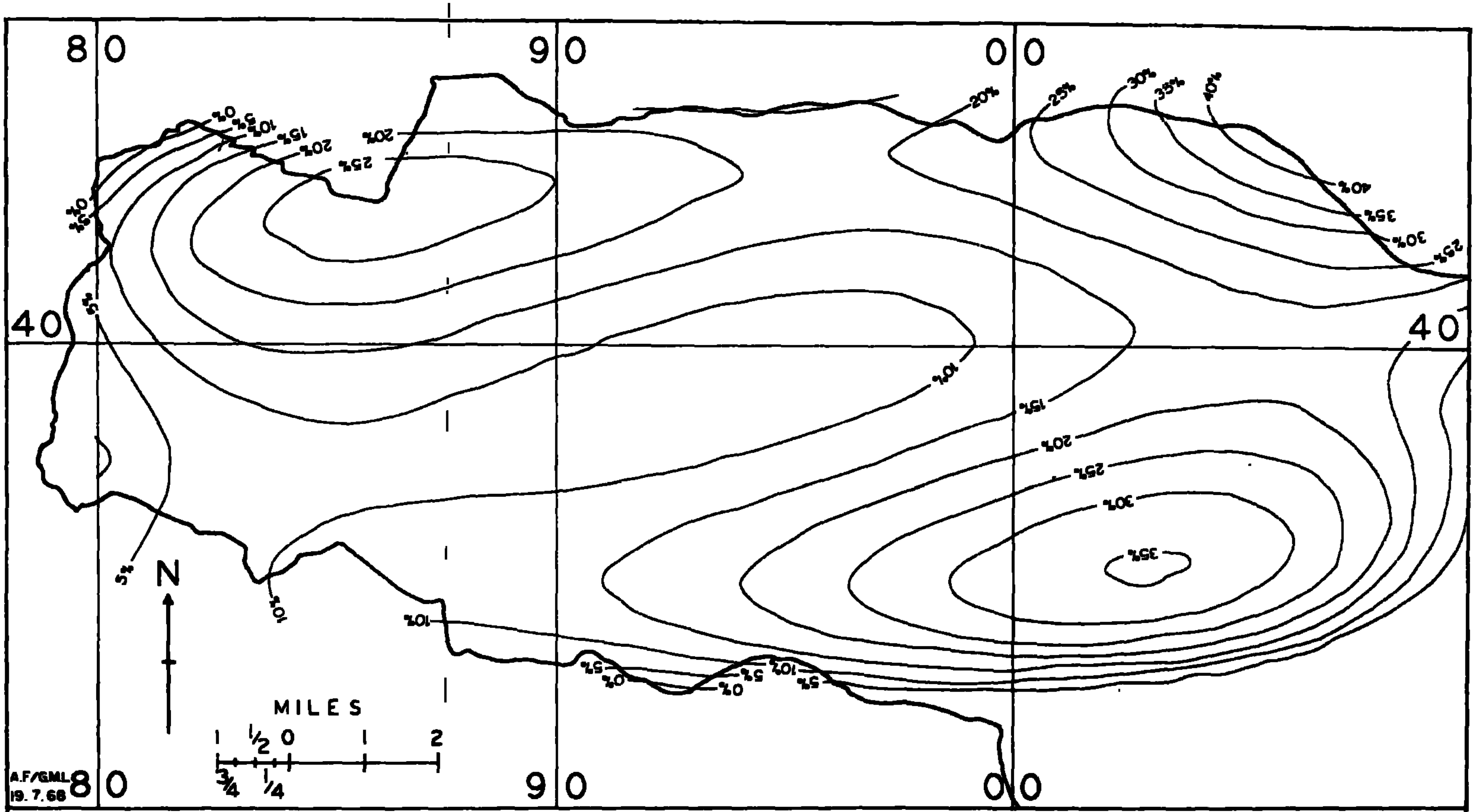
CONTOURED SECOND DEGREE SURFACE



UPPER WEARDALE

MAP OF GRAVEL CONTENT OF SURFACE LAYER

CONTOURED THIRD DEGREE SURFACE



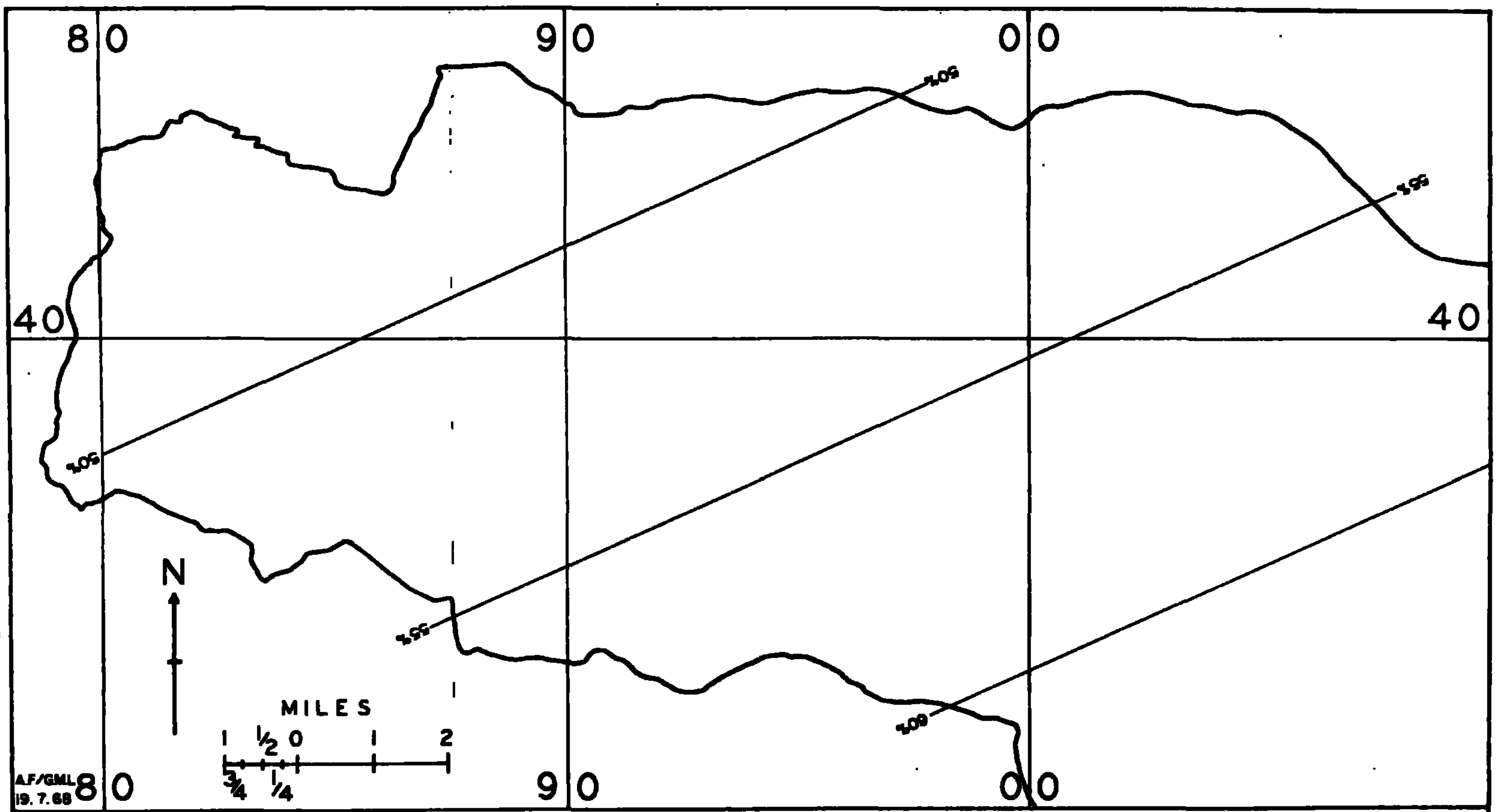
UPPER WEARDALE

MAP OF GRAVEL CONTENT SURFACE LAYER
CONTOURED FOURTH DEGREE SURFACE

MAPS OF % SAND CONTENT OF SURFACE LAYER

TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT
OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

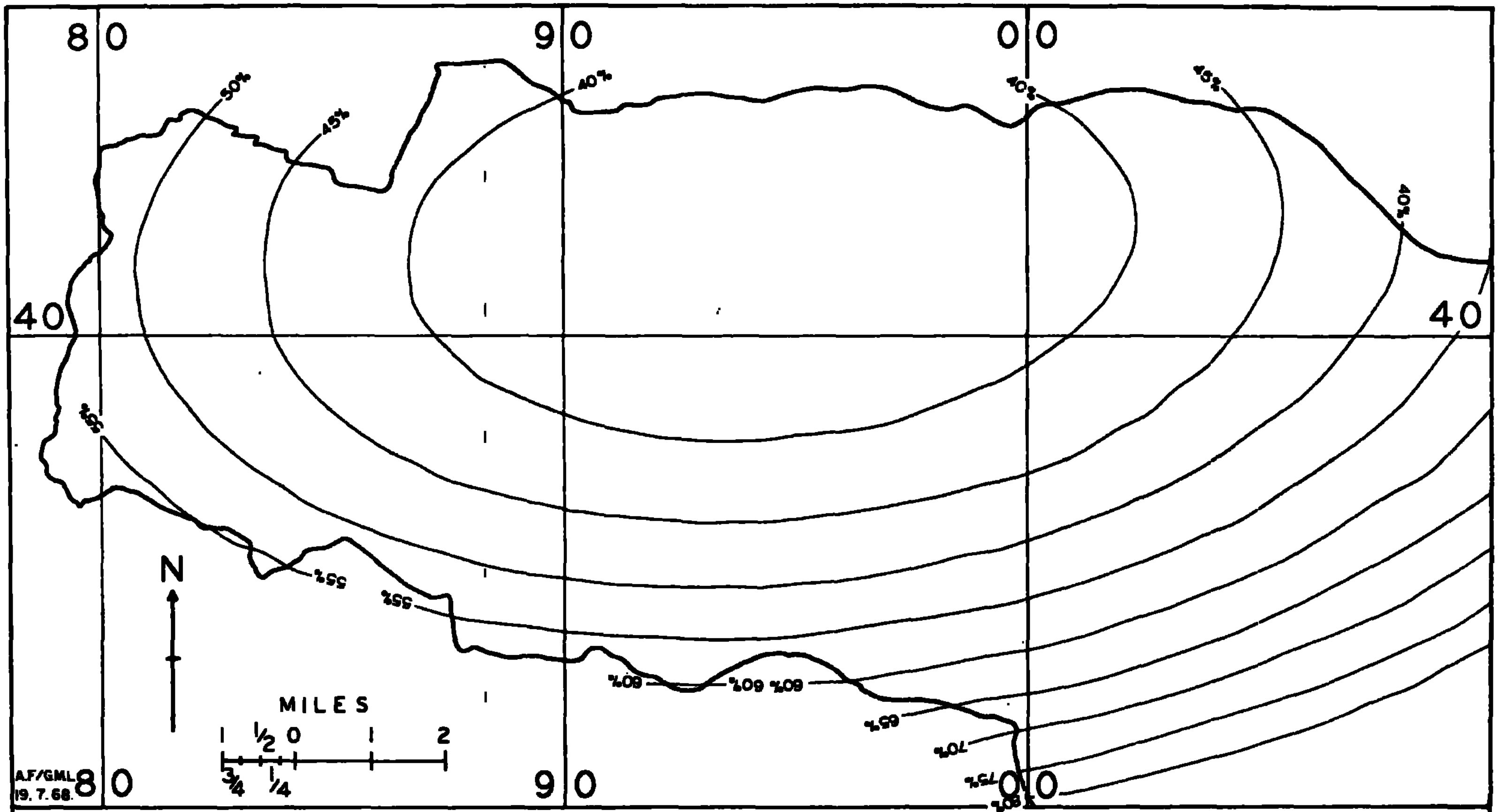
source	sum of squares	degrees of freedom	mean square	F	% confidence
linear surface deviations from above	95 1140	2 42	47.5 27.14	1.75	75+
quadratic surface deviations from quadratic	2578 8825	3 39	859.33 226.28	3.79	97.5+
cubic surface deviations from cubic	694 8131	4 35	173.5 232.31	0.74	25+
quartic surface deviations from quartic	811 7319	5 30	162.20 243.96	0.66	25+
quintic surface deviations from quintic	1097 6221	6 24	182.83 259.20	0.70	25+
TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE					
first order surface deviations from first order	95 1140	2 42	47.5 27.14	1.75	75+
second order surface deviations from second order	3524 8325	5 39	704.80 226.28	3.12	97.5+
third order surface deviations from third order	4218 8131	9 35	468.66 232.31	2.01	90+
fourth order surface deviations from fourth order	5030 7319	14 30	359.28 243.96	1.47	75+
fifth order surface deviations from fifth order	6128 6221	20 24	306.40 259.20	1.18	50+
source	sum of squares	degrees of freedom	mean square	F	% confidence



UPPER WEARDALE

MAP OF % SAND CONTENT OF SURFACE LAYER

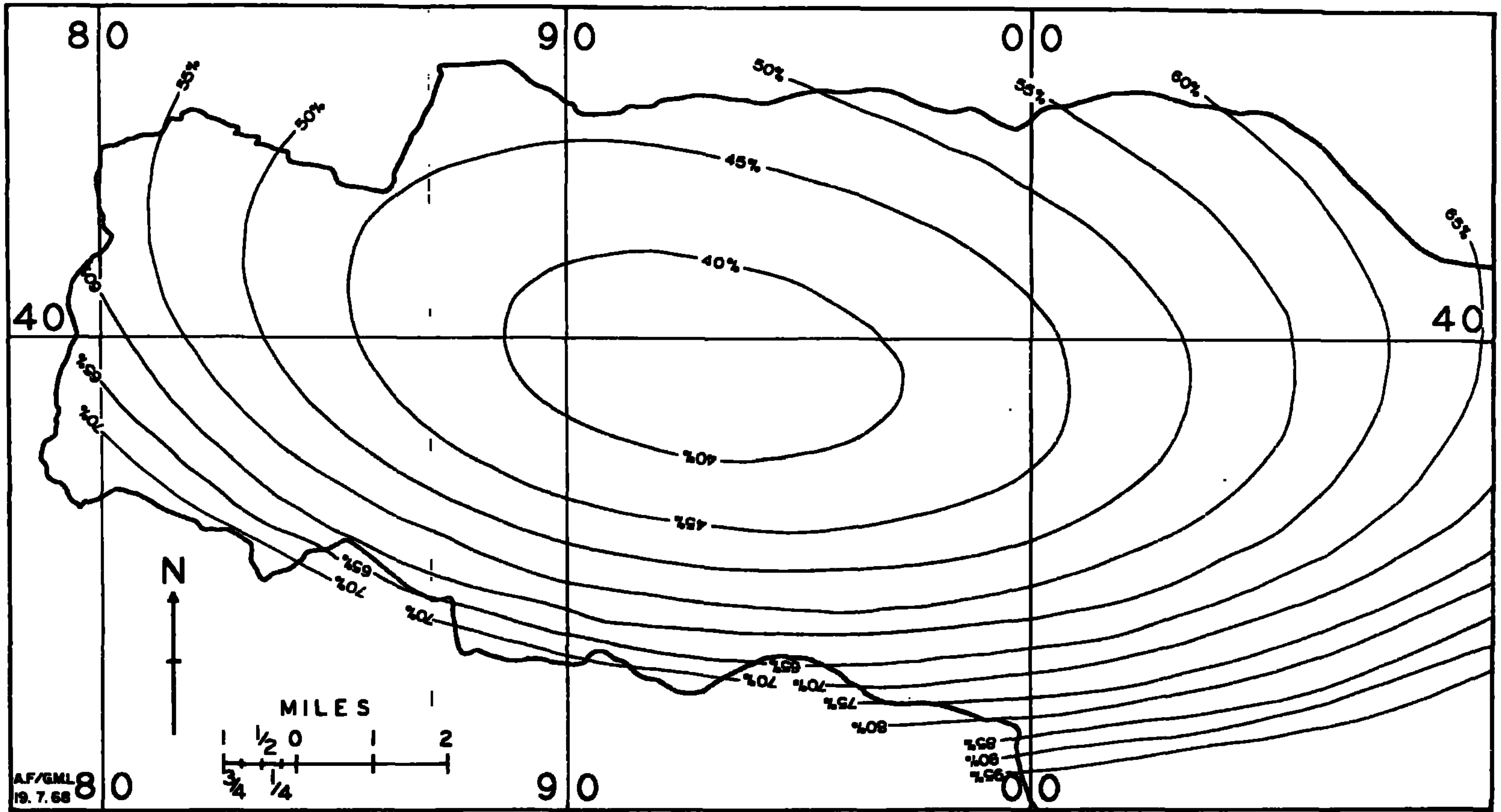
CONTOUR FIRST-DEGREE SURFACE



UPPER WEARDALE

MAP OF % SAND CONTENT OF SURFACE LAYER

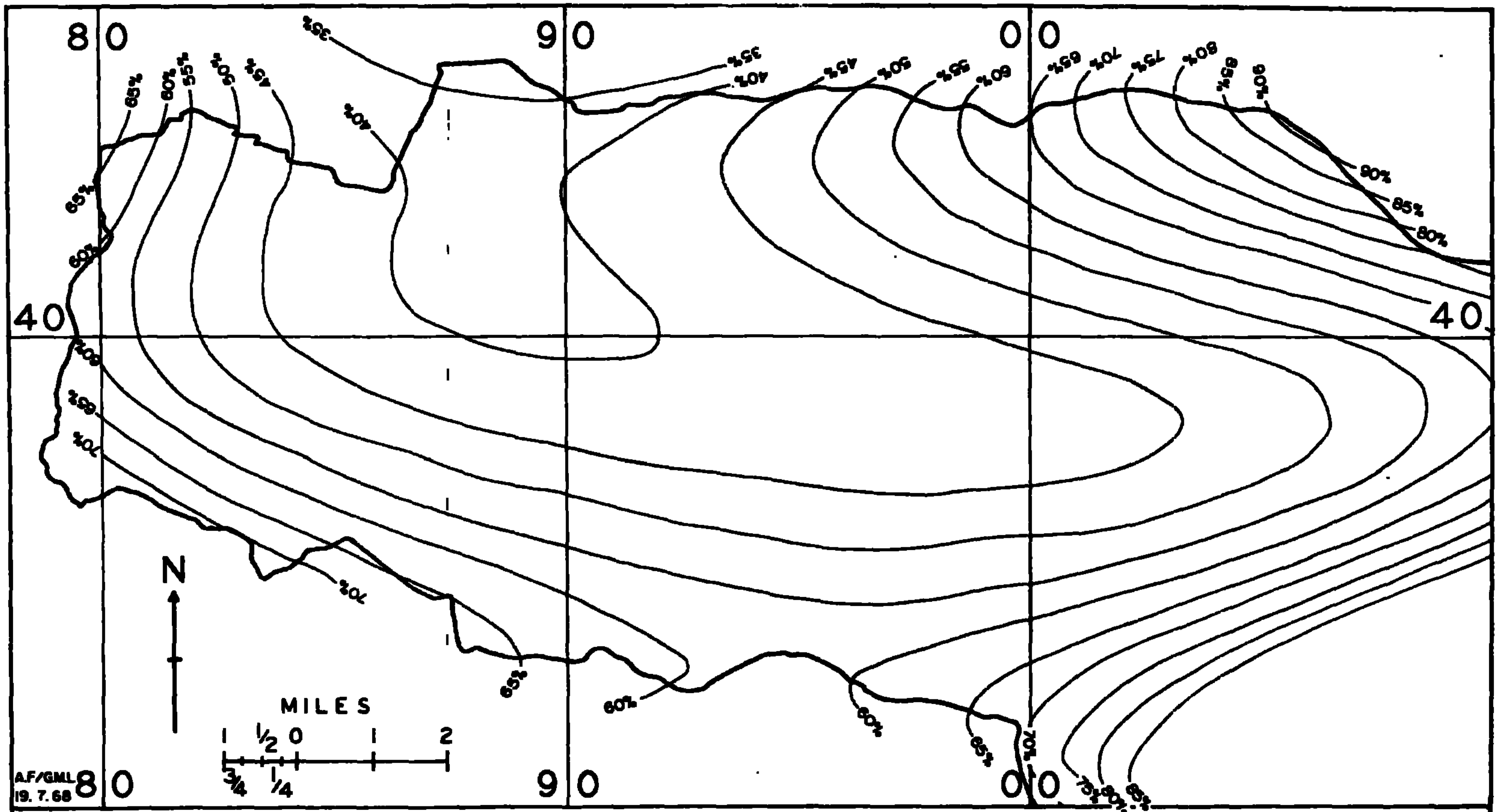
CONTOURED SECOND DEGREE SURFACE



UPPER WEARDALE

MAP OF % SAND CONTENT OF SURFACE LAYER

CONTOUR THIRD DEGREE SURFACE



UPPER WEARDALE

MAP OF % SAND CONTENT OF SURFACE LAYER

CONTOUR FOURTH DEGREE SURFACE

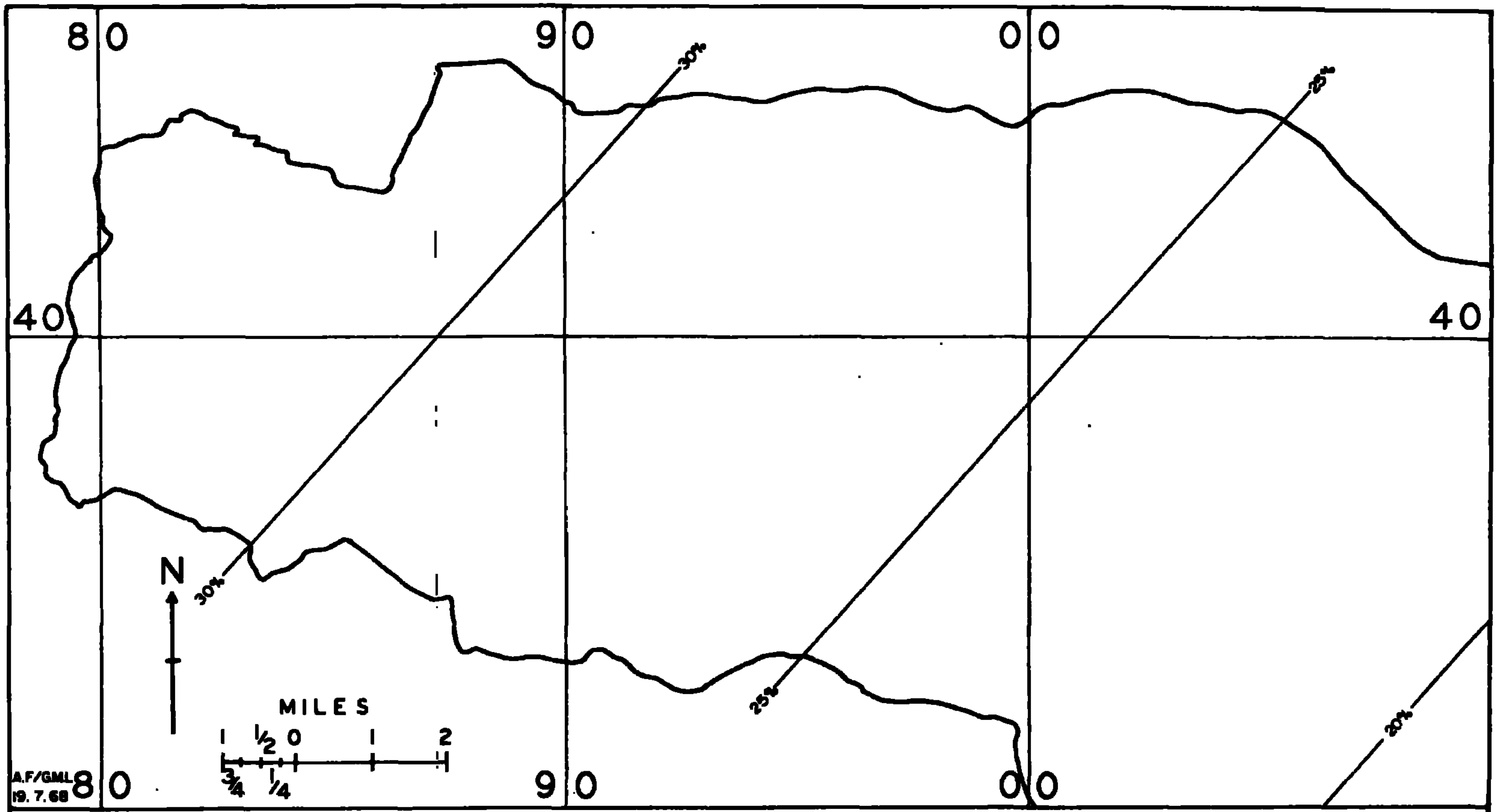
MAPS OF % SILT CONTENT OF SURFACE LAYER

TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

source	sum of squares	degrees of freedom	mean square	F	%confidence
linear surface deviations from above	632 5270	2 42	210.66 125.47	1.67	75+
quadratic surface deviations from quadratic	821 4449	3 39	273.66 114.07	2.39	90+
cubic surface deviations from cubic	561 3888	4 35	140.25 111.08	1.26	50+
quartic surface deviations from quartic	229 3659	5 30	45.80 121.96	0.37	10+
quintic surface deviations from quintic	795 2864	6 24	132.50 119.33	1.11	50+

TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

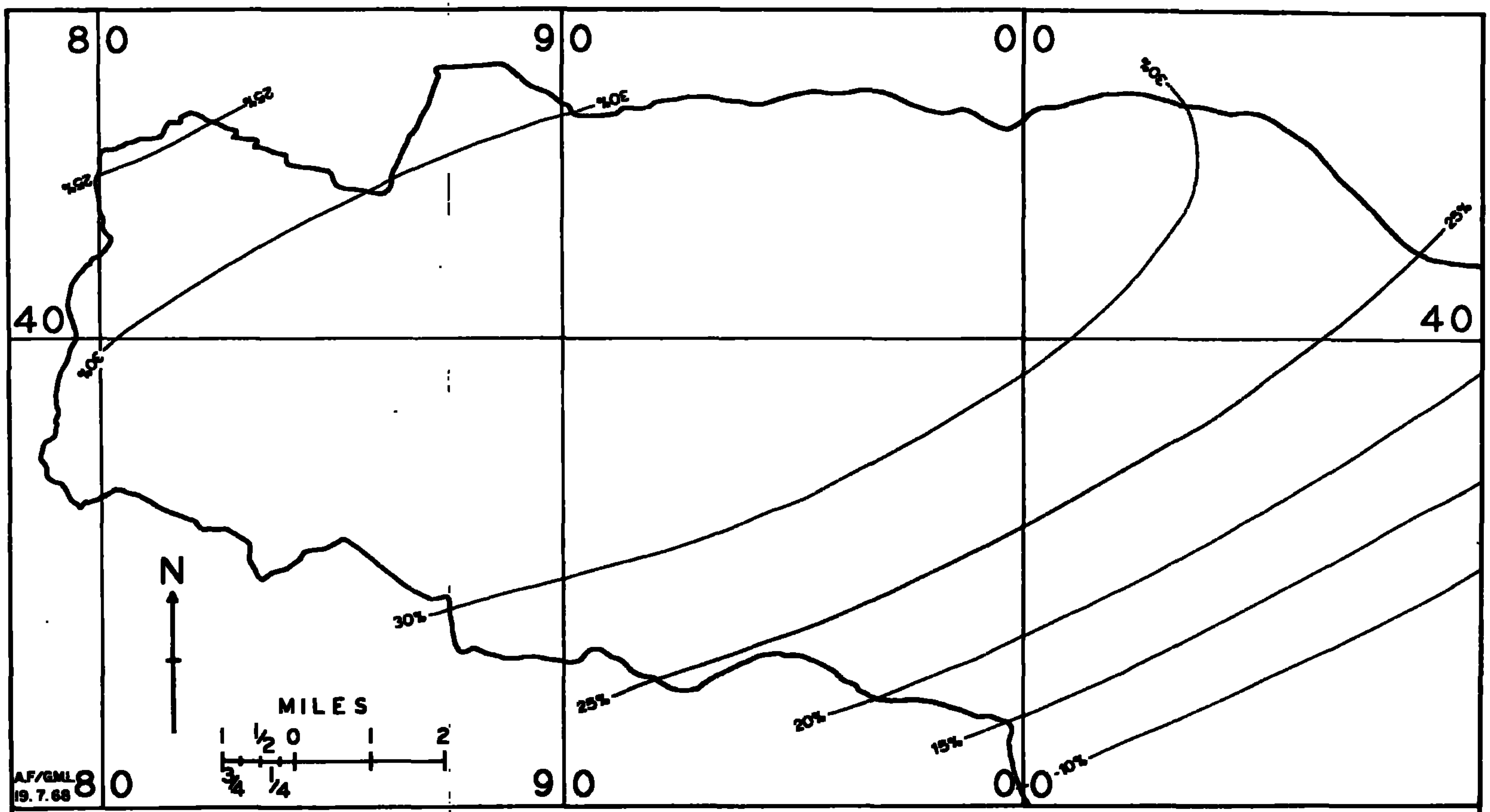
source	sum of squares	degrees of freedom	mean square	F	%confidence
first order surface deviations from first order	632 5270	2 42	210.66 125.47	1.67	75+
second order surface deviations from second order	1453 4449	5 39	290.60 114.07	2.54	95+
third order surface deviations from third order	2014 3888	9 35	223.77 111.08	2.01	90+
fourth order surface deviations from fourth order	2243 3659	14 30	160.21 121.96	1.31	50+
fifth order surface deviations from fifth order	3038 2864	20 24	151.90 119.33	1.27	50+
source	sum of squares	degrees of freedom	mean square	F	%confidence



UPPER WEARDALE

MAP OF % SILT CONTENT OF SURFACE LAYER

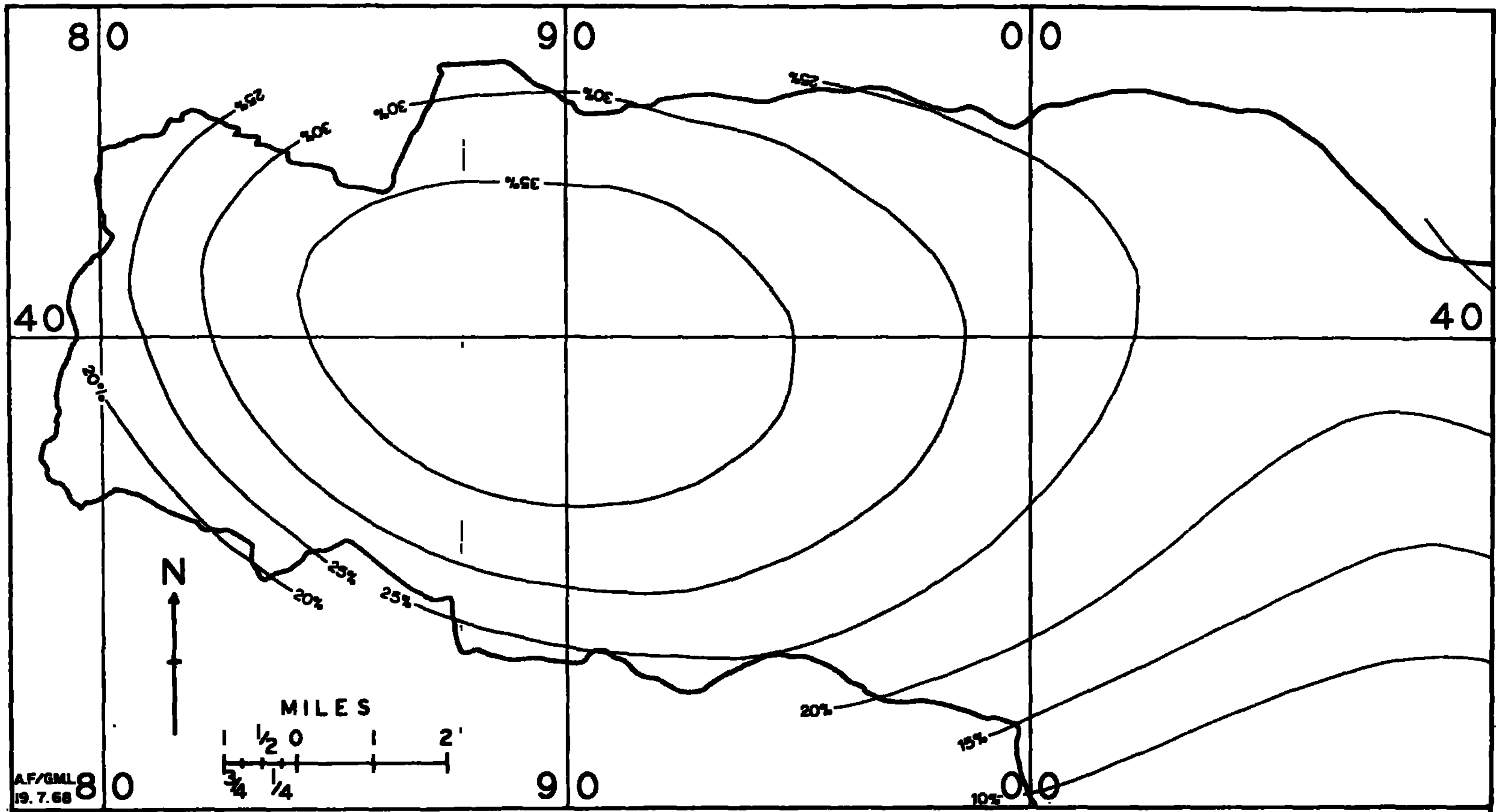
CONTOUR FIRST DEGREE SURFACE



UPPER WEARDALE

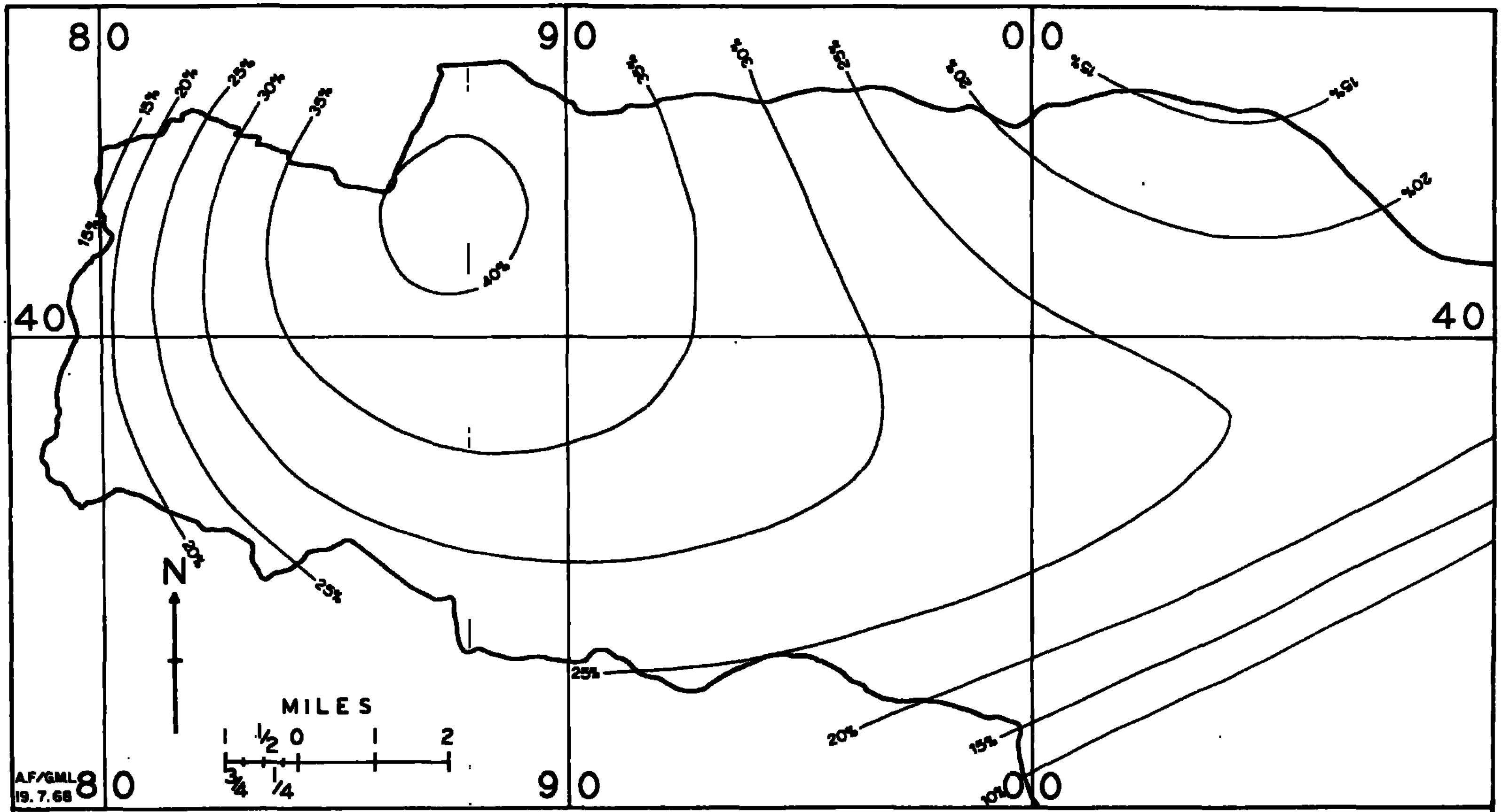
MAP OF % SILT CONTENT OF SURFACE LAYER

CONTOUR SECOND-DEGREE SURFACE



UPPER WEARDALE

MAP OF % SILT CONTENT OF SURFACE LAYER
CONTOUR THIRD-DEGREE SURFACE



UPPER WEARDALE

MAP OF % SILT CONTENT OF SURFACE LAYER

CONTOURED FOURTH DEGREE SURFACE

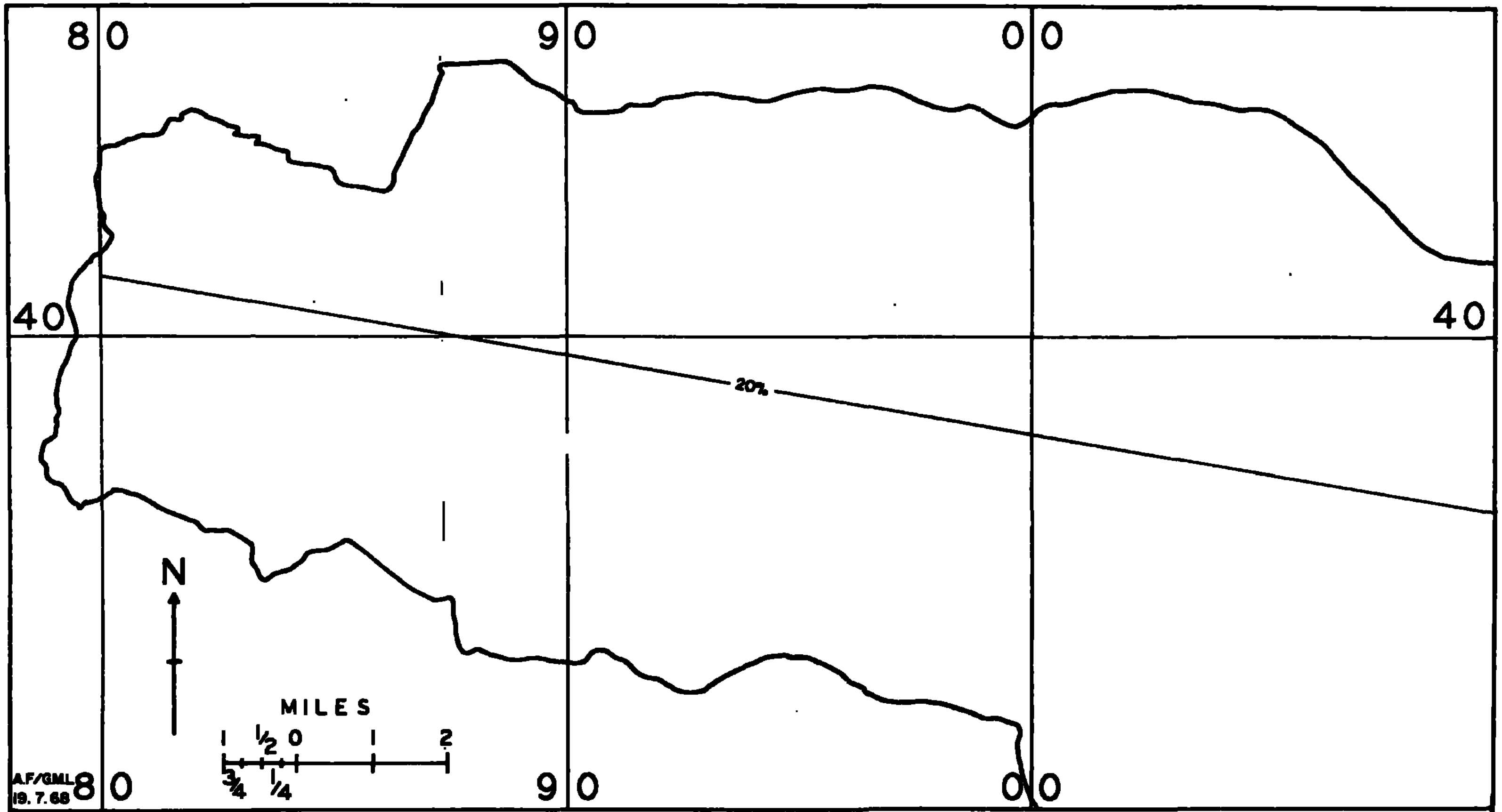
MAPS OF % CLAY CONTENT OF SURFACE LAYER

TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

source	sum of squares	degrees of freedom	mean square	F	% confidence
linear surface deviations from above	109 4233	2 42	54.50 100.78	0.54	25+
quadratic surface deviations from quadratic	822 3410	3 39	274.00 87.43	3.13	95+
cubic surface deviations from cubic	382 3130	4 35	95.50 89.42	1.07	50+
quartic surface deviations from quartic	190 2940	5 30	38.00 98.00	0.38	10+
quintic surface deviations from quintic					

TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

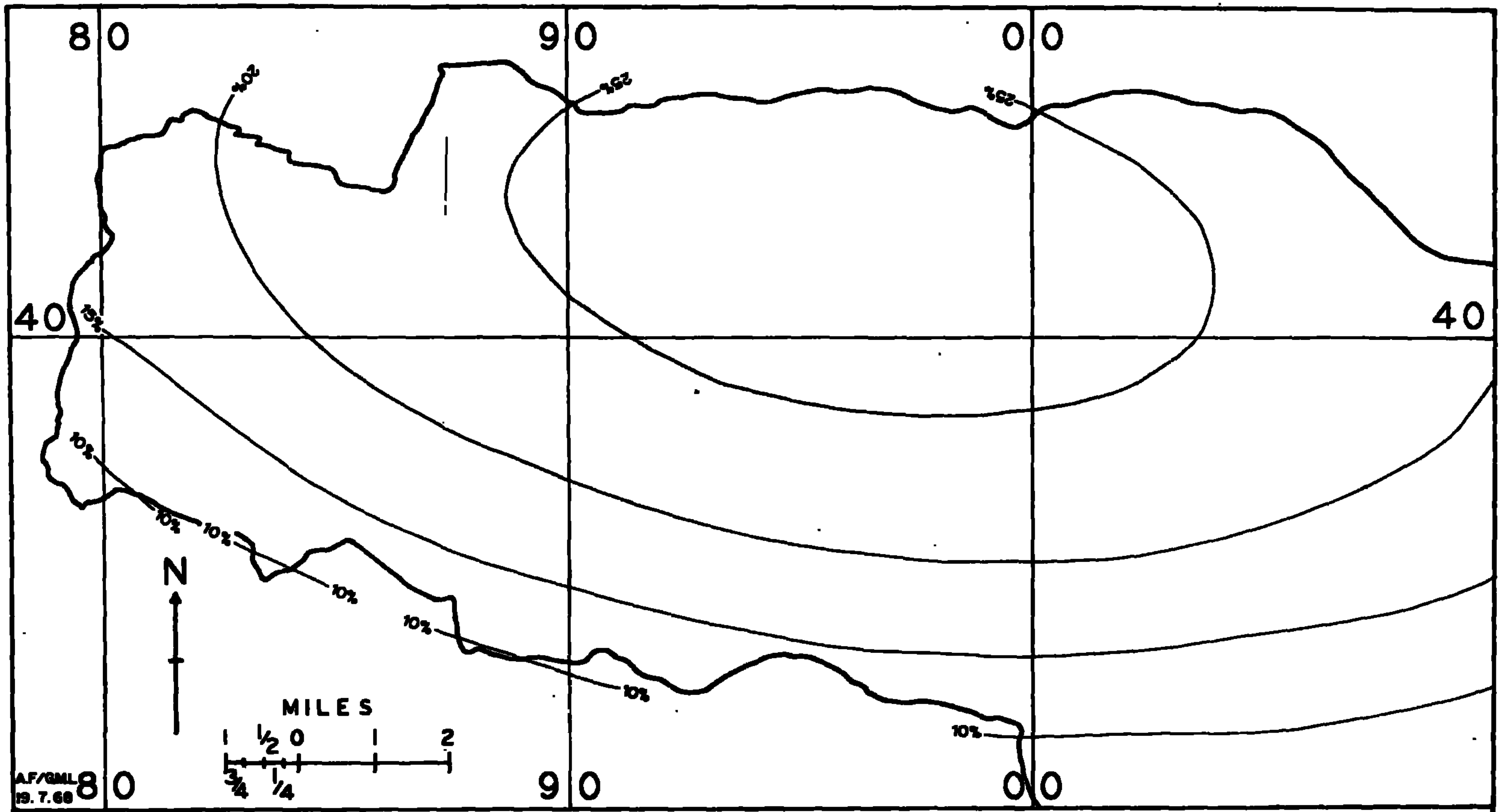
source	sum of squares	degrees of freedom	mean square	F	% confidence
first order surface deviations from first order	109 4233	2 42	54.50 100.78	0.54	25+
second order surface deviations from second order	931 3410	5 39	186.20 87.40	2.13	90+
third order surface deviations from third order	1213 3130	9 35	134.77 89.42	1.50	75+
fourth order surface deviations from fourth order	1402 2940	14 30	100.14 98.00	1.02	50+
fifth order surface deviations from fifth order					
source	sum of squares	degrees of freedom	mean square	F	% confidence



UPPER WEARDALE

MAP OF % CLAY CONTENT OF SURFACE LAYER

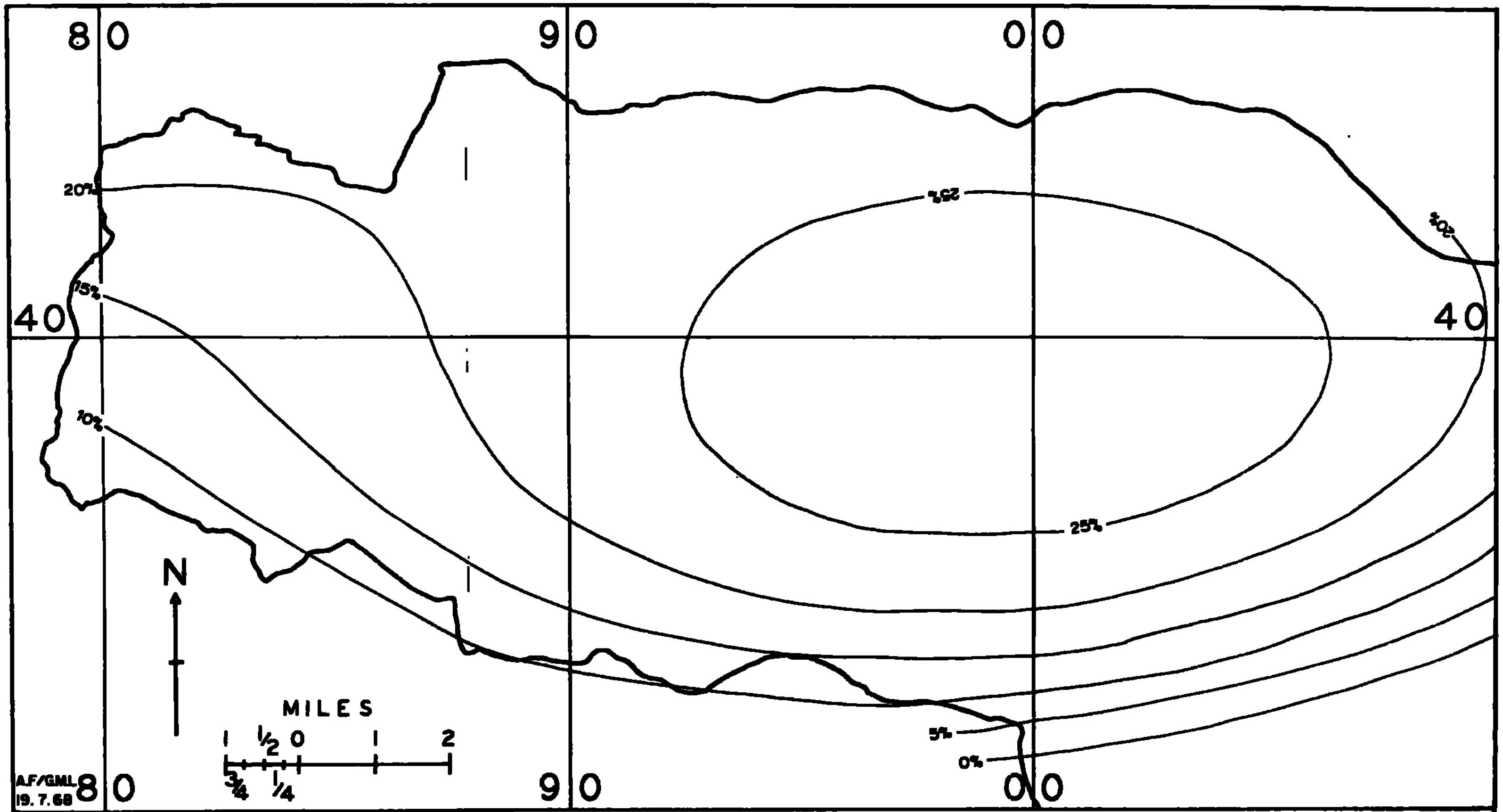
CONTOURED FIRST DEGREE SURFACE



UPPER WEARDALE

MAP OF % CLAY CONTENT OF SURFACE LAYER

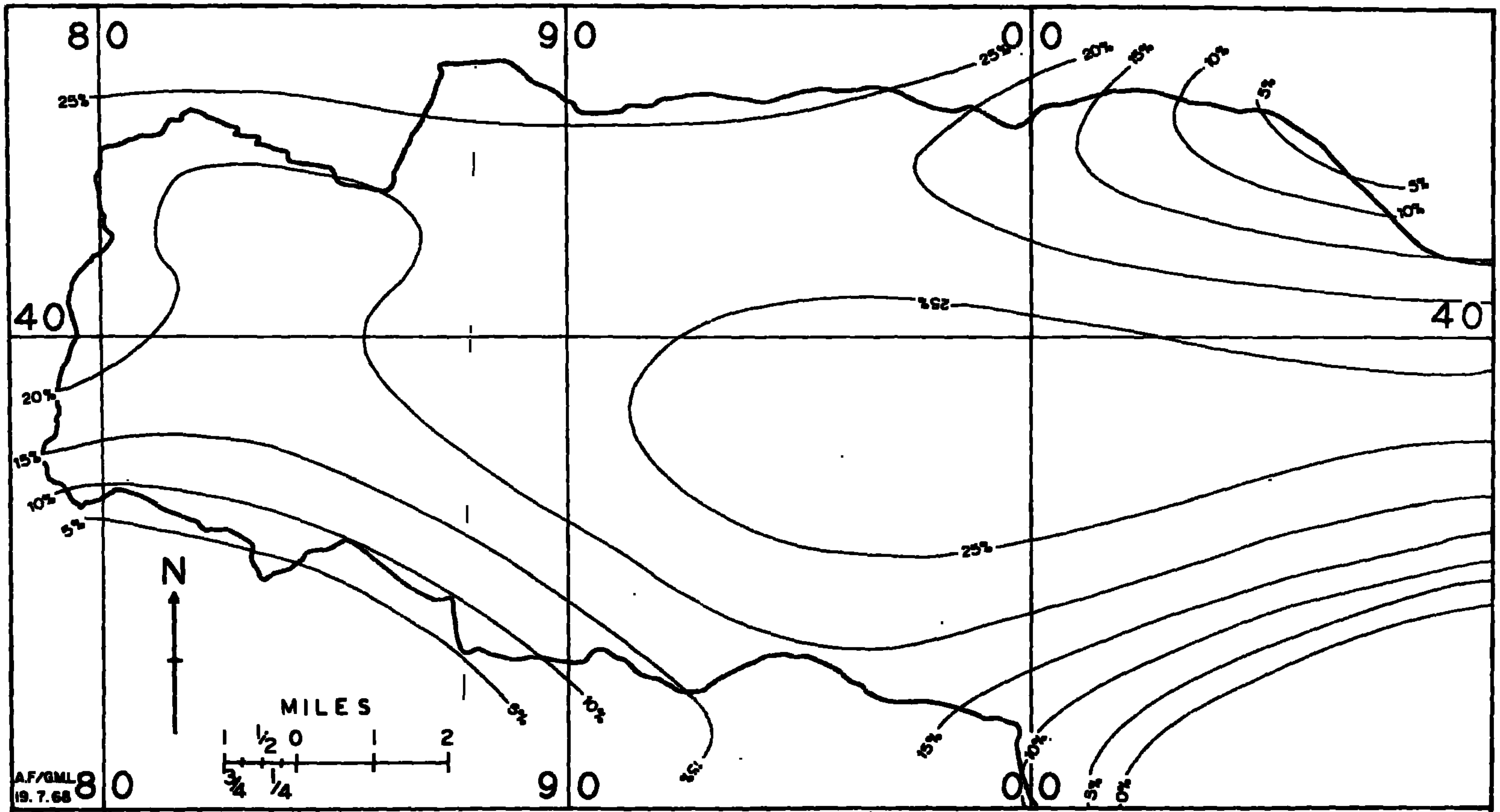
CONTOURED SECOND DEGREE SURFACE.



UPPER WEARDALE

MAP OF % CLAY CONTENT OF SURFACE LAYER

CONTOURED THIRD DEGREE SURFACE



UPPER WEARDALE

MAP OF % CLAY CONTENT OF SURFACE LAYER
CONTOURED FOURTH DEGREE SURFACE

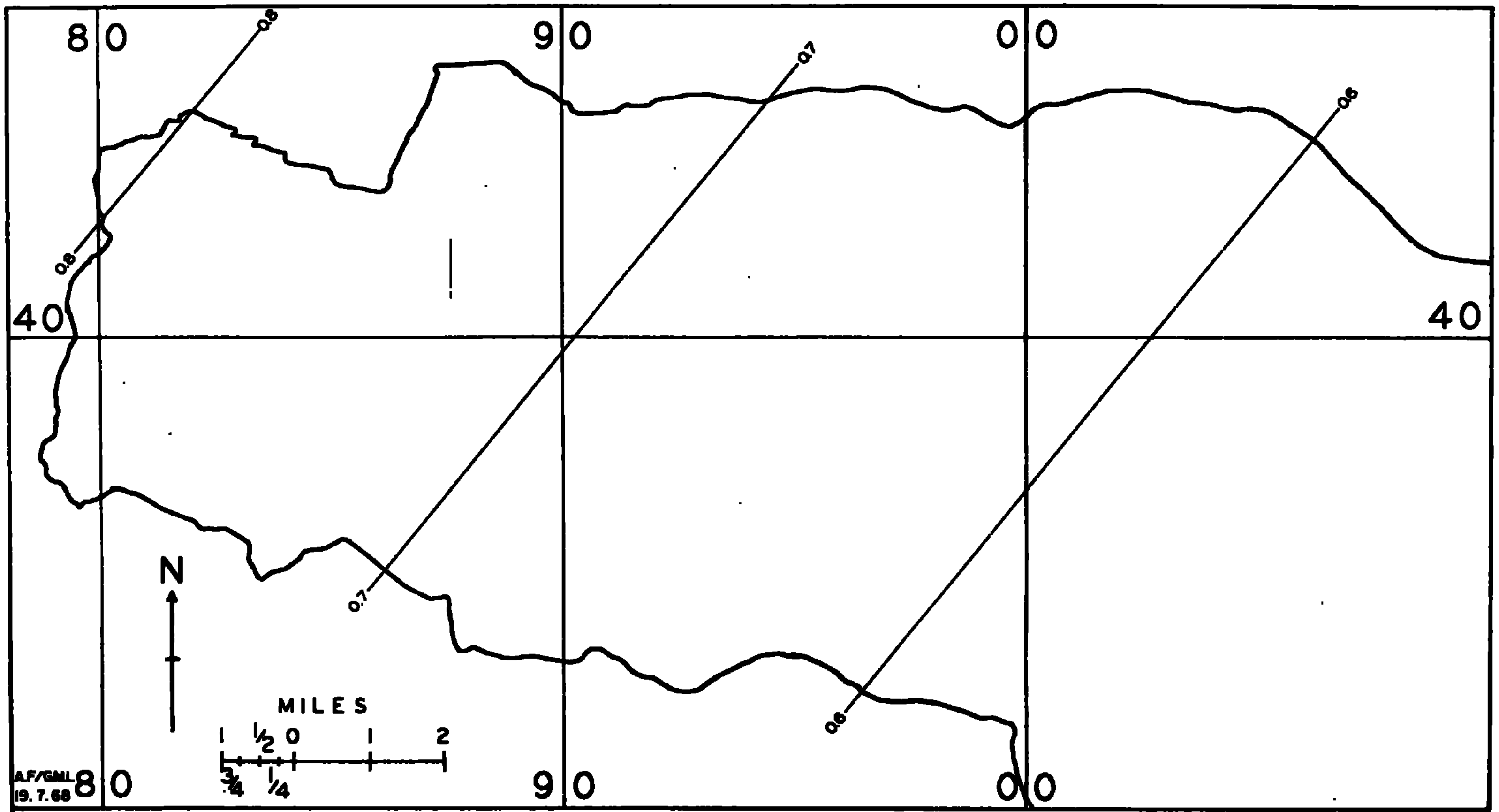
MAPS OF FACTOR 1 LOADINGS

TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT
OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

source	sum of squares	degrees of freedom	mean square	F	%confidence
linear surface deviations from above	317 2374	2 42	158.50 56.52	2.80	90+
quadratic surface deviations from quadratic	455 1919	3 39	151.66 49.20	3.08	95+
cubic surface deviations from cubic	140 1780	4 35	35.00 50.85	0.68	25+
quartic surface deviations from quartic	184 1596	5 30	36.80 53.320	0.69	25+
quintic surface deviations from quintic					

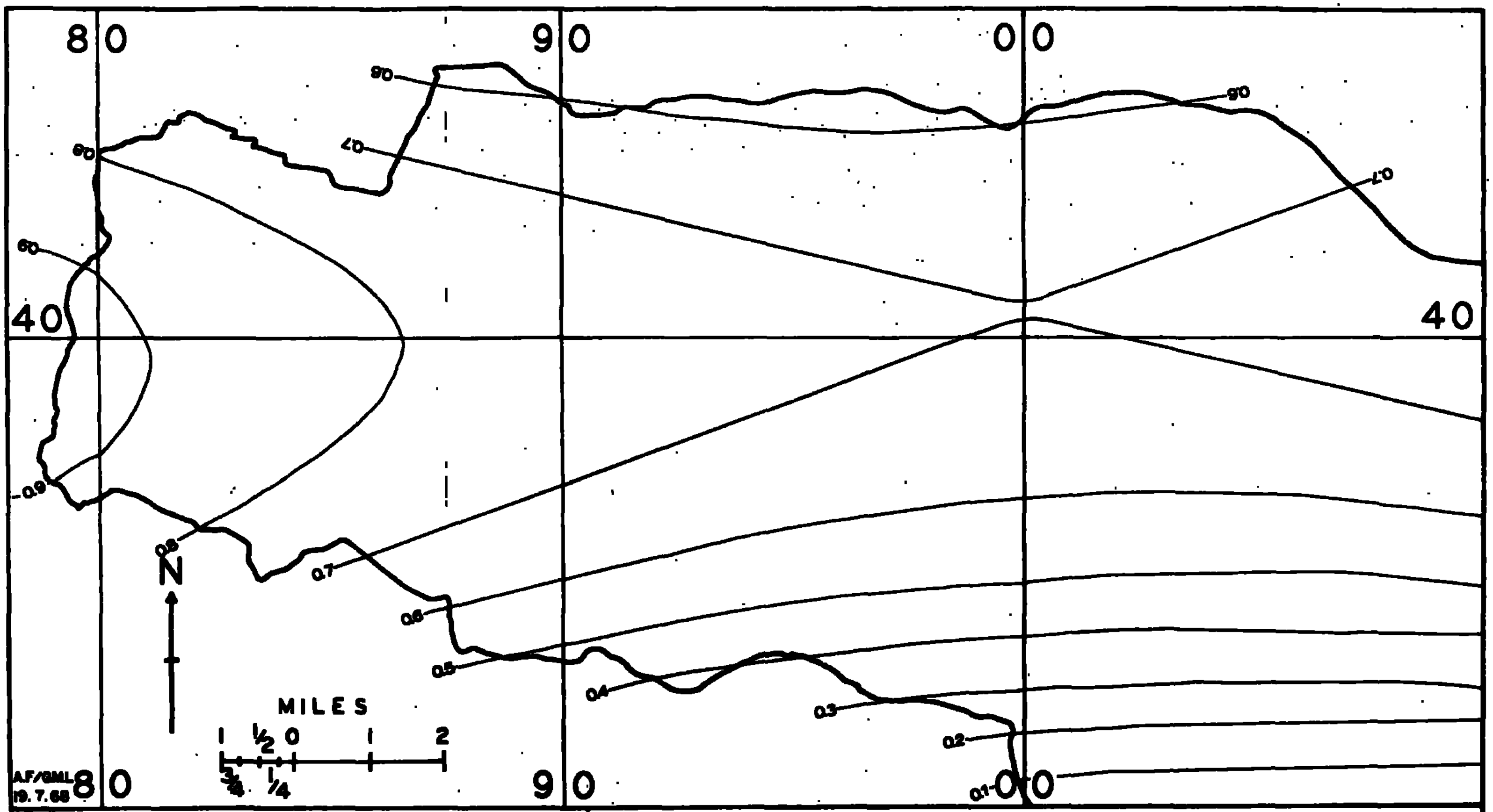
TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

source	sum of squares	degrees of freedom	mean square	F	%confidence
first order surface deviations from first order	317 2374	2 42	158.50 56.52	2.80	90+
second order surface deviations from second order	772 1919	5 39	154.40 49.20	3.13	97.5+
third order surface deviations from third order	911 1780	9 35	101.22 50.85	1.99	90+
fourth order surface deviations from fourth order	1095 1596	14 30	78.21 53.20	1.47	75+
fifth order surface deviations from fifth order					
source	sum of squares	degrees of freedom	mean square	F	%confidence



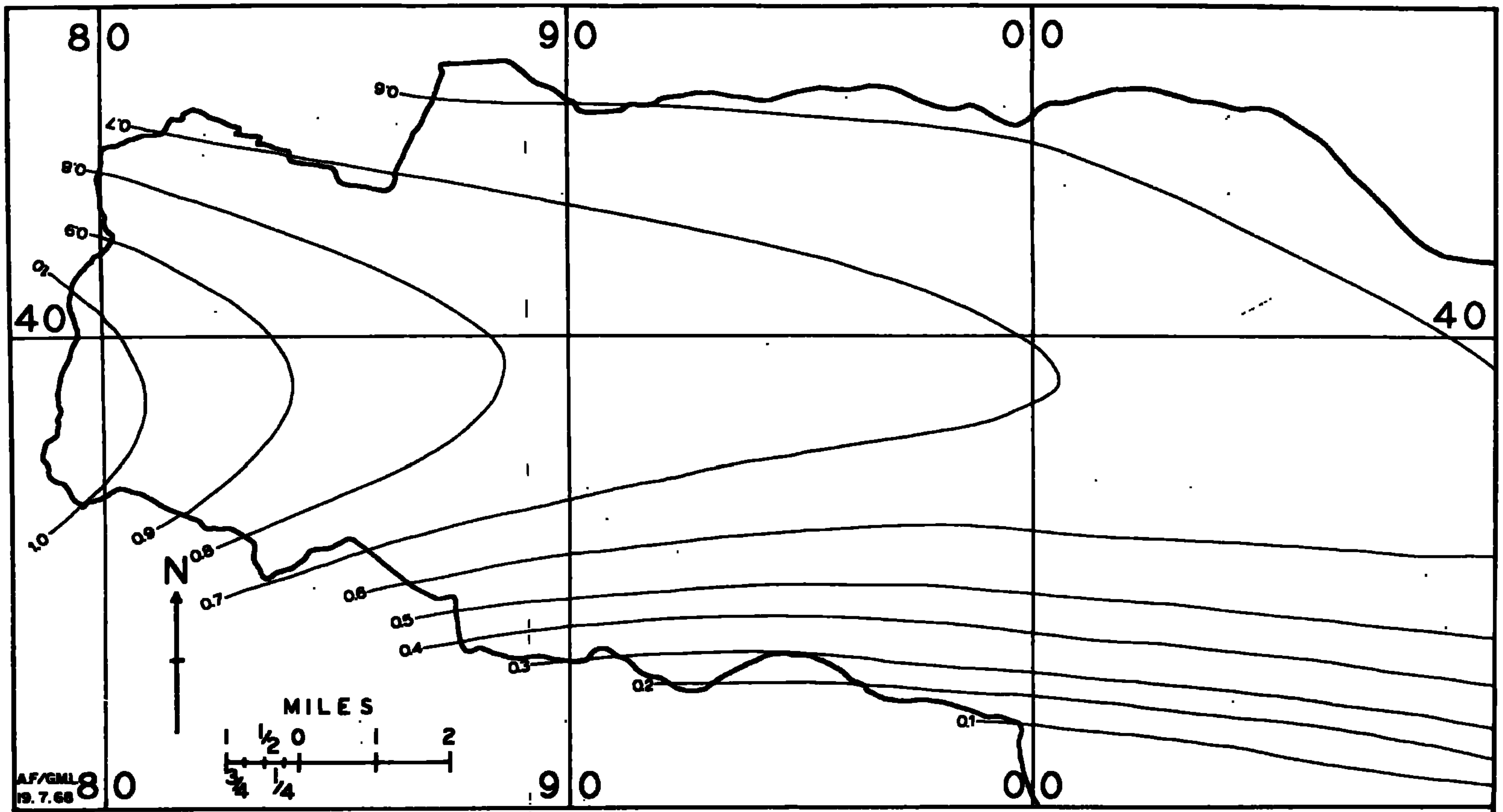
UPPER WEARDALE

MAP OF FACTOR 1 LOADINGS USING MAX FACTOR LOADING AT SITE CONTOURED FIRST-DEGREE SURFACE



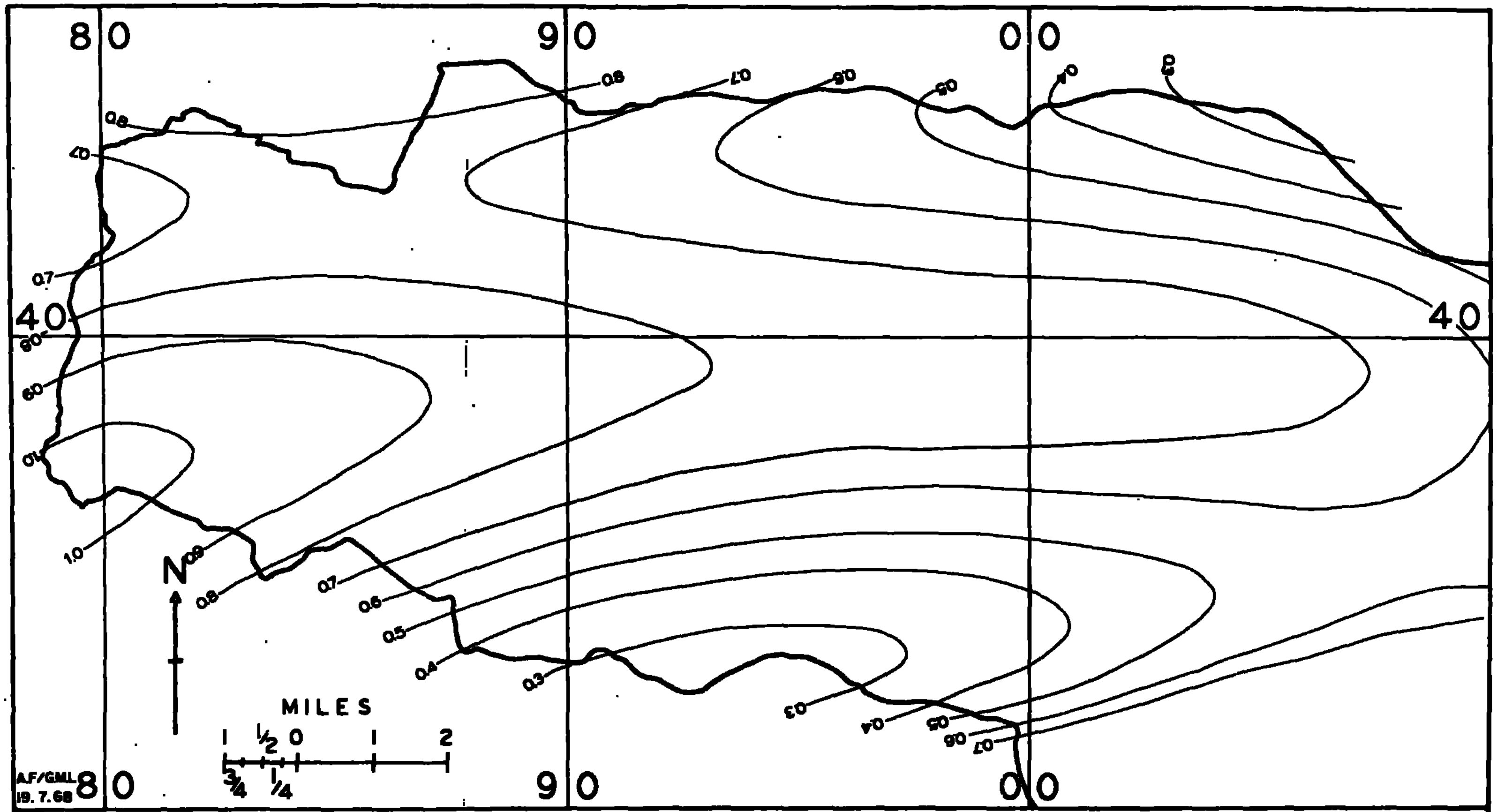
UPPER WEARDALE

MAP OF FACTOR 1 LOADINGS USING MAX FACTOR LOADING AT SITE CONTOURED SECOND-DEGREE SURFACE



UPPER WEARDALE

MAP OF FACTOR 1 LOADINGS USING MAX FACTOR LOADING AT SITE CONTOURED THIRD-DEGREE SURFACE



UPPER WEARDALE

MAP OF FACTOR 1 LOADINGS USING MAX FACTOR LOADING AT SITE CONTOURED FOURTH DEGREE SURFACE

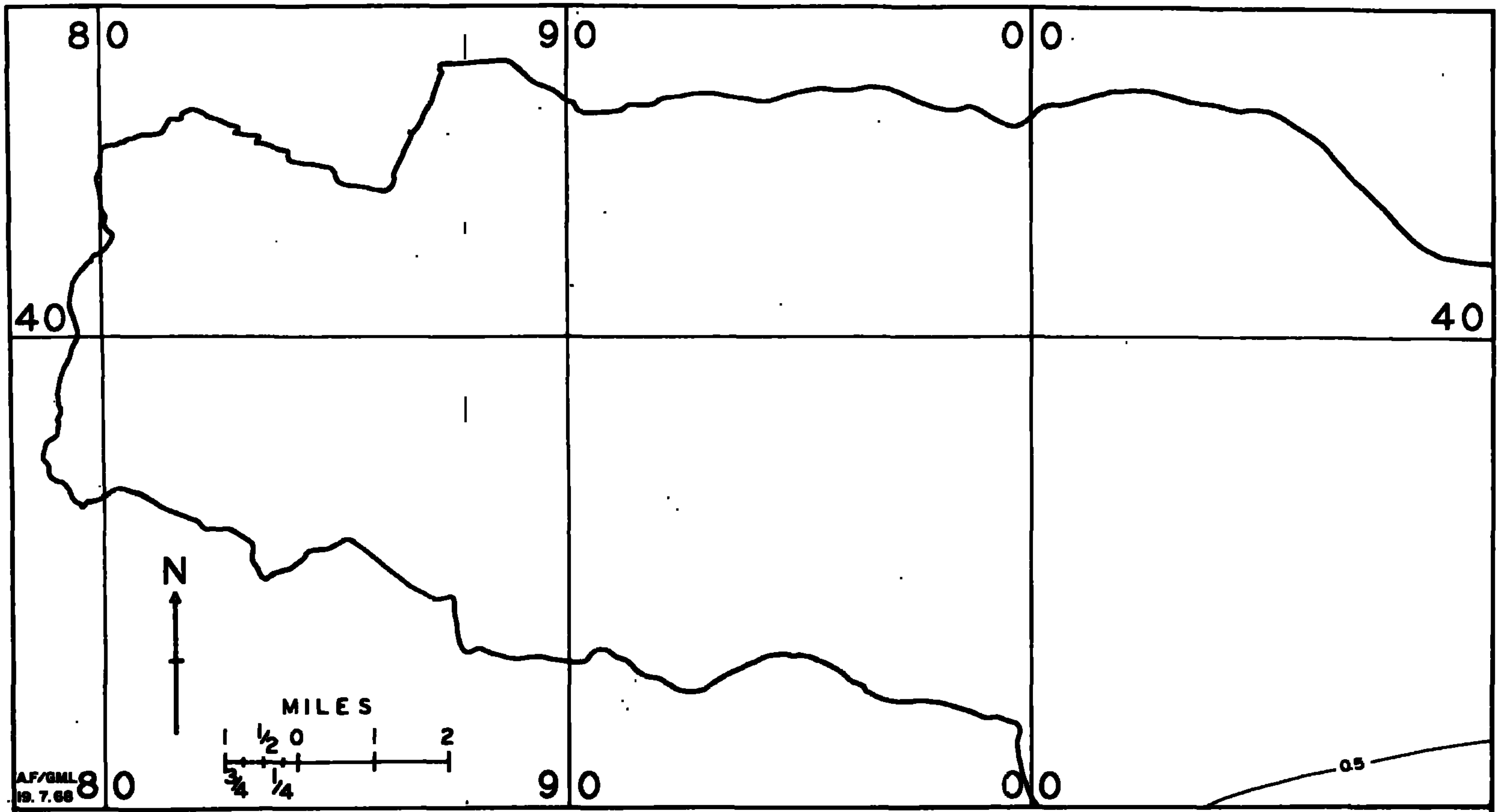
MAPS OF FACTOR 2 LOADINGS

TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

source	sum of squares	degrees of freedom	mean square	F	%confidence
linear surface deviations from above	10 2210	2 42	5.00 52.67	0.09	5+
quadratic surface deviations from quadratic	243 1967	3 39	81.00 50.43	1.60	75+
cubic surface deviations from cubic	.128 1839	4 35	32.00 52.54	0.60	25+
quartic surface deviations from quartic	58 1781	5 30	11.60 59.36	0.19	2.5+
quintic surface deviations from quintic					

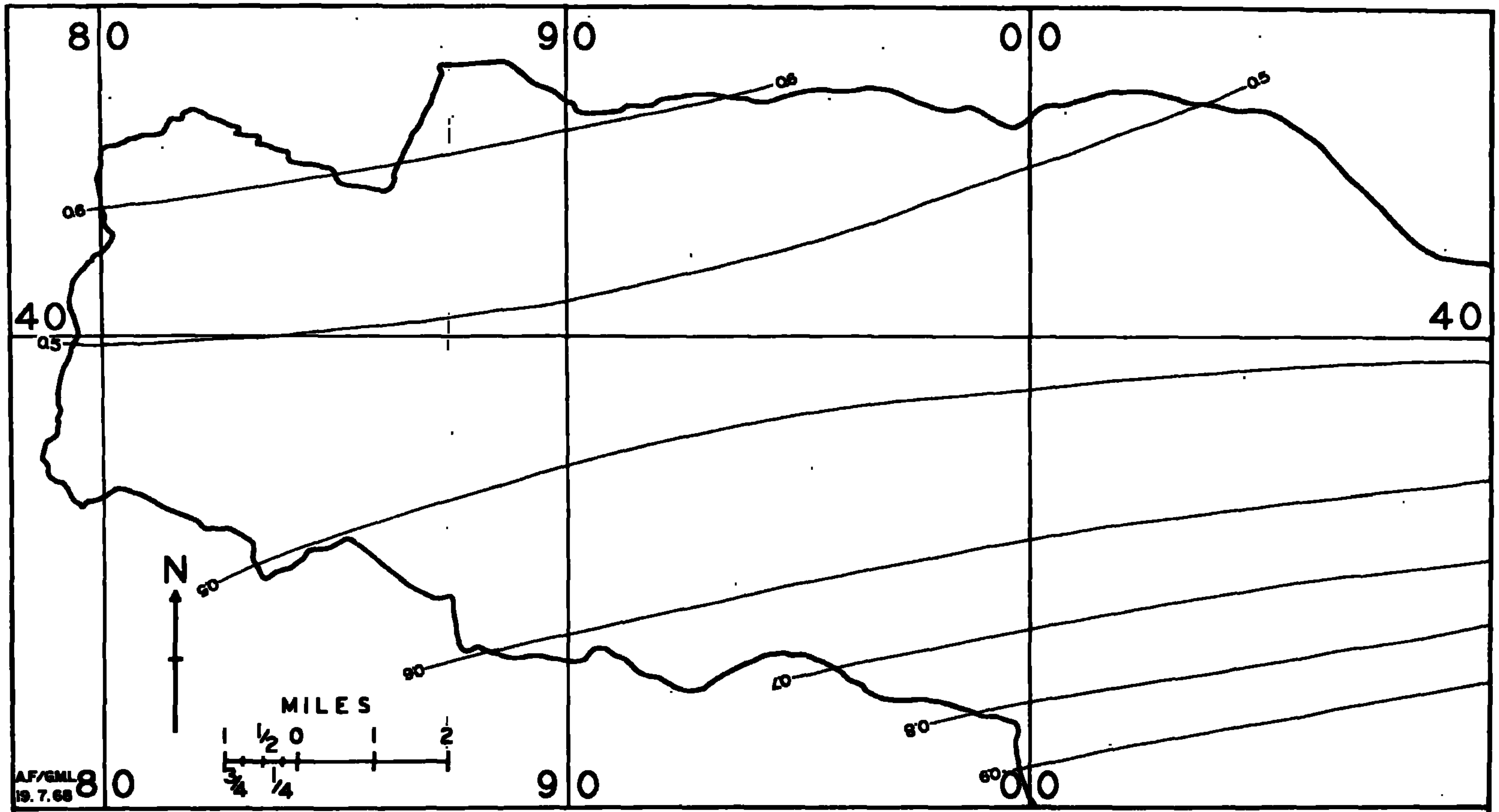
TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

source	sum of squares	degrees of freedom	mean square	F	%confidence
first order surface deviations from first order	10 2210	2 42	5.00 52.61	0.09	5+
second order surface deviations from second order	253 1967	5 39	50.60 50.43	1.00	50+
third order surface deviations from third order	381 1839	9 35	42.33 52.54	0.80	25+
fourth order surface deviations from fourth order	439 1781	14 30	31.35 59.36	0.53	5+
fifth order surface deviations from fifth order					



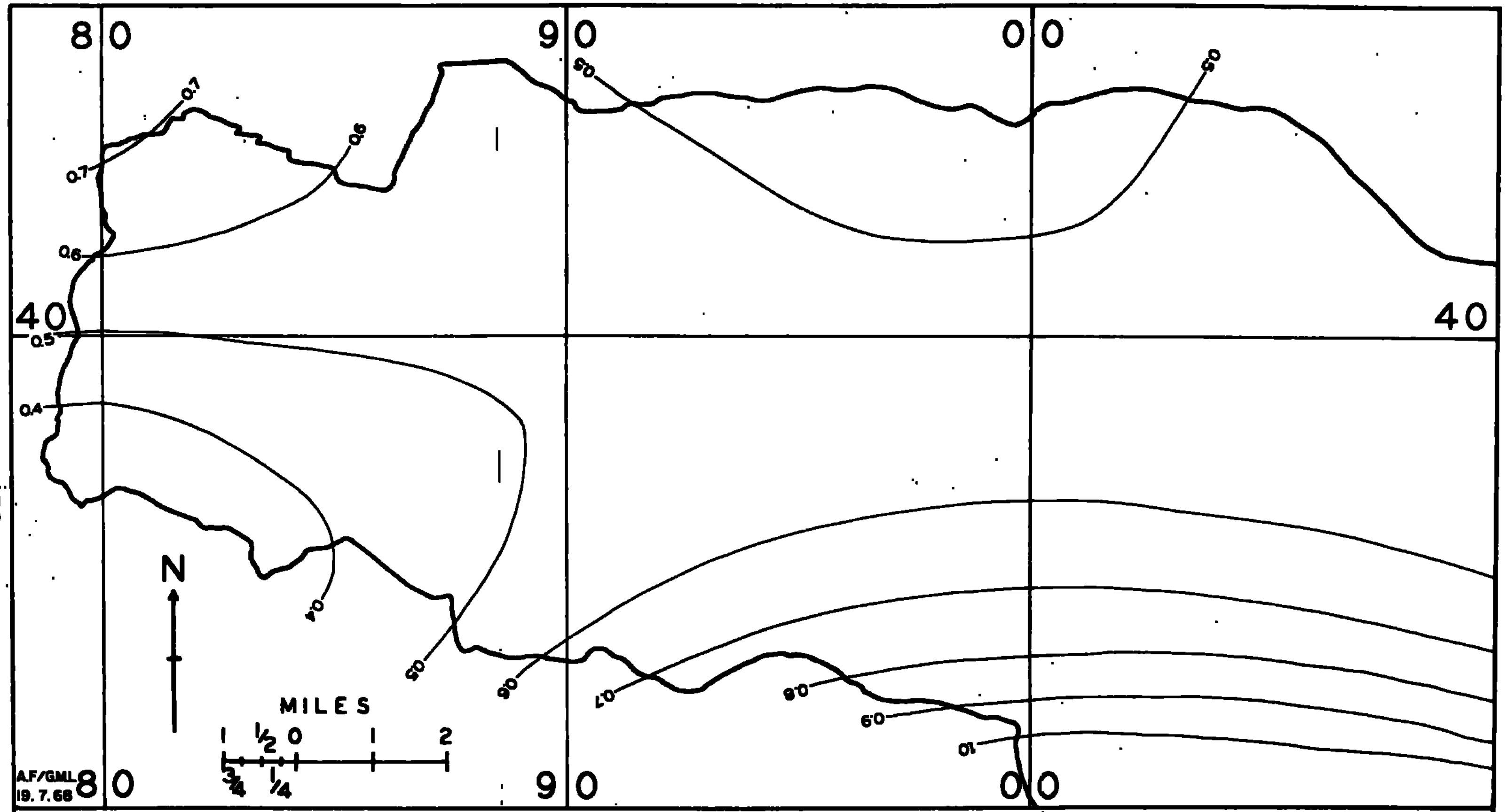
UPPER WEARDALE

MAP OF FACTOR 2 LOADINGS USING MAX FACTOR LOADING AT SITE CONTOURED FIRST-DEGREE SURFACE



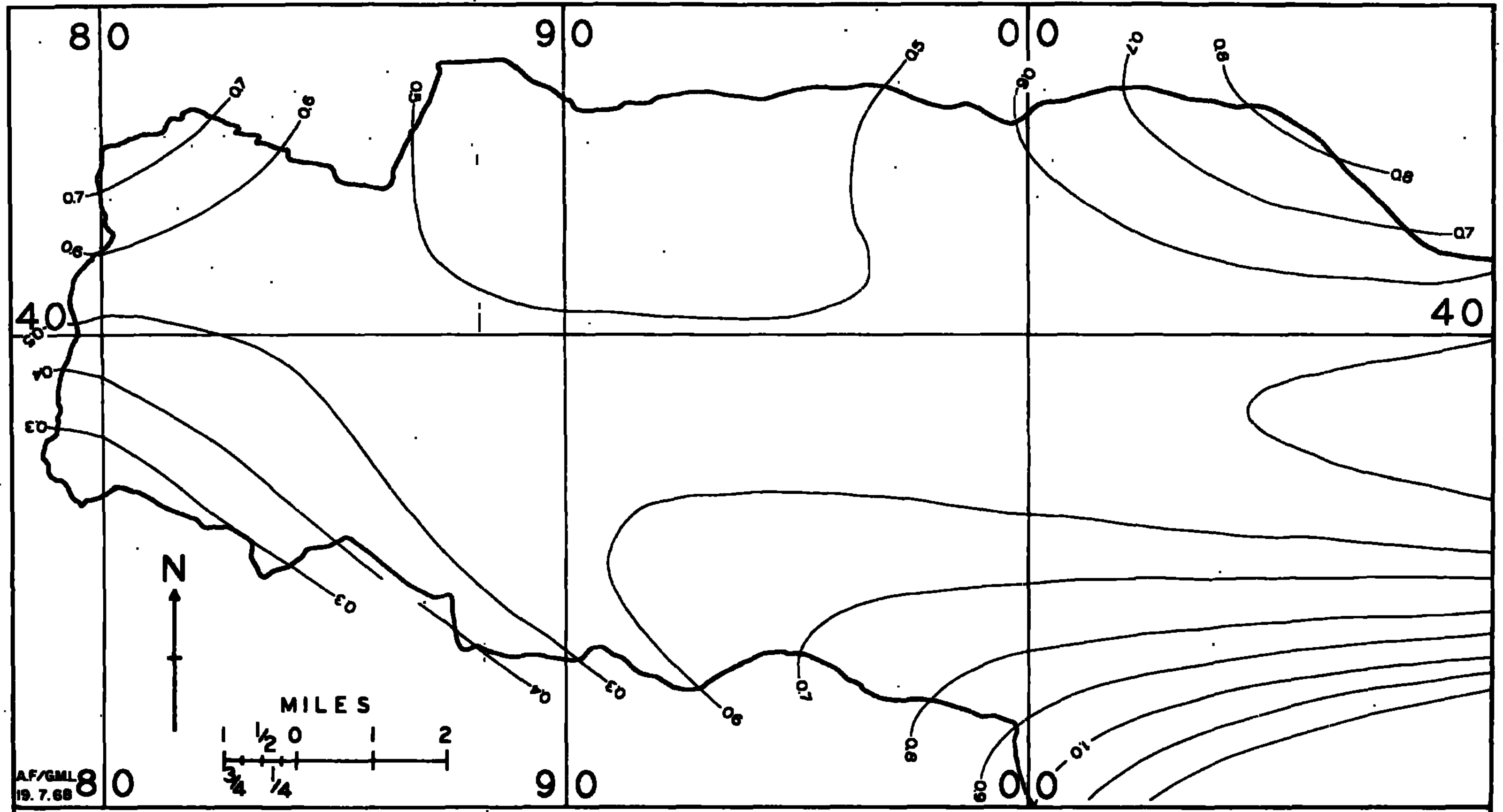
UPPER WEARDALE

MAP OF FACTOR 2 LOADINGS USING MAX FACTOR LOADING AT SITE CONTOURED SECOND-DEGREE SURFACE



UPPER WEARDALE

MAP OF FACTOR 2 LOADINGS USING MAX FACTOR LOADING AT SITE CONTOURED THIRD-DEGREE SURFACE



UPPER WEARDALE

MAP OF FACTOR 2 LOADINGS USING MAX FACTOR LOADING AT SITE CONTOURED FOURTH DEGREE SURFACE

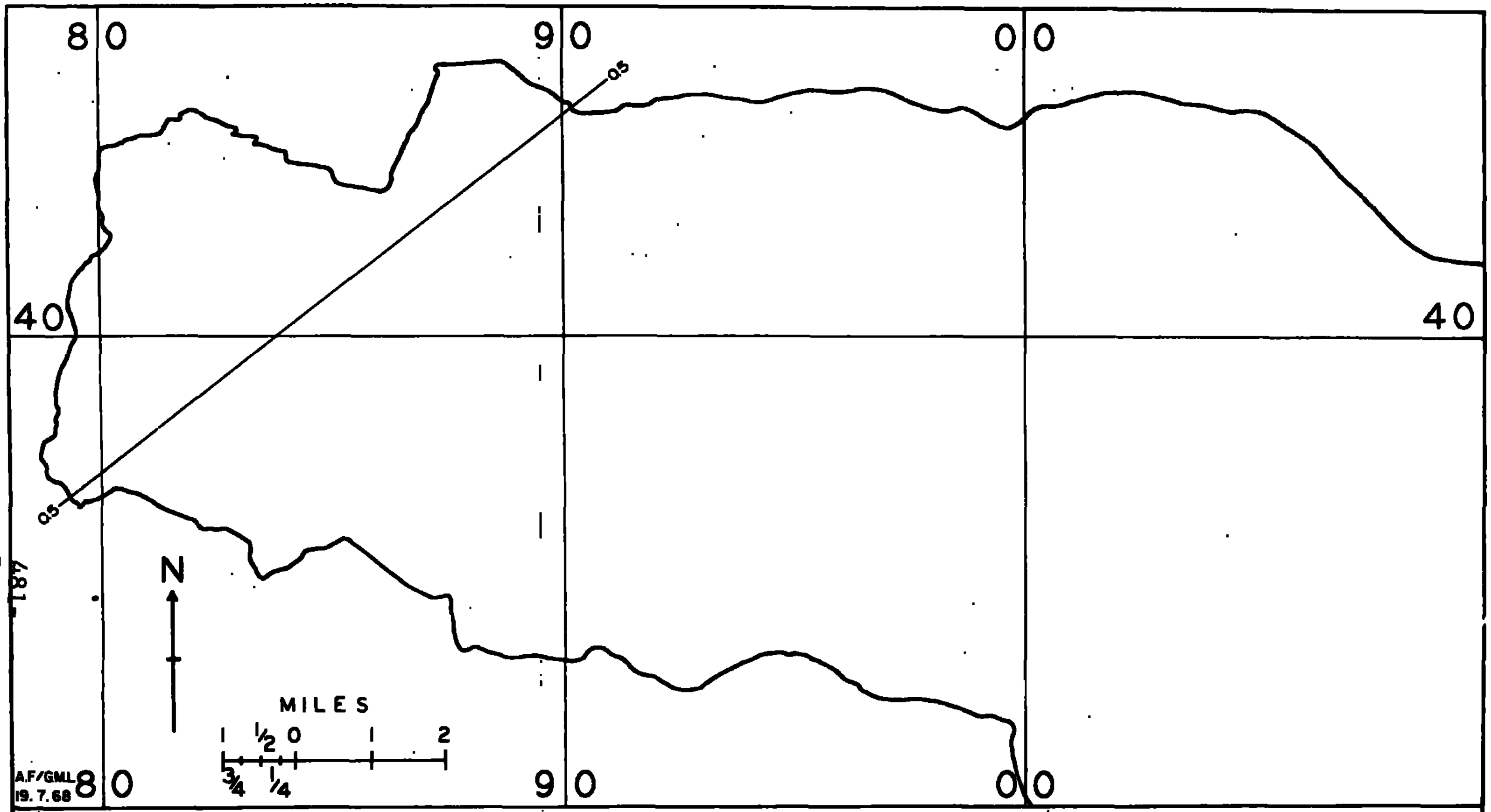
MAPS OF FACTOR 3 LOADINGS

TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT
OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

source	sum of squares	degrees of freedom	mean square	F	% confidence
linear surface deviations from above	34 1905	2 42	17.00 45.35	0.37	25+
quadratic surface deviations from quadratic	242 1662	3 39	80.66 42.61	1.89	75+
cubic surface deviations from cubic	214 1448	4 35	53.50 41.37	1.29	50+
quartic surface deviations from quartic	214 1235	5 30	42.80 41.16	1.04	50+
quintic surface deviations from quintic					

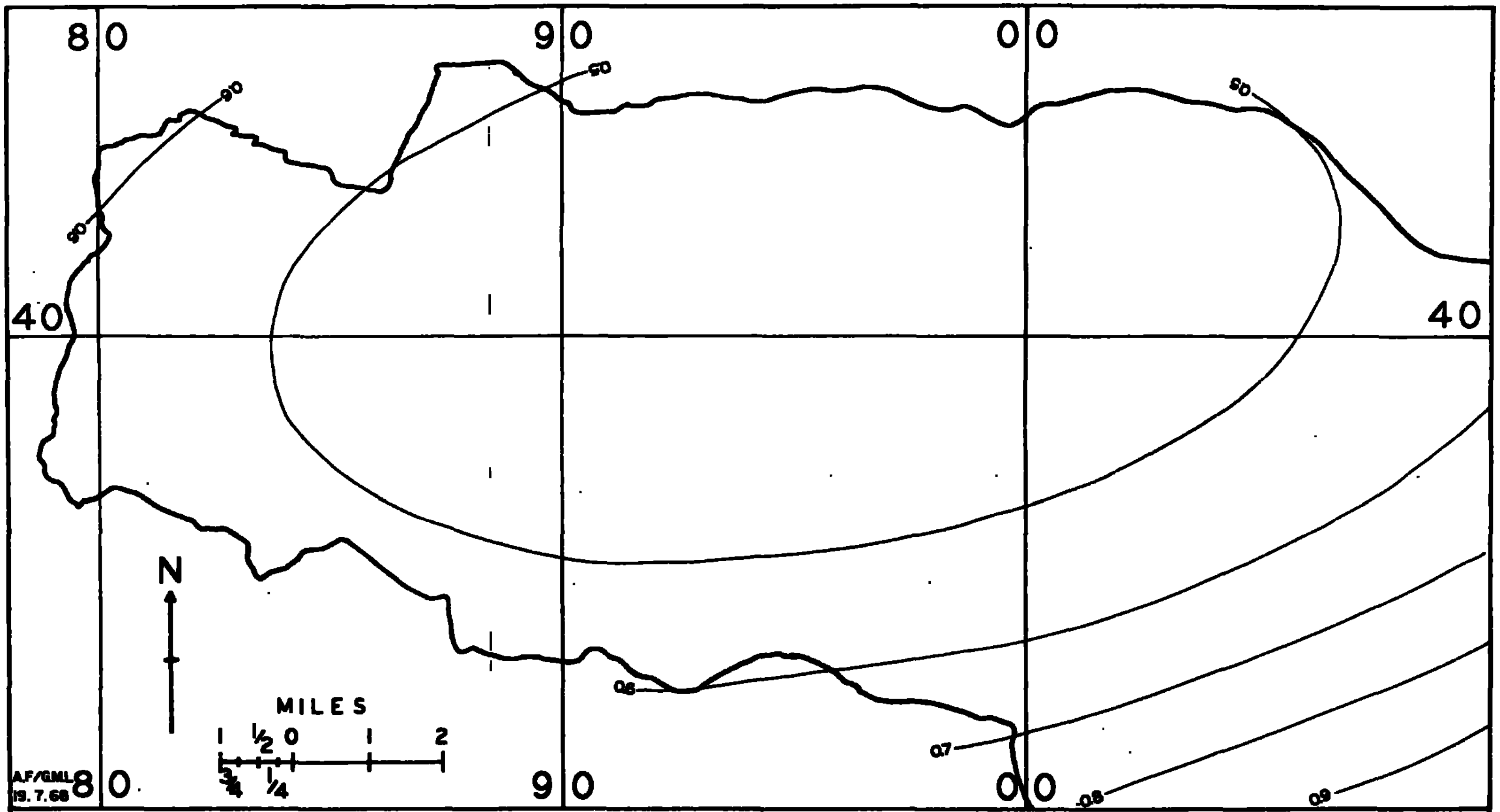
TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

source	sum of squares	degrees of freedom	mean square	F	% confidence
first order surface deviations from first order	34 1905	2 42	17.00 45.35	0.37	25+
second order surface deviations from second order	276 1662	5 39	55.20 42.61	1.29	50+
third order surface deviations from third order	490 1448	9 35	54.44 41.37	1.32 1.2	50+ 50+
fourth order surface deviations from fourth order	704 1235	14 30	50.28 41.16	1.2	50+
fifth order surface deviations from fifth order					
source	sum of squares	degrees of freedom	mean square	F	% confidence



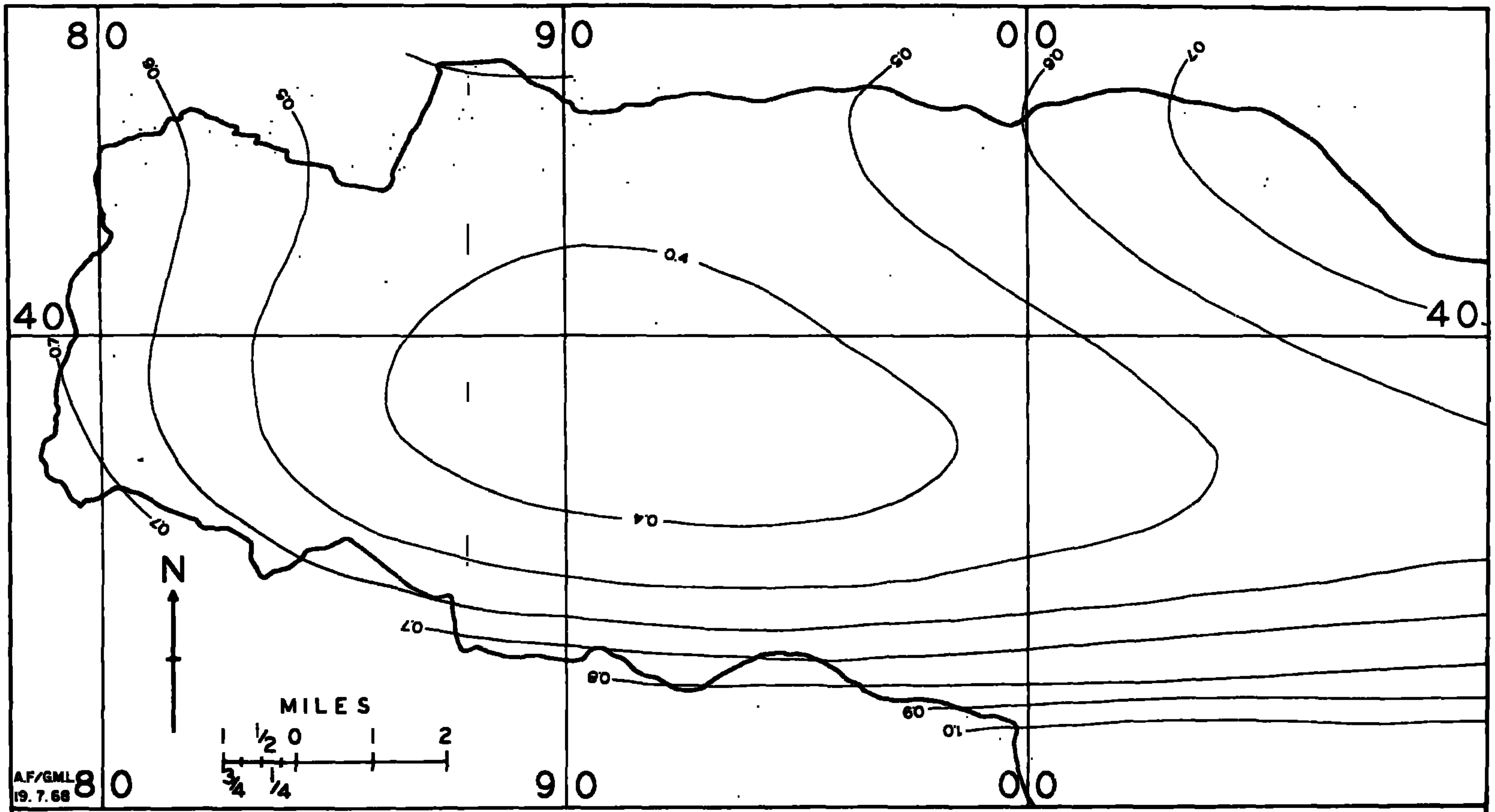
UPPER WEARDALE

MAP OF FACTOR 3 LOADINGS USING MAX FACTOR LOADING AT SITE CONTOURED FIRST-DEGREE SURFACE



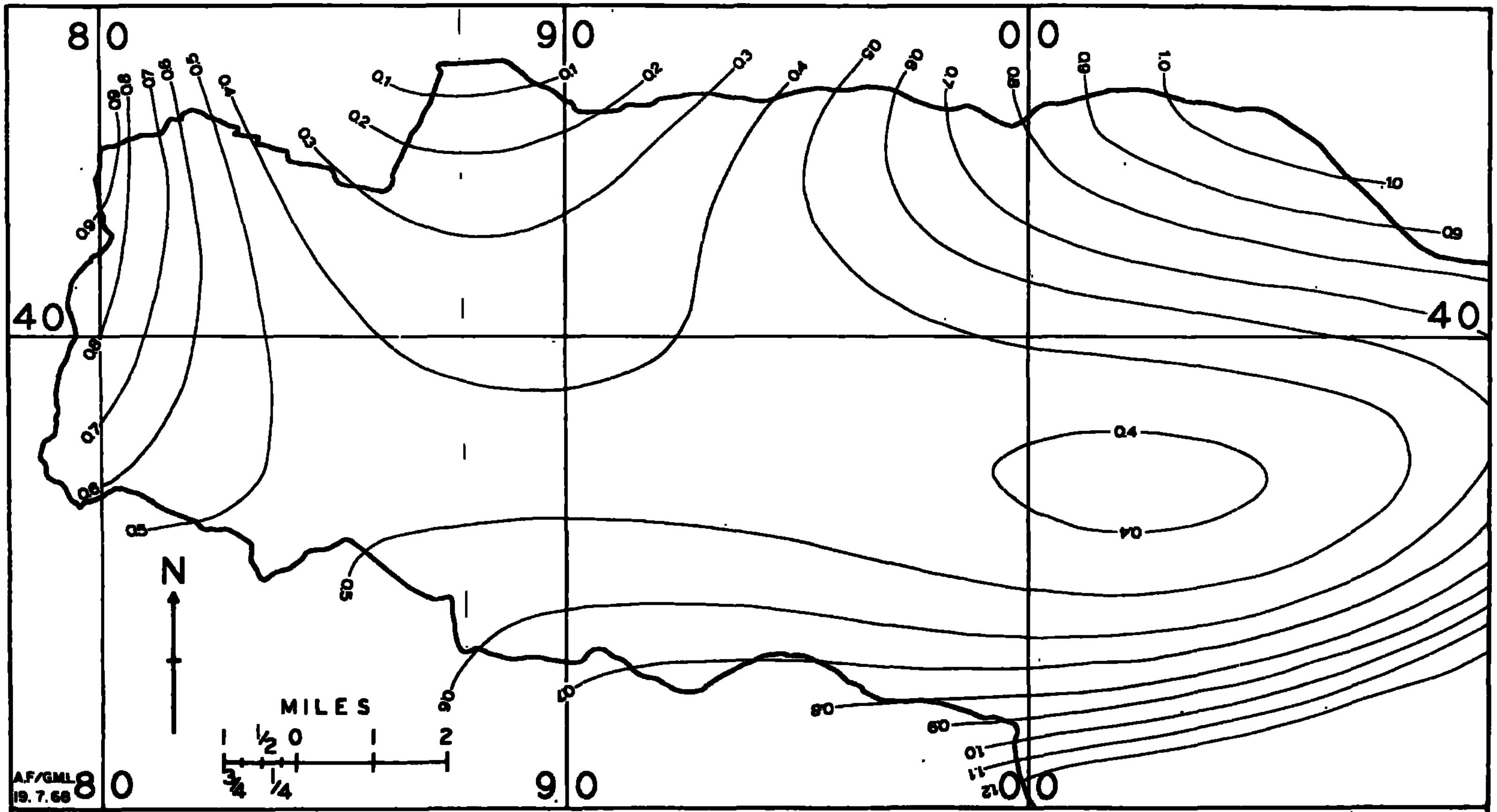
UPPER WEARDALE

MAP OF FACTOR 3 LOADINGS USING MAX FACTOR LOADING AT SITE CONTOURED SECOND-DEGREE SURFACE



UPPER WEARDALE

MAP OF FACTOR 3 LOADINGS USING MAX FACTOR LOADING AT SITE CONTOURED THIRD - DEGREE SURFACE



UPPER WEARDALE

MAP OF FACTOR 3 LOADINGS USING MAX FACTOR LOADING AT SITE CONTOURED FOURTH DEGREE SURFACE

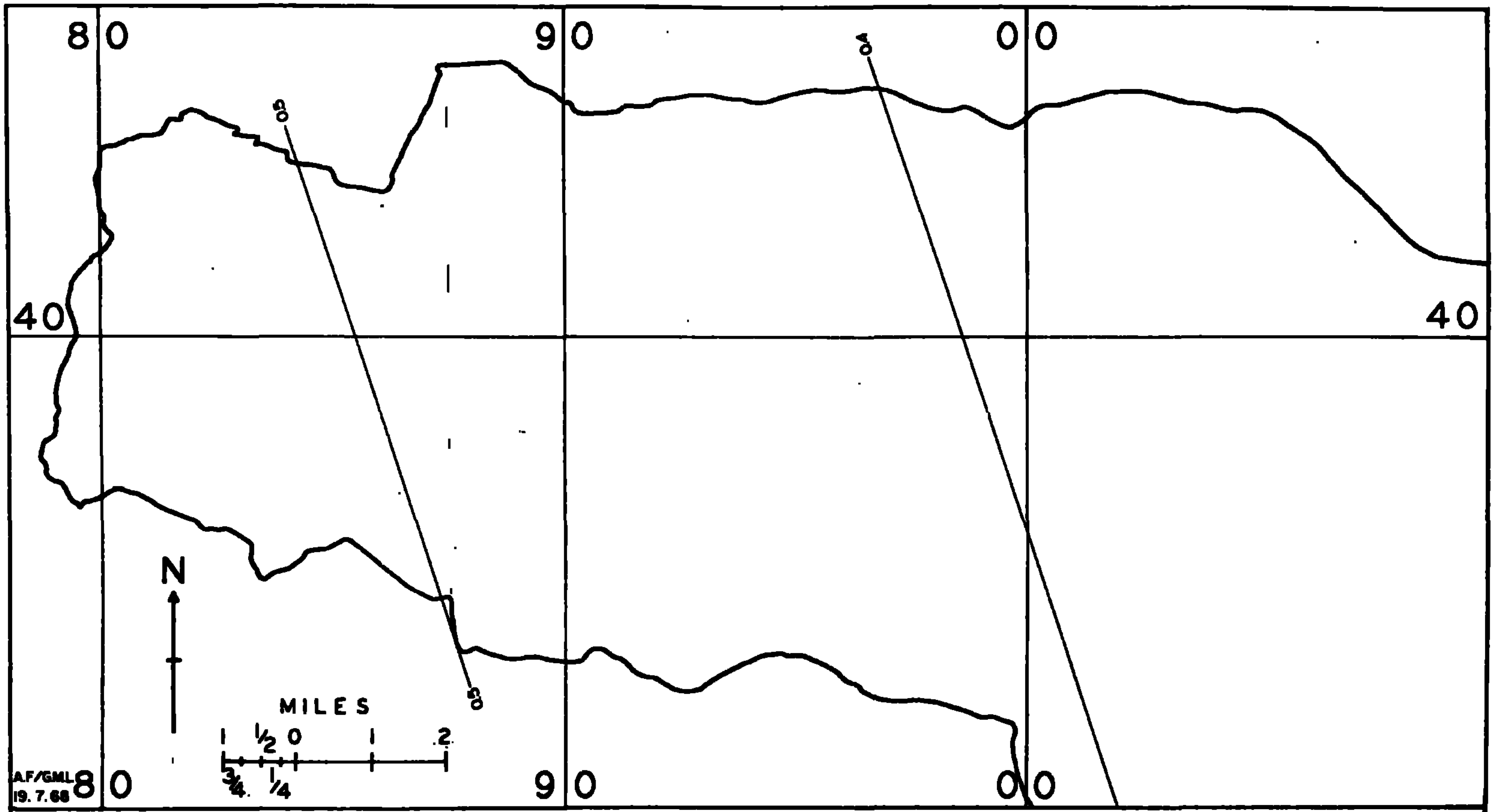
MAPS OF FACTOR 4 LOADINGS

TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT
OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

source	sum of squares	degrees of freedom	mean square	F	%confidence
linear surface deviations from above	209 1635	2 42	104.50 38.92	2.68	90+
quadratic surface deviations from quadratic	265 1371	3 39	88.33 35.15	2.51	90+
cubic surface deviations from cubic	75 1296	4 35	18.75 37.02	0.50	25+
quartic surface deviations from quartic	112 1183	5 30	22.40 39.43	0.56	25+
quintic surface deviations from quintic					

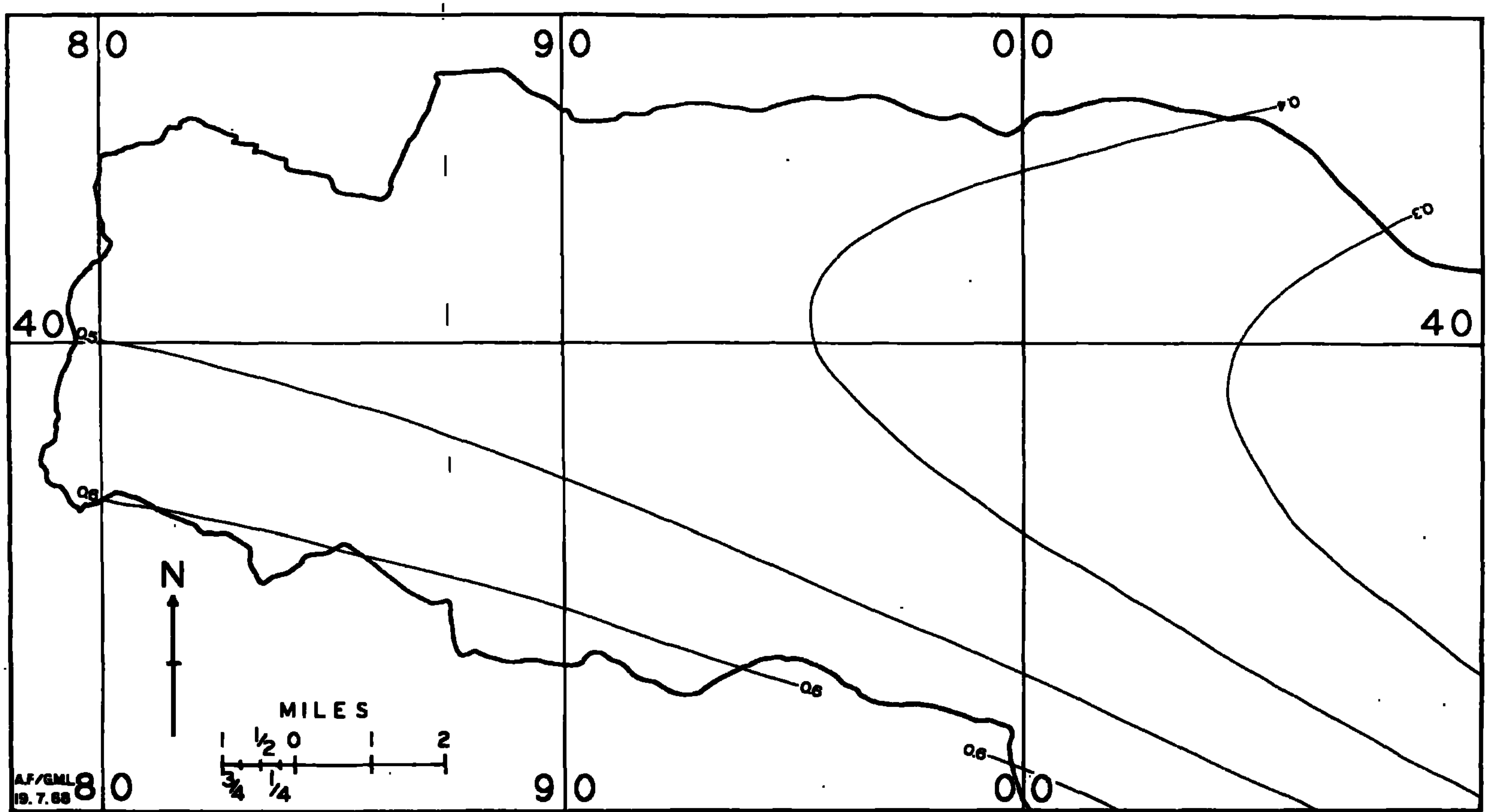
TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

source	sum of squares	degrees of freedom	mean square	F	%confidence
first order surface deviations from first order	209 1635	2 42	104.50 38.92	2.68	90+
second order surface deviations from second order	474 1371	5 39	94.80 35.15	2.69	95+
third order surface deviations from third order	549 1296	9 35	61.00 37.02	1.64	75+
fourth order surface deviations from fourth order	661 1183	14 30	47.33 39.43	1.20	50+
fifth order surface deviations from fifth order					
source	sum of squares	degrees of freedom	mean square	F	%confidence



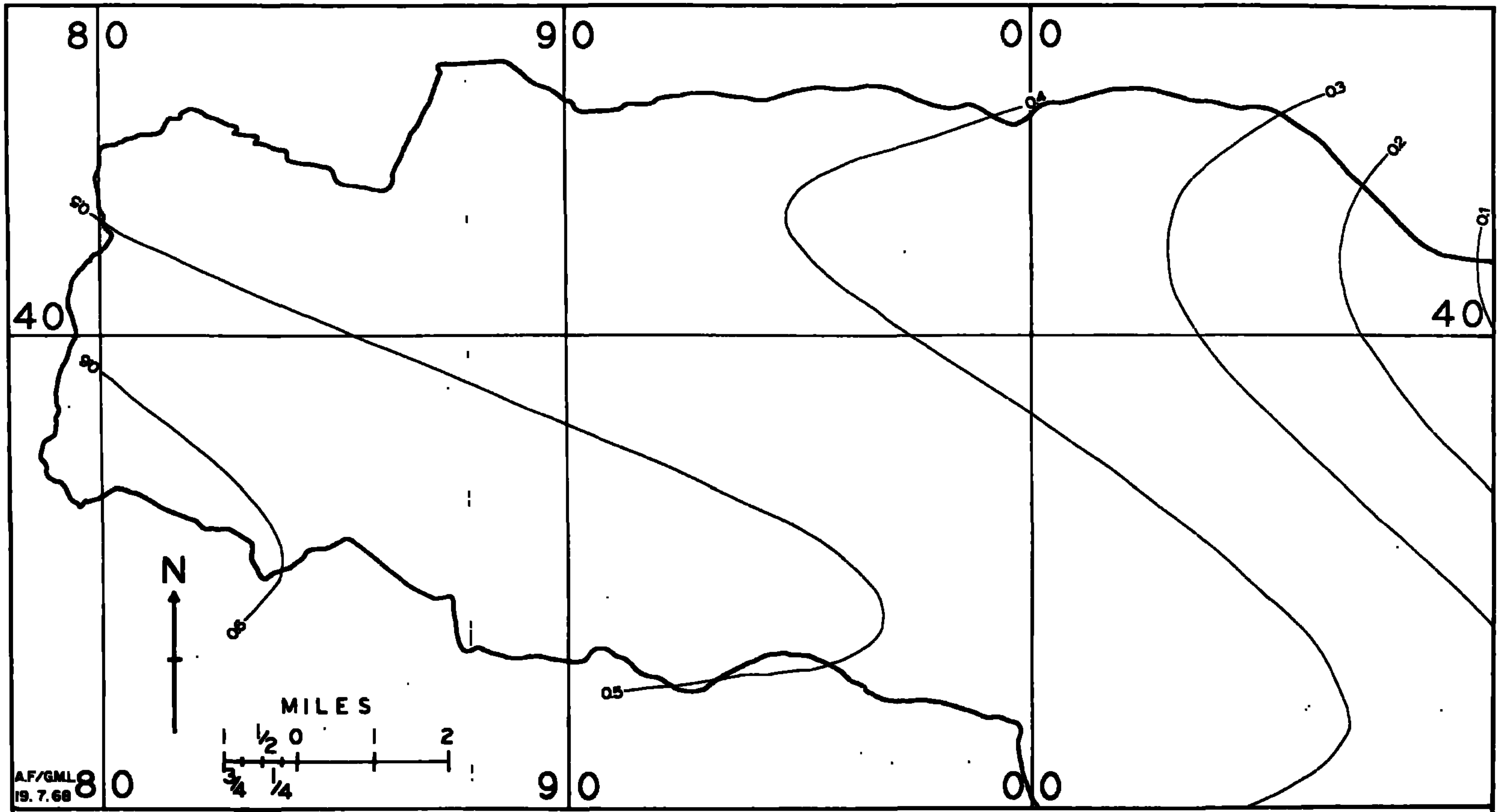
UPPER WEARDALE

MAP OF FACTOR 4 LOADINGS USING MAX FACTOR LOADING AT SITE CONTOURED FIRST-DEGREE SURFACE



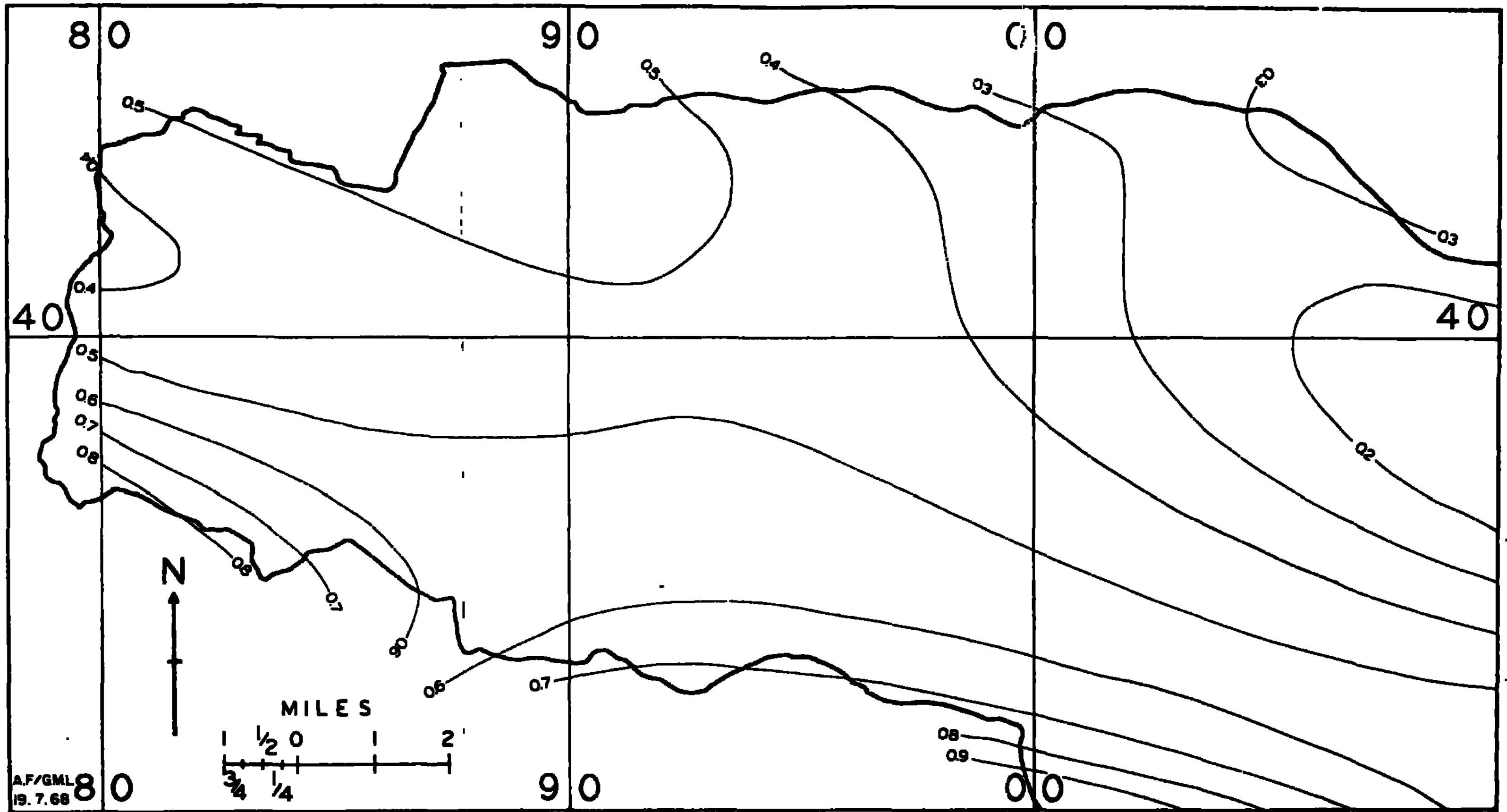
UPPER WEARDALE

MAP OF FACTOR 4 LOADINGS USING MAX FACTOR LOADING AT SITE CONTOURED -SECOND-DEGREE SURFACE



UPPER WEARDALE

MAP OF FACTOR 4 LOADINGS USING MAX FACTOR LOADING AT SITE CONTOURED THIRD - DEGREE SURFACE



UPPER WEARDALE

MAP OF FACTOR 4 LOADING USING MAX. FACTING LOADING AT SITE CONTOURED FOURTH DEGREE SURFACE

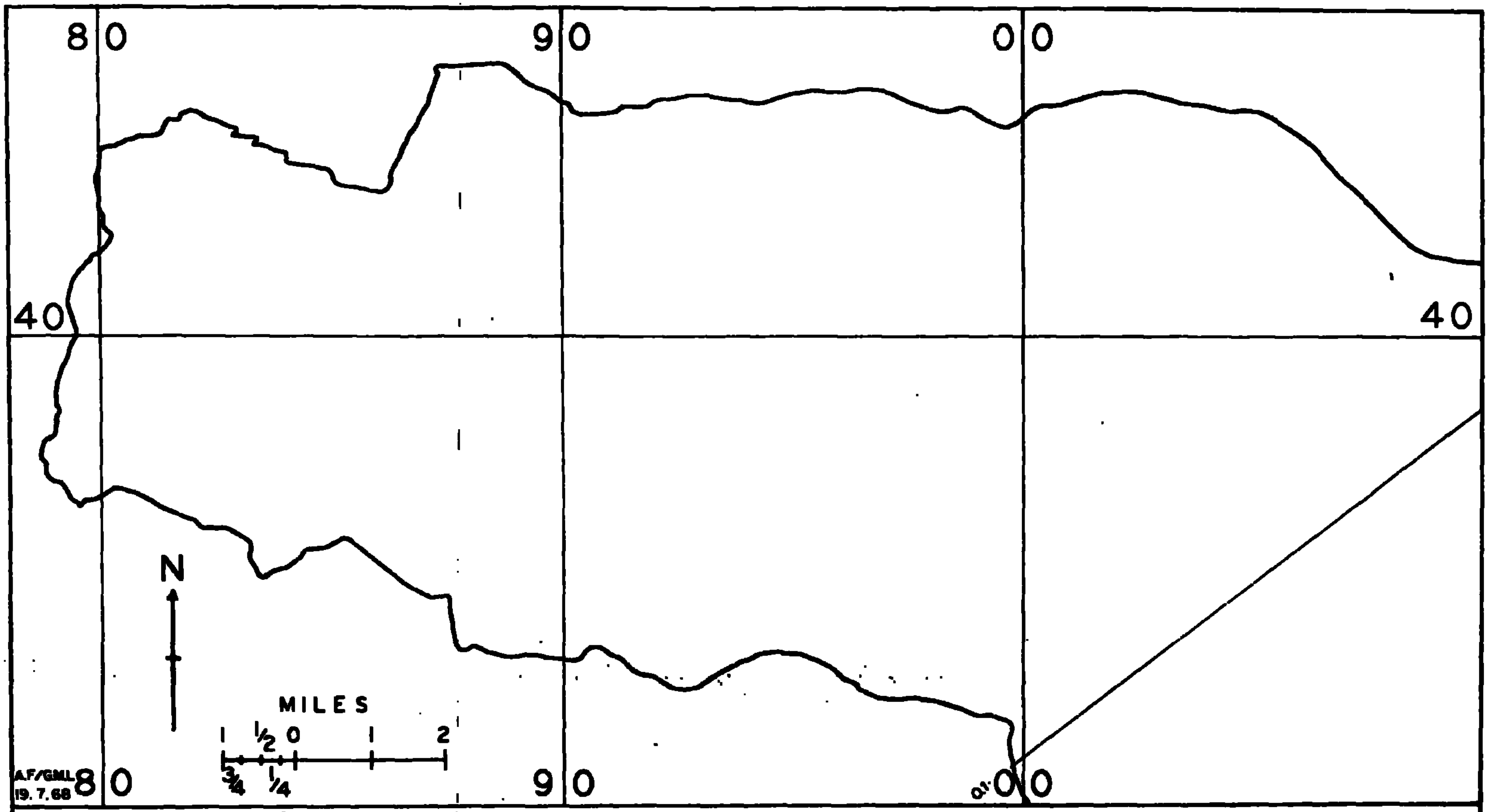
MAPS OF FACTOR 5 LOADINGS

TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

source	sum of squares	degrees of freedom	mean square	F	%confidence
linear surface deviations from above	271 9645	2 42	135.50 229.64	0.59	25+
quadratic surface deviations from quadratic	744 8901	3 39	248.00 228.23	1.08	50+
cubic surface deviations from cubic	280 8621	4 35	70.00 246.31	0.28	10+
quartic surface deviations from quartic	1130 7491	5 30	226.00 249.70	0.90	50+
quintic surface deviations from quintic					

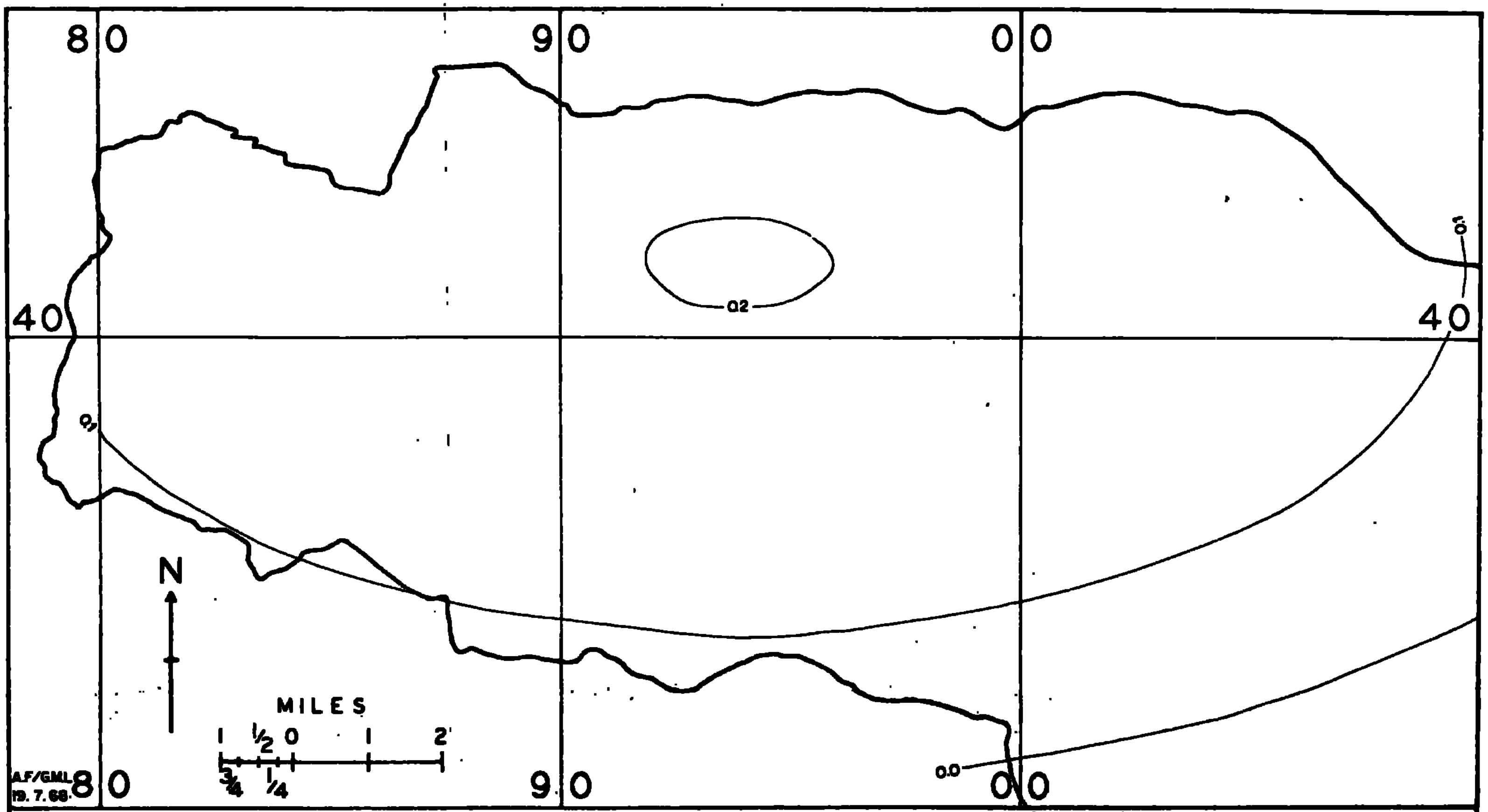
TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

source	sum of squares	degrees of freedom	mean square	F	%confidence
first order surface deviations from first order	271 9645	2 42	135.50 229.64	0.59	25+
second order surface deviations from second order	1015 8901	5 39	203.00 228.23	0.88	50+
third order surface deviations from third order	1295 8621	9 35	143.88 246.31	0.58	10+
fourth order surface deviations from fourth order	2425 7491	14 30	173.21 249.70	0.69	10+
fifth order surface deviations from fifth order					
source	sum of squares	degrees of freedom	mean square	F	%confidence



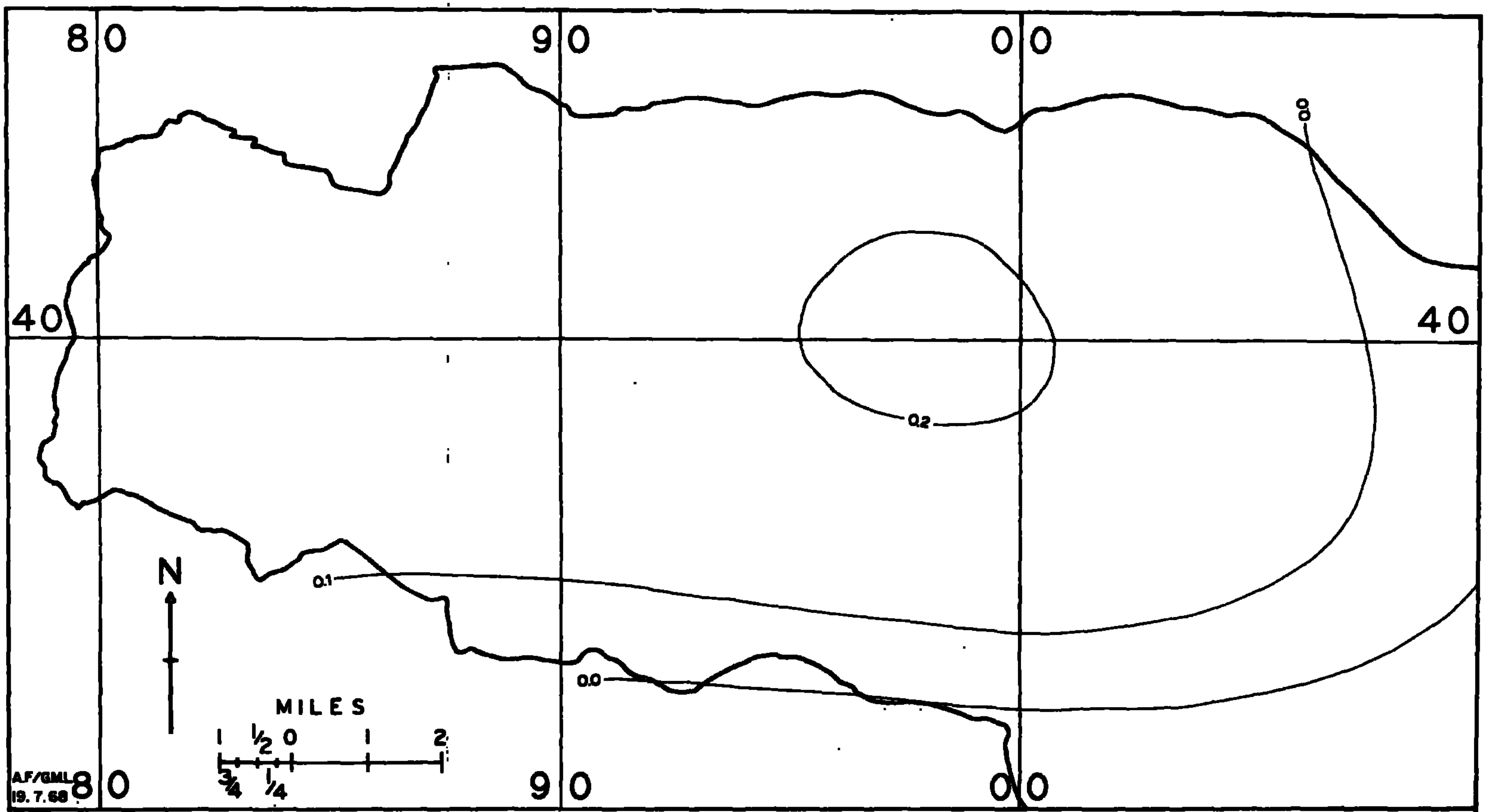
UPPER WEARDALE

MAP OF FACTOR 5 LOADINGS USING MAX FACTOR LOADING AT SITE CONTOURED FIRST-DEGREE SURFACE



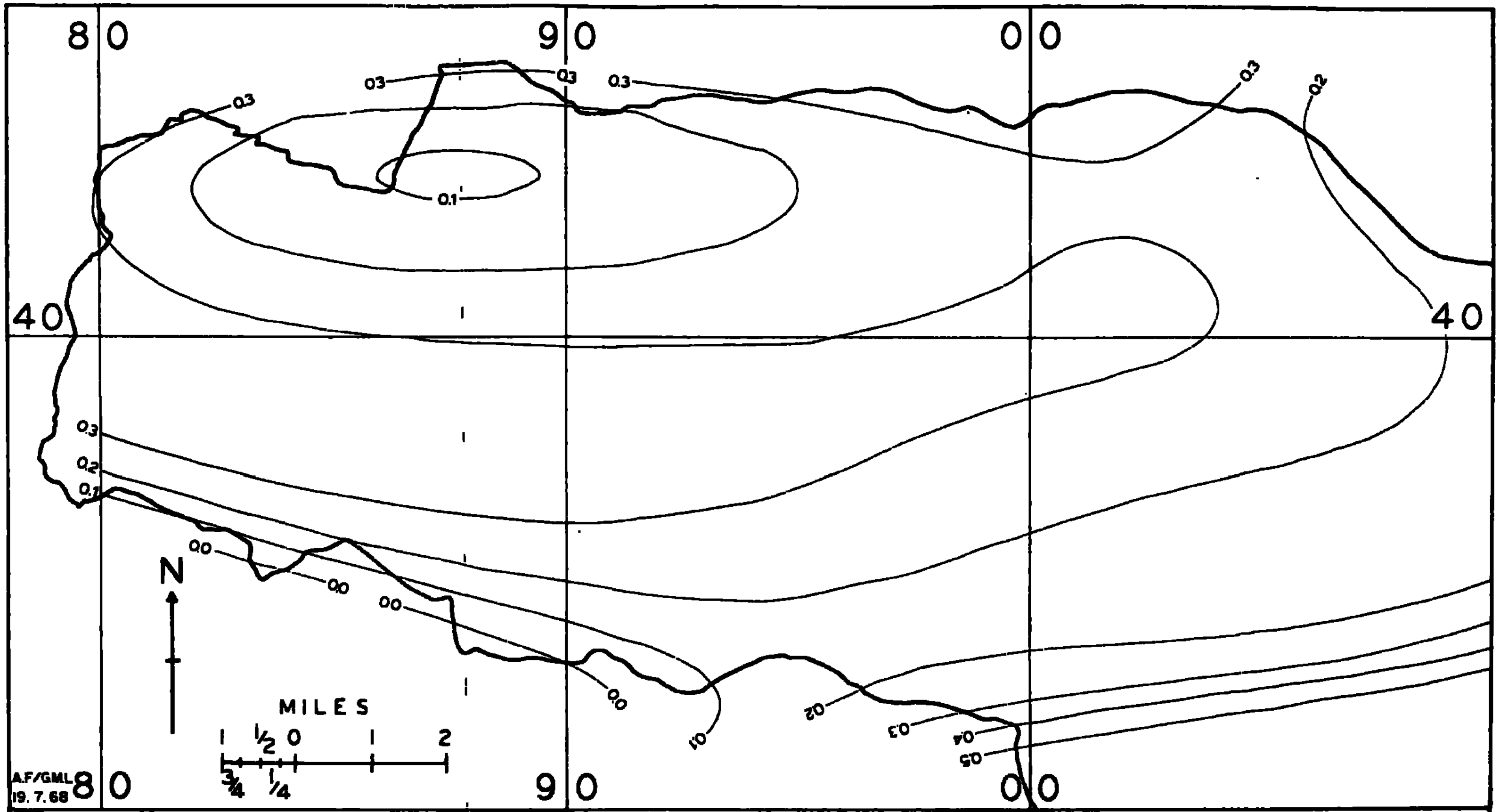
UPPER WEARDALE

MAP OF FACTOR 5 LOADINGS USING MAX FACTOR LOADING AT SITE CONTOURED SECOND-DEGREE SURFACE



UPPER WEARDALE

MAP OF FACTOR 5 LOADINGS USING MAX FACTOR LOADING AT SITE CONTOURED THIRD DEGREE SURFACE



UPPER WEARDALE

MAP OF FACTOR 5 LOADINGS USING MAX FACTOR LOADING AT SITE CONTOURED FOURTH DEGREE SURFACE

APPENDIX IV

Containing the significance tests and Vertical trend surface diagrams of

(i) Gravel Content
(ii) Sand Content
(iii) Silt Content
(iv) Clay Content

These calculations repeated, using only the fine fraction (Sand, Silt, Clay)

(vi) % Sand Content
(vii) % Silt Content
(viii) % Clay Content
(ix) Factor 1 loadings
(x) Factor 2 loadings
(xi) Factor 3 loadings
(xii) Factor 4 loadings
(xiii) Factor 5 loadings

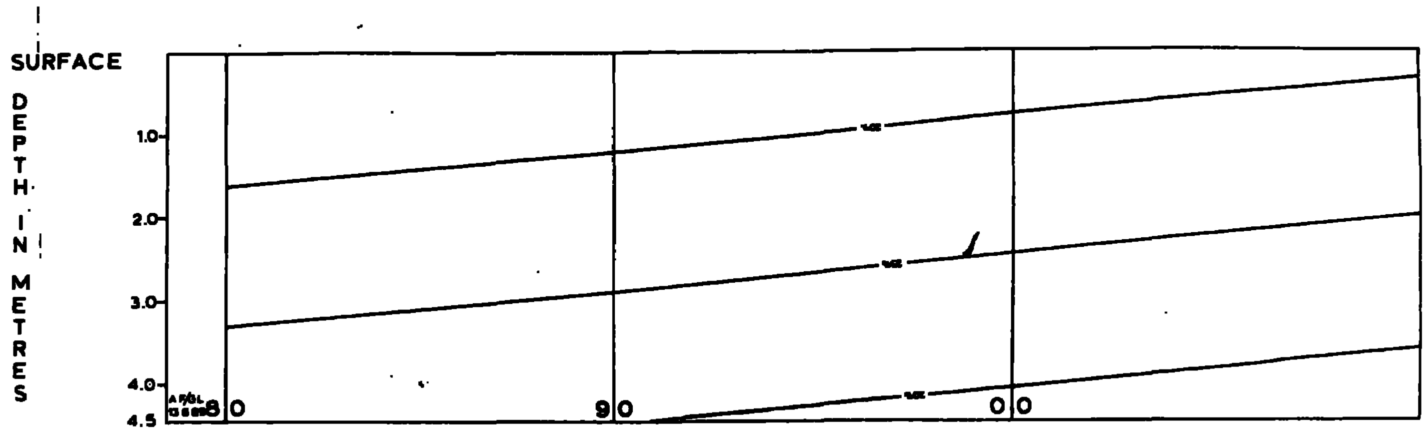
VERTICAL SURFACE DIAGRAMS OF GRAVEL CONTENT

TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

source	sum of squares	degrees of freedom	mean square	F	%confidence
linear surface deviations from above	77 3518	2 132	38.50 26.65	1.44	75+
quadratic surface deviations from quadratic	225 3393	3 129	75.00 26.30	2.85	95+
cubic surface deviations from cubic	115 3278	4 125	28.75 26.22	1.09	50+
quartic surface deviations from quartic	111 3167	5 120	22.20 26.39	0.84	25+
quintic surface deviations from quintic					

TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

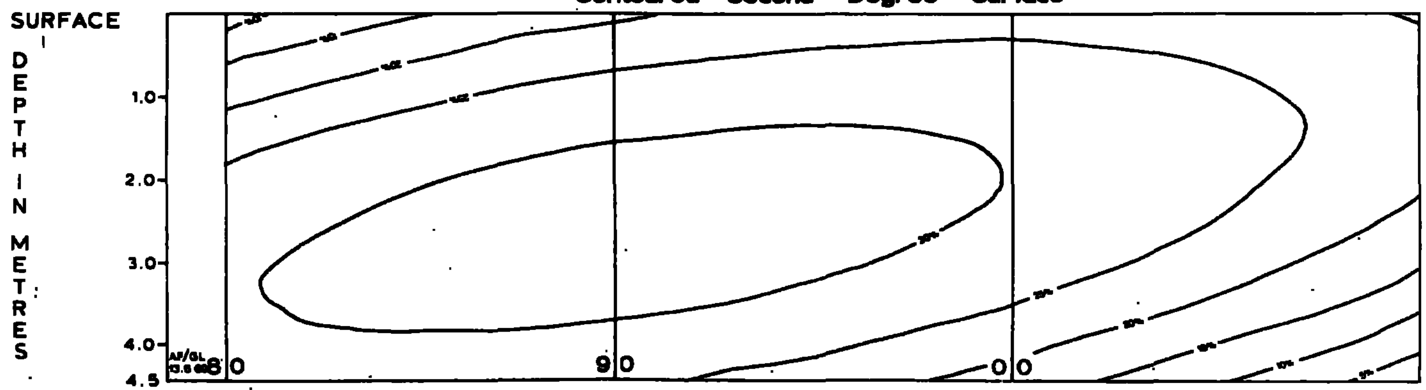
source	sum of squares	degrees of freedom	mean square	F	%confidence
first order surface deviations from first order	77 3518	2 132	38.50 26.65	1.44	75+
second order surface deviations from second order	202 3393	5 129	40.40 26.30	1.53	75+
third order surface deviations from third-order	317 3278	9 125	35.22 26.22	1.34	75+
fourth order surface deviations from fourth order	428 3167	14 120	30.59 26.39	1.15	50+
fifth order surface deviations from fifth order					
source	sum of squares	degrees of freedom	mean square	F	%confidence

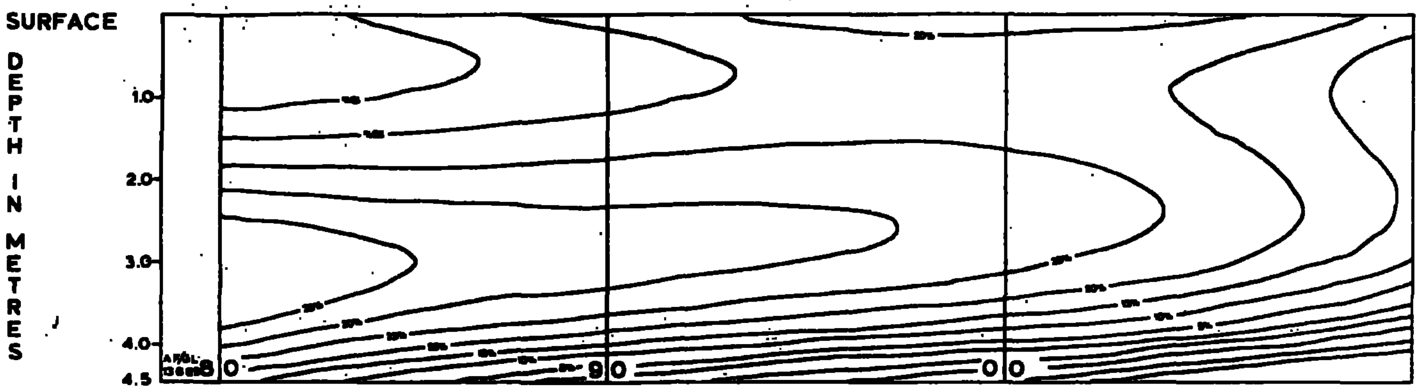


Contoured First Degree Surface

VARIATION IN GRAVEL CONTENT PROJECTED ONTO W—E VERTICAL PLANE

Contoured Second Degree Surface

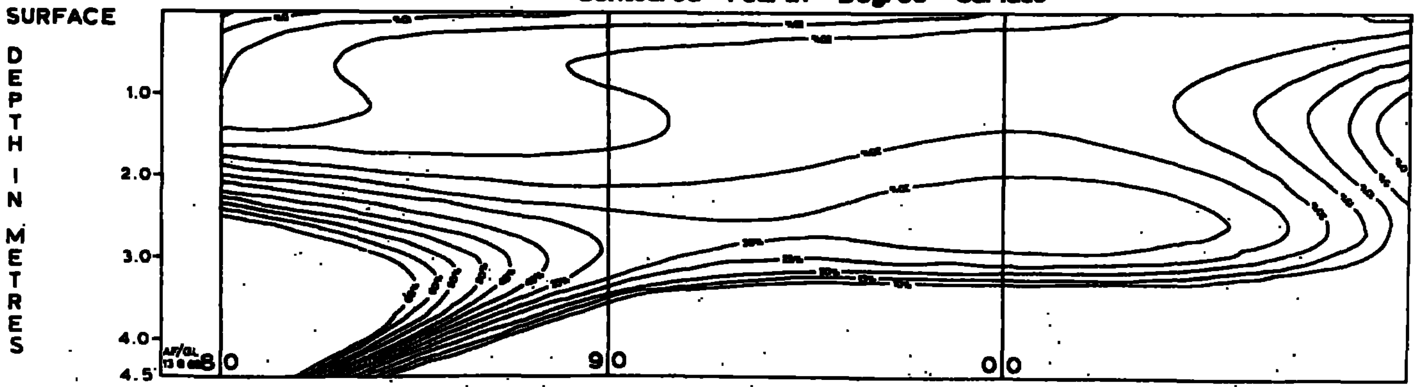




Contoured Third Degree Surface

VARIATION IN GRAVEL CONTENT PROJECTED ONTO W—E VERTICAL PLANE

Contoured Fourth Degree Surface



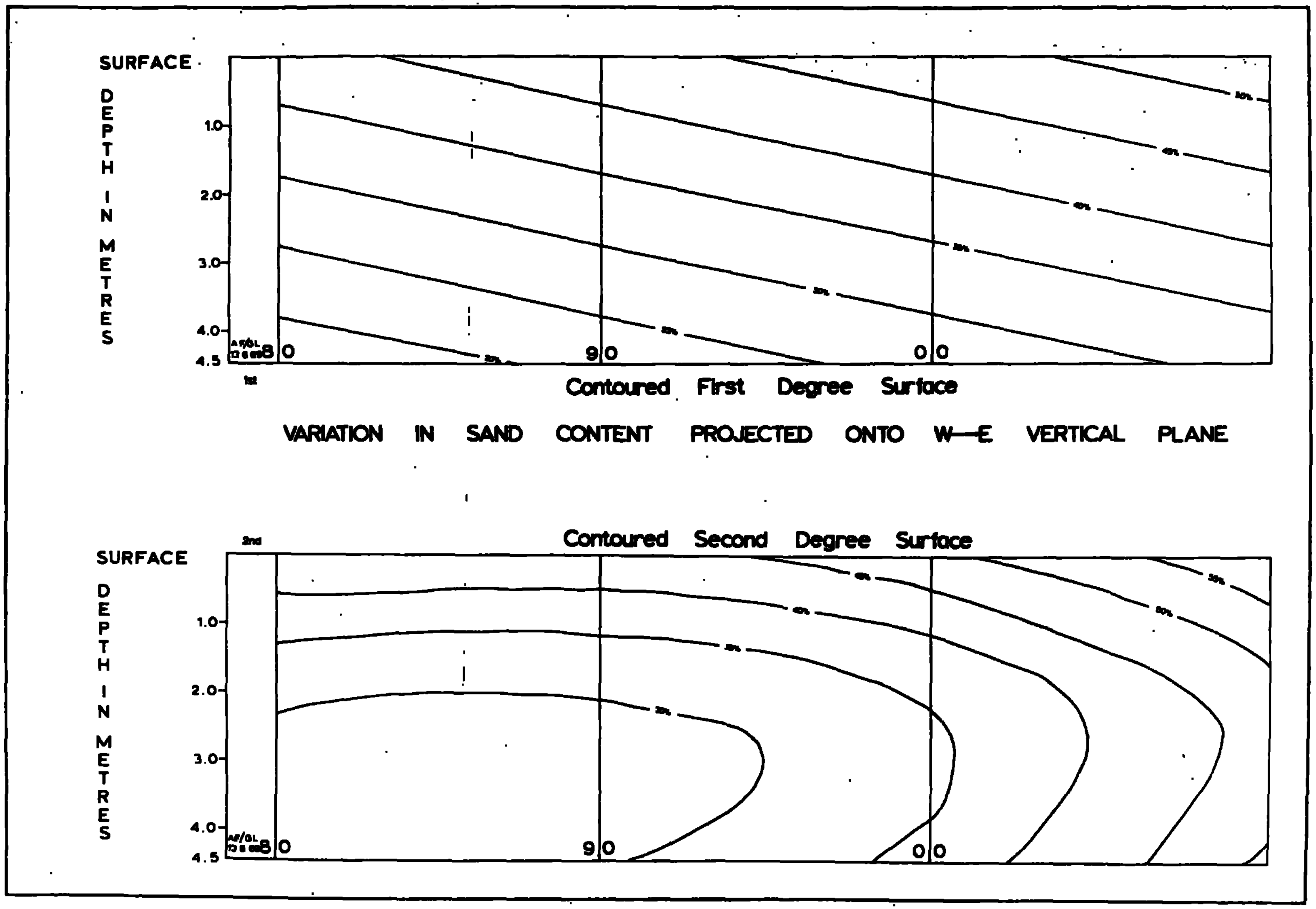
VERTICAL SURFACE DIAGRAMS OF SAND CONTENT

TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT
OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

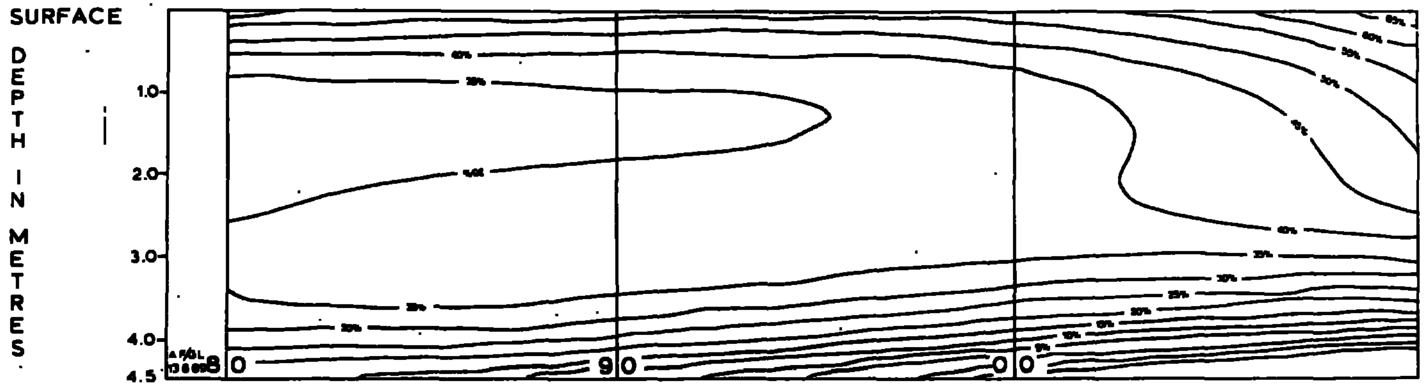
source	sum of squares	degrees of freedom	mean square	F	%confidence
linear surface deviations from above	478 2658	2 132	239.00 20.13	11.87	99.99+
quadratic surface deviations from quadratic	91 2567	3 129	30.33 19.89	1.52	75+
cubic surface deviations from cubic	109 2460	4 125	27.25 19.68	1.38	75+
quartic surface deviations from quartic	83 2375	5 120	16.60 19.79	0.83	25+
quintic surface deviations from quintic					

TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

source	sum of squares	degrees of freedom	mean square	F	%confidence
first order surface deviations from first order	478 2658	2 132	239.00 20.13	11.87	99.99+
second order surface deviations from second order	569 2567	5 129	113.8 19.89	5.72	99.99+
third order surface deviations from third order	678 2460	9 125	75.33 19.68	3.82	99.9+
fourth order surface deviations from fourth order	761 2375	14 120	54.35 19.79	2.74	99.5+
fifth order surface deviations from fifth order					
source	sum of squares	degrees of freedom	mean square	F	%confidence



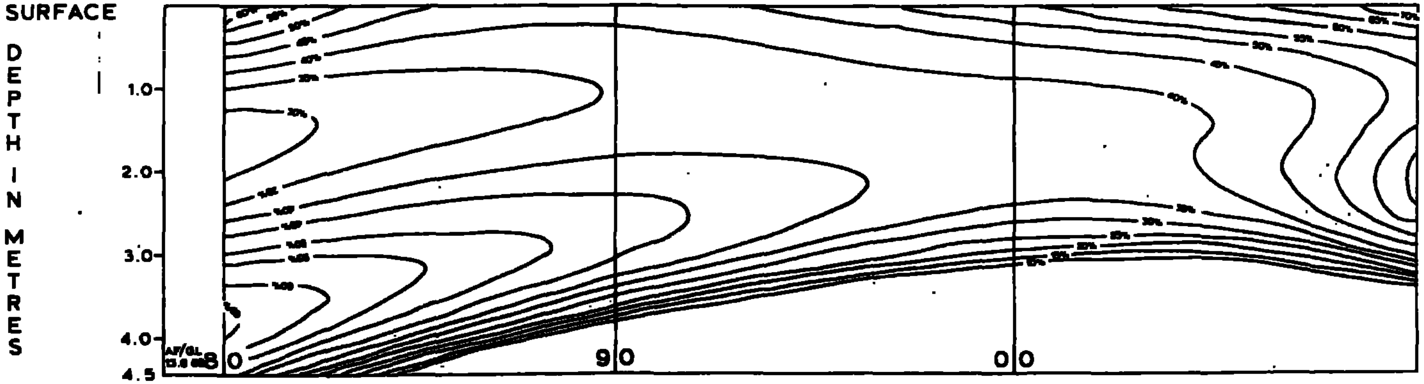
VARIATION IN SAND CONTENT PROJECTED ONTO W—E VERTICAL PLANE



Contoured Third Degree Surface

VARIATION IN SAND CONTENT PROJECTED ONTO W—E VERTICAL PLANE

Contoured Fourth Degree Surface



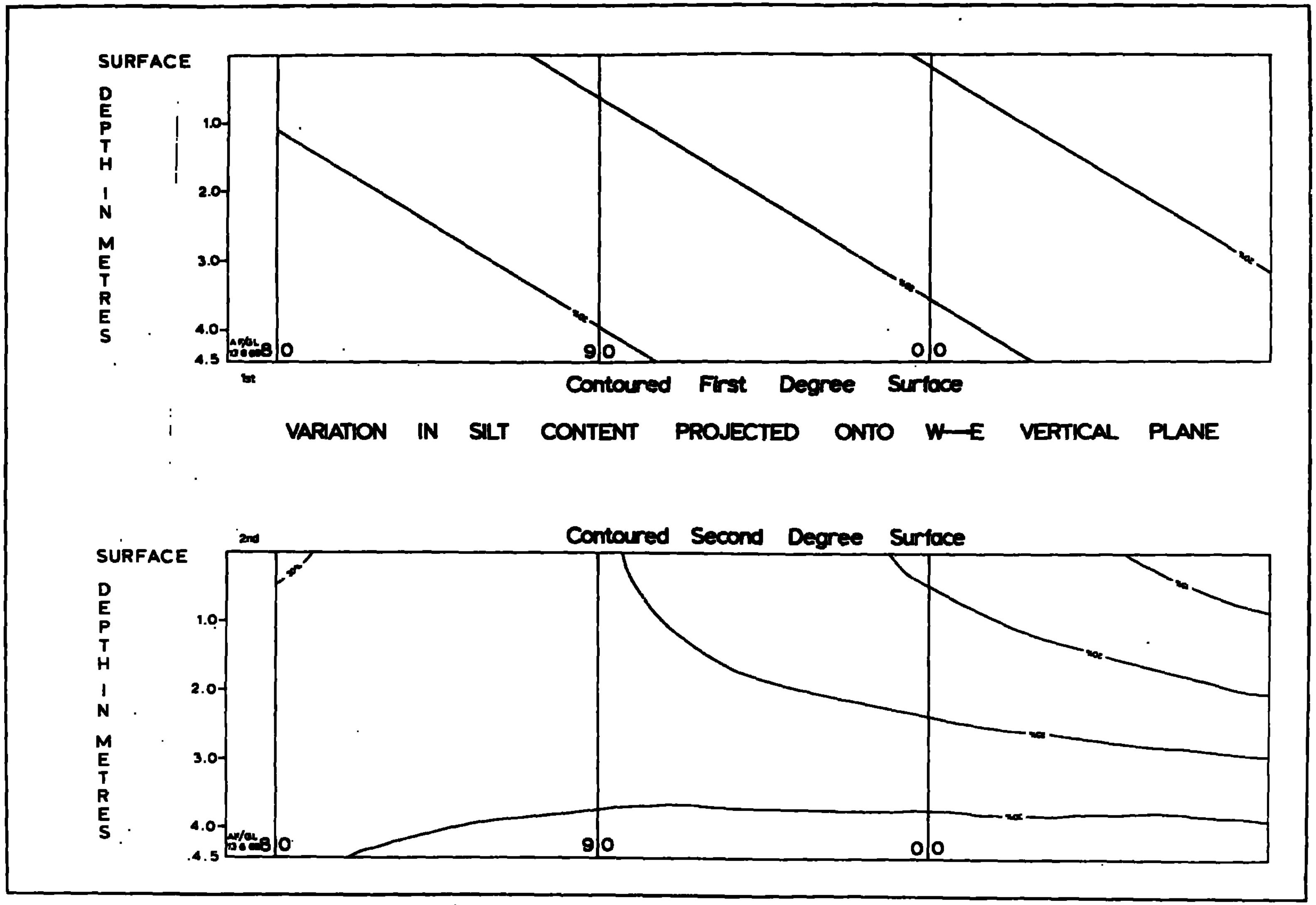
VERTICAL SURFACE DIAGRAMS OF SILT CONTENT

TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

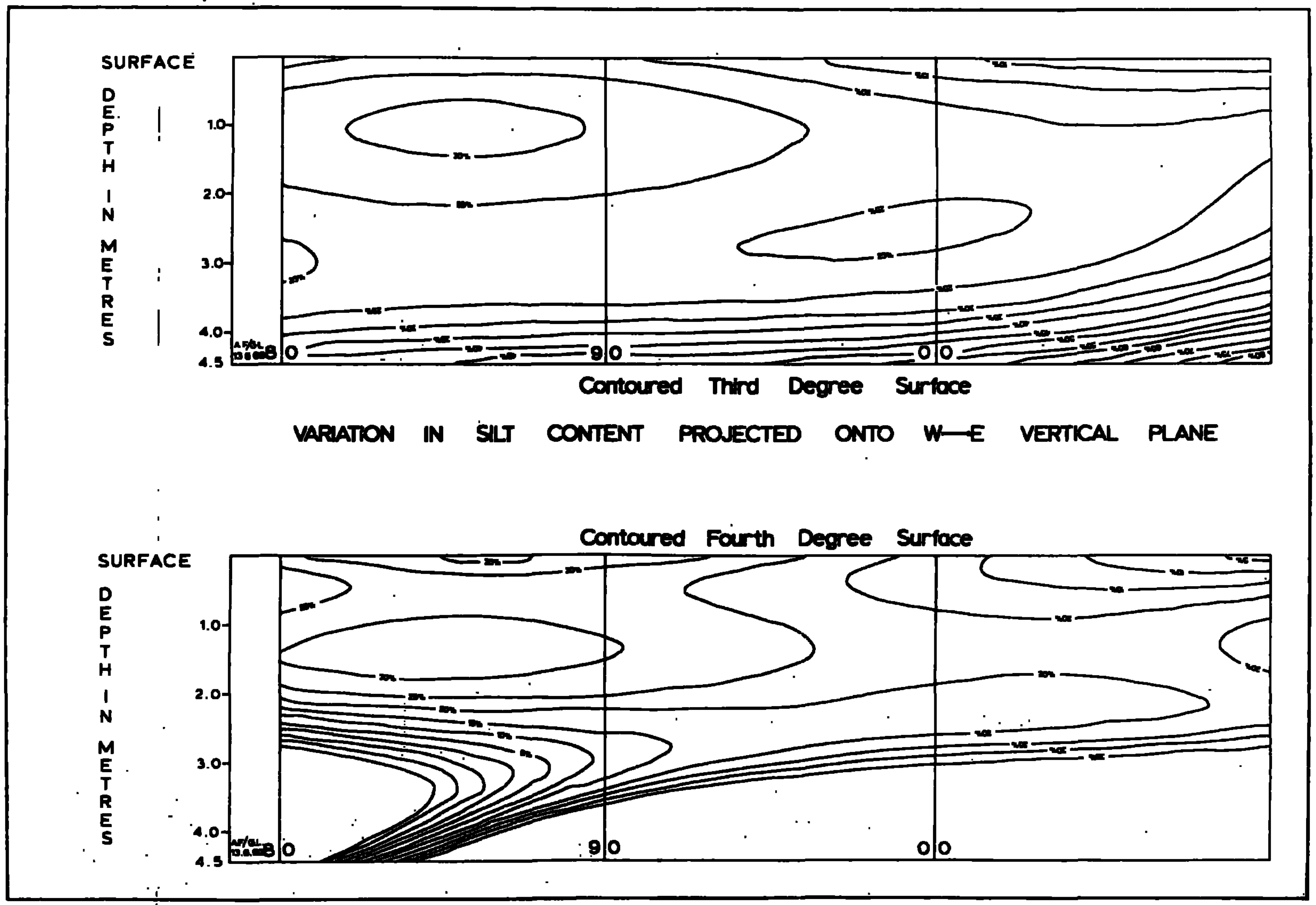
source	sum of squares	degrees of freedom	mean square	F	% confidence
linear surface deviations from above	231 1674	2 132	121.84 12.68	9.60	99.9+
quadratic surface deviations from quadratic	21 1654	3 129	7.00 12.82	0.54	25+
cubic surface deviations from cubic	119 1535	4 125	29.75 12.28	2.42	95+
quartic surface deviations from quartic	60 1475	5 120	12.00 12.29	0.97	50+
quintic surface deviations from quintic					-

TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

source	sum of squares	degrees of freedom	mean square	F	% confidence
first order surface deviations from first order	231 1674	2 132	121.84 12.68	9.60	99.9+
second order surface deviations from second order	252 1654	5 129	50.40 12.82	3.93	99+
third order surface deviations from third order	371 1535	9 125	41.22 12.28	3.35	99.9+
fourth order surface deviations from fourth order	431 1475	14 120	30.78 12.29	2.50	99.5+
fifth order surface deviations from fifth order					
source	sum of squares	degrees of freedom	mean square	F	% confidence



VARIATION IN SILT CONTENT PROJECTED ONTO W—E VERTICAL PLANE



VARIATION IN SILT CONTENT PROJECTED ONTO W—E VERTICAL PLANE

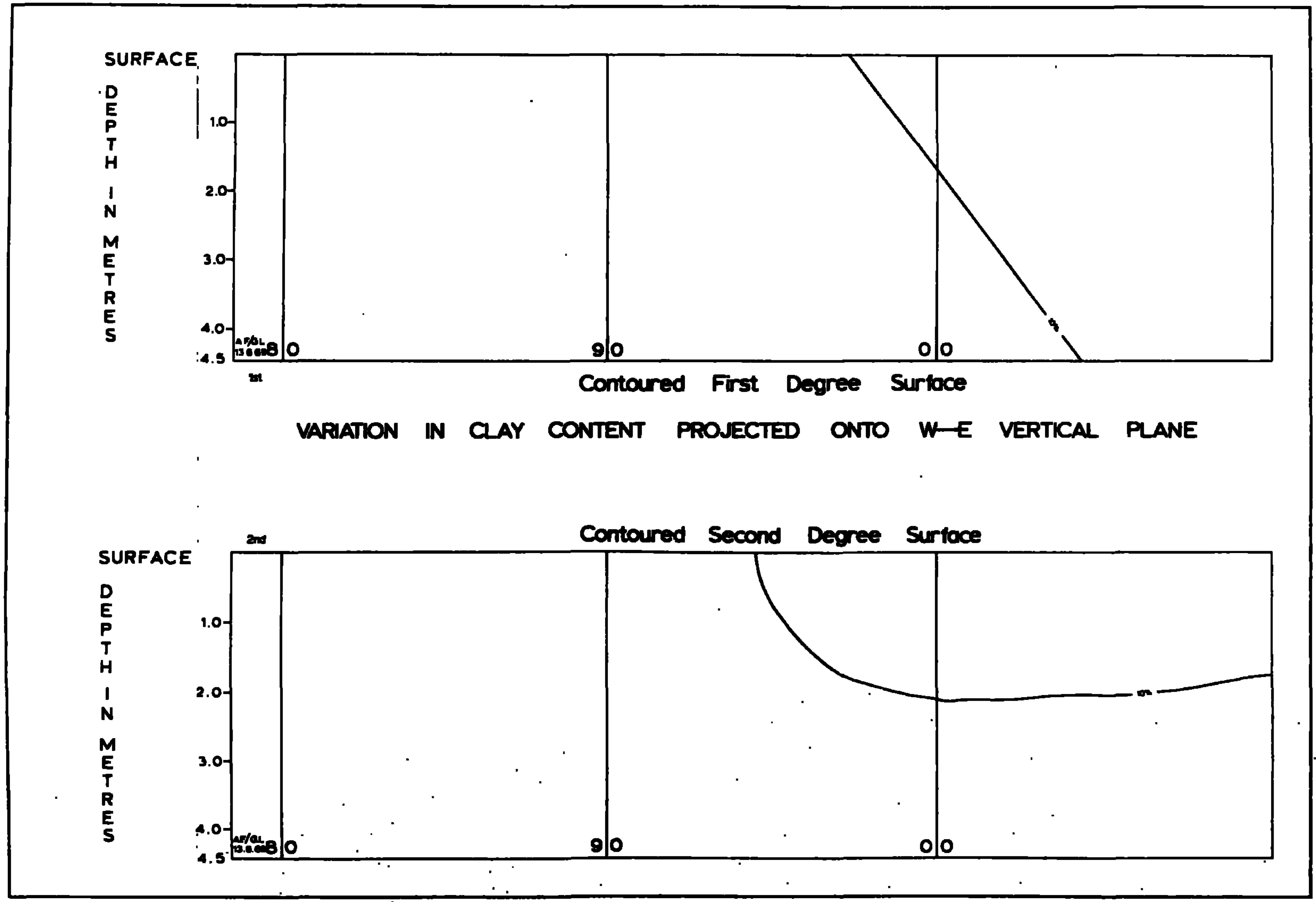
VERTICAL SURFACE DIAGRAMS OF CLAY CONTENT

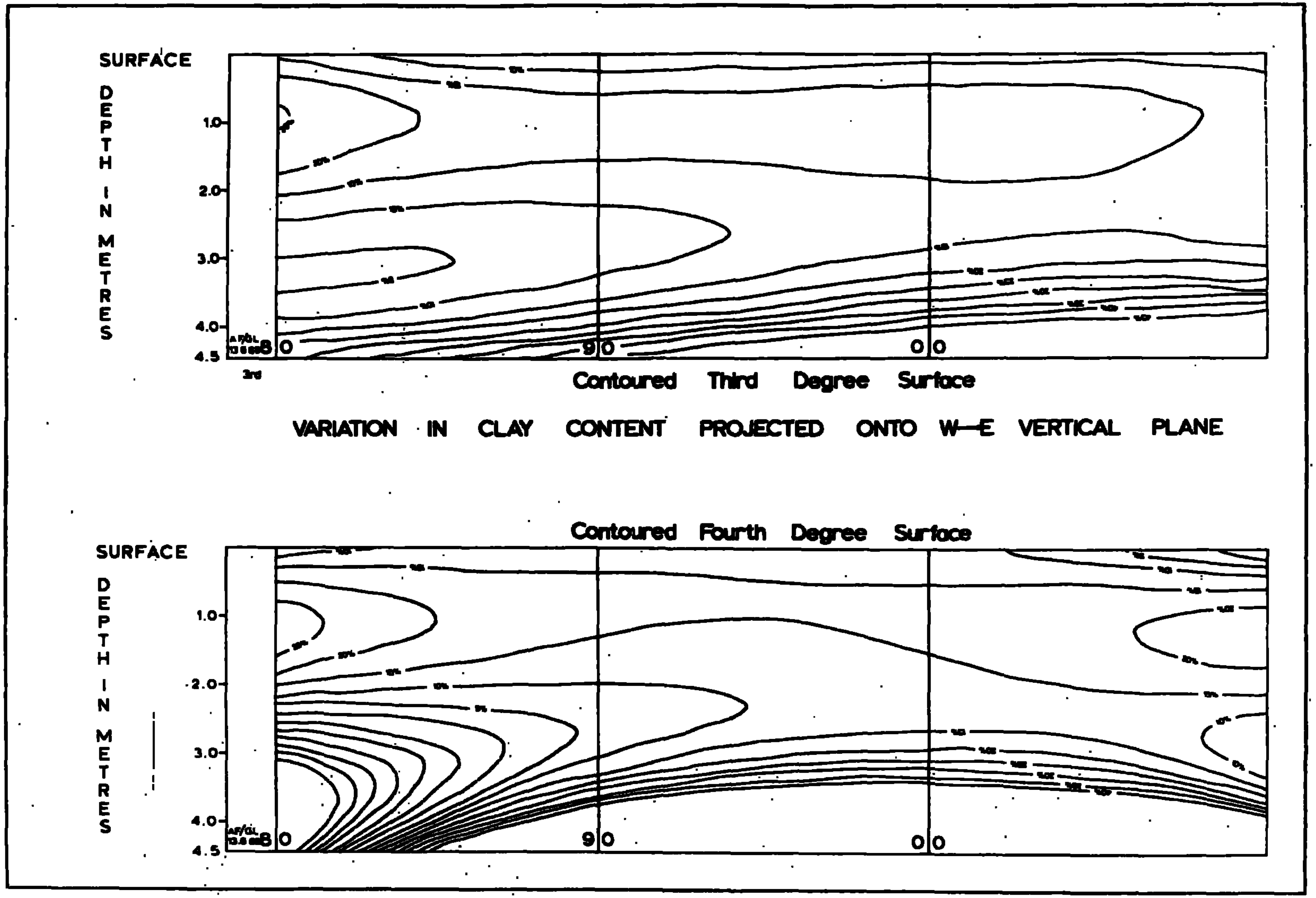
TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT
OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

source	sum of squares	degrees of freedom	mean square	F	%confidence
linear surface deviations from above	37 1285	2 132	18.50 9.73	1.90	75+
quadratic surface deviations from quadratic	5 1280	3 129	1.66 9.92	0.16	5+
cubic surface deviations from cubic	106 1174	4 125	26.50 9.39	2.82	95+
quartic surface deviations from quartic	62 1112	5 120	12.40 9.26	1.33	70+
quintic surface deviations from quintic					

TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

source	sum of squares	degrees of freedom	mean square	F	%confidence
first order surface deviations from first order	37 1285	2 132	18.50 9.73	1.90	75+
second order surface deviations from second order	42 1280	5 129	8.40 9.92	0.84	25+
third order surface deviations from third order	148 1174	9 125	16.44 9.39	1.75	90+
fourth order surface deviations from fourth order	210 1112	14 120	15.00 9.26	1.62	90+
fifth order surface deviations from fifth order					
source	sum of squares	degrees of freedom	mean square	F	%confidence


SURFACE
DEPTH IN METRES
1.0
2.0
3.0
4.0
4.5
1st
8 0
9 0
0 0
Contoured First Degree Surface
VARIATION IN CLAY CONTENT PROJECTED ONTO W—E VERTICAL PLANE
Contoured Second Degree Surface
2nd
SURFACE
DEPTH IN METRES
1.0
2.0
3.0
4.0
4.5
8 0
9 0
0 0



VARIATION IN CLAY CONTENT PROJECTED ONTO W—E VERTICAL PLANE

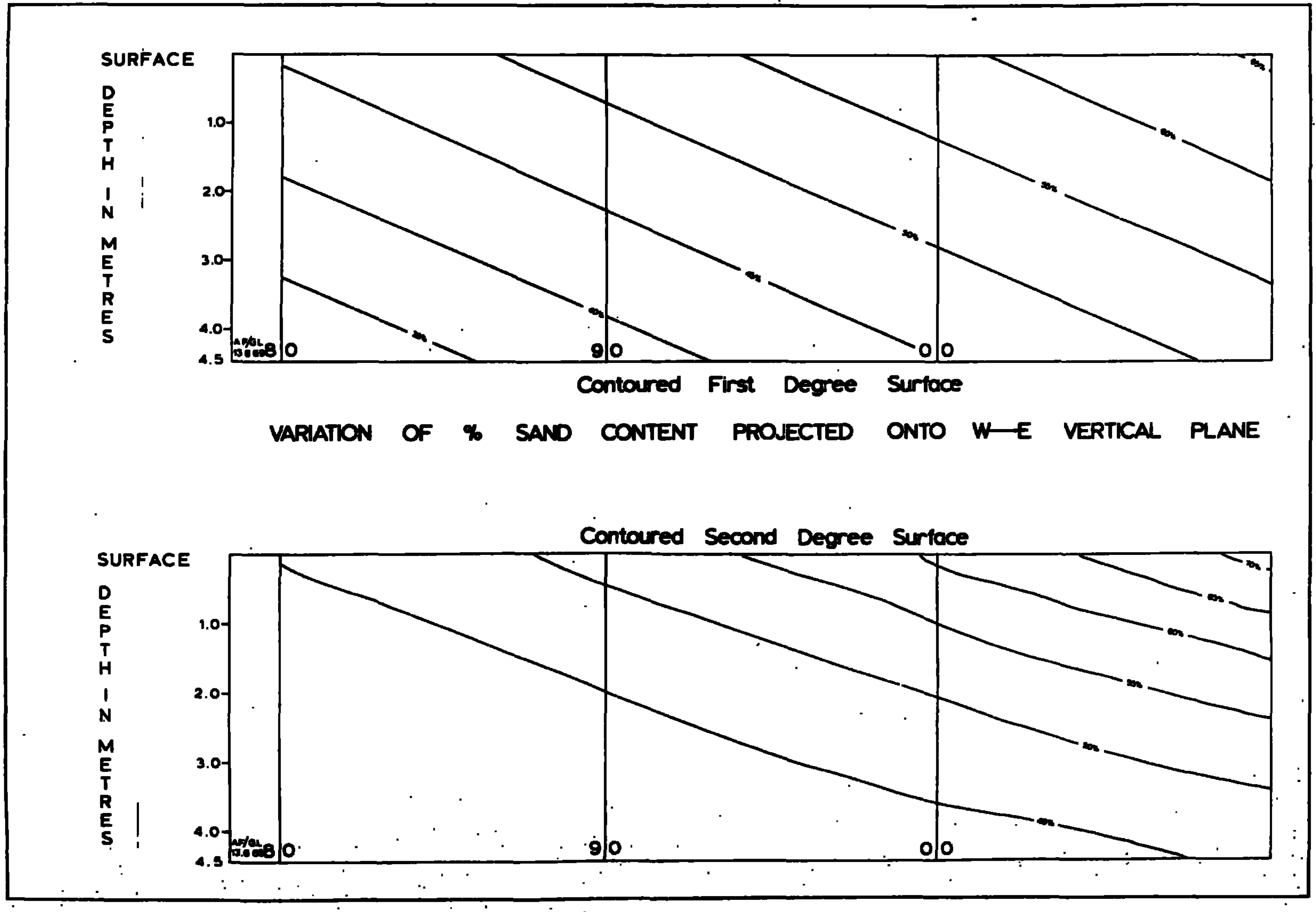
VERTICAL SURFACE DIAGRAMS OF % SAND CONTENT

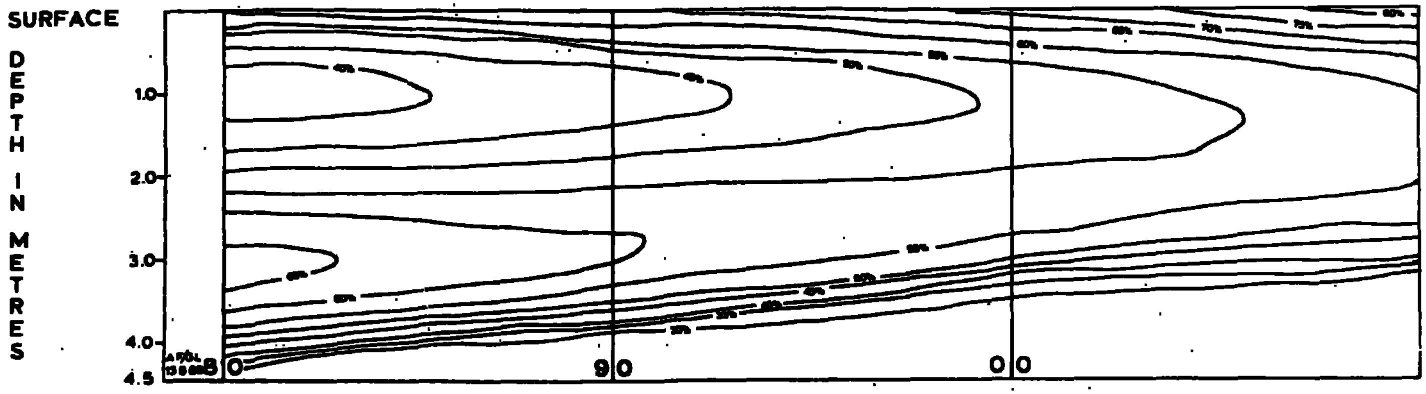
TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT
OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

source	sum of squares	degrees of freedom	mean square	F	% confidence
linear surface deviations from above	616 4045	2 132	308.00 30.64	10.05	99.99+
quadratic surface deviations from quadratic	41 4004	3 129	13.66 31.03	0.44	25+
cubic surface deviations from cubic	371 3632	4 125	74.20 29.05	2.55	95+
quartic surface deviations from quartic	196 3437	5 120	39.20 28.60	1.37	75+
quintic surface deviations from quintic					-

TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

source	sum of squares	degrees of freedom	mean square	F	% confidence
first order surface deviations from first order	616 4045	2 132	308.00 30.64	10.05	99.99+
second order surface deviations from second order	657 4004	5 129	131.40 31.03	4.23	99.5+
third order surface deviations from third order	1028 3632	9 125	114.22 29.05	3.93	99.9+
fourth order surface deviations from fourth order	1223 3437	14 120	87.35 28.60	3.05	99.9+
fifth order surface deviations from fifth order					
source	sum of squares	degrees of freedom	mean square	F	% confidence

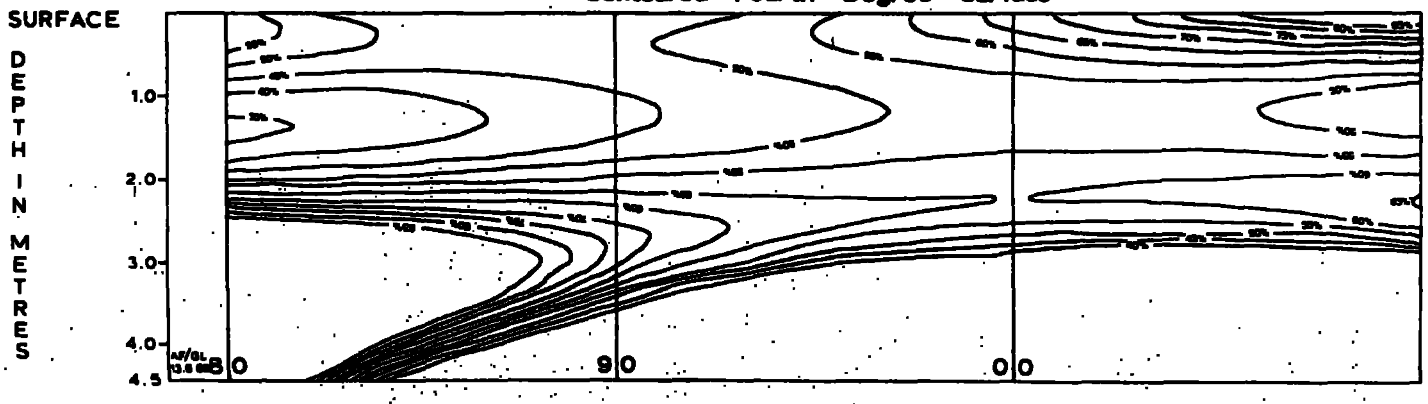

SURFACE
DEPTH IN METRES
1.0
2.0
3.0
4.0
4.5
8|0
9|0
0|0
Contoured First Degree Surface
VARIATION OF % SAND CONTENT PROJECTED ONTO W—E VERTICAL PLANE
Contoured Second Degree Surface
SURFACE
DEPTH IN METRES
1.0
2.0
3.0
4.0
4.5
8|0
9|0
0|0



Contoured Third Degree Surface

VARIATION OF % SAND CONTENT PROJECTED ONTO W—E VERTICAL PLANE

Contoured Fourth Degree Surface



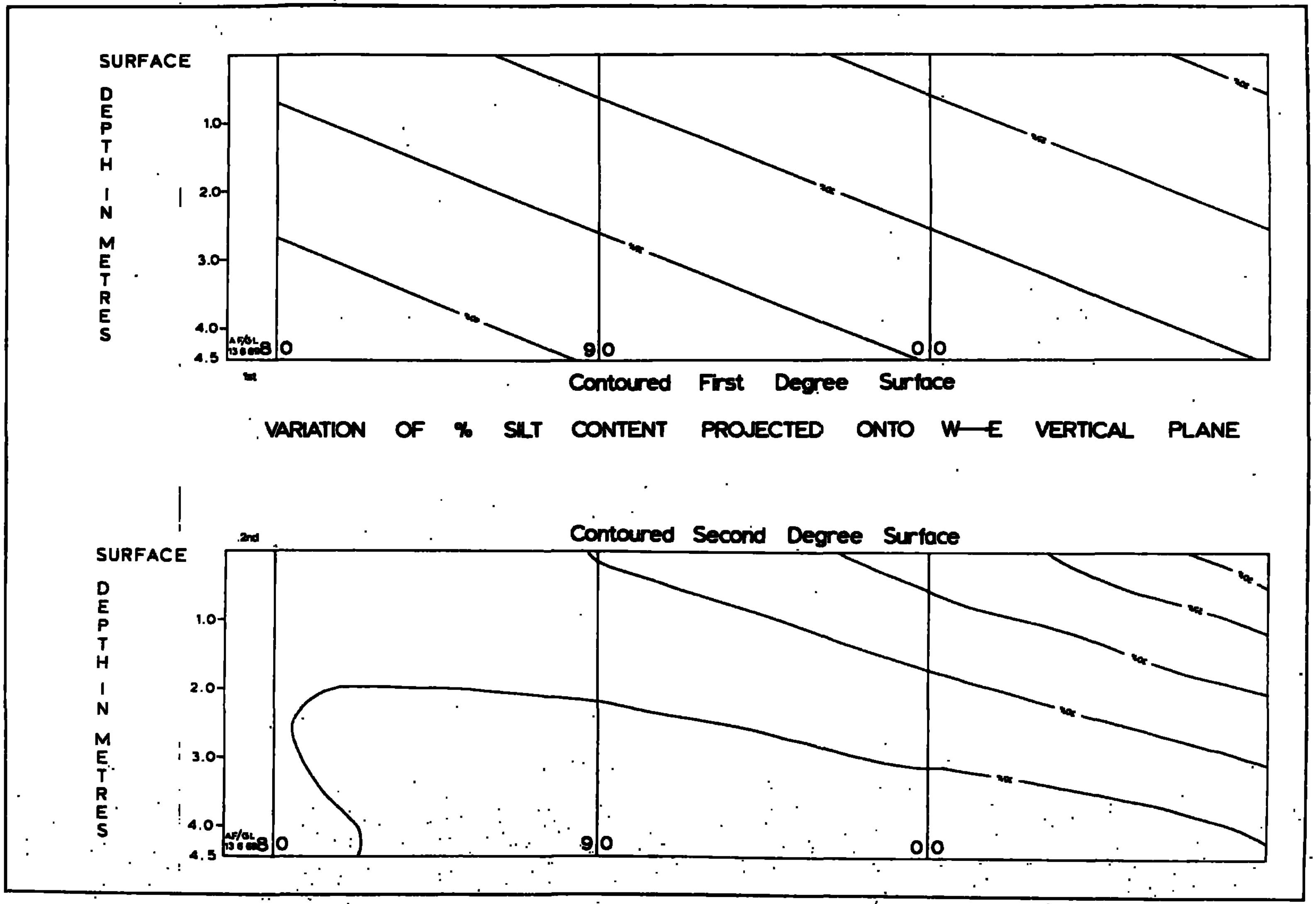
VERTICAL SURFACE DIAGRAMS OF % SILT CONTENT

TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT
OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

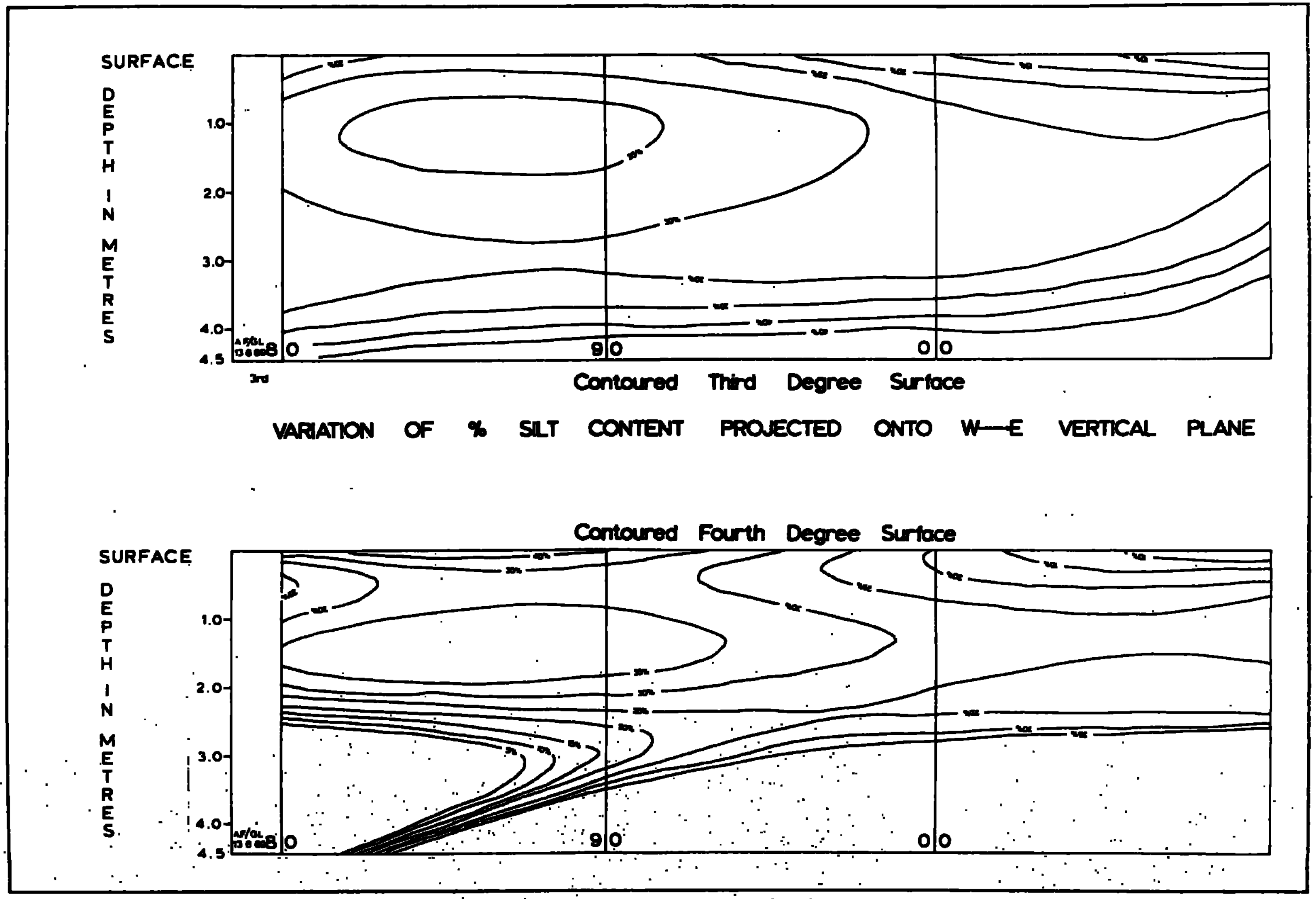
source	sum of squares	degrees of freedom	mean square	F	%confidence
linear surface deviations from above	327 1704	2 132	163.50 12.90	12.67	99.99+
quadratic surface deviations from quadratic	40 1664	3 129	17.63 12.89	1.36	50+
cubic surface deviations from cubic	116 1547	4 125	29.00 12.37	2.34	90+
quartic surface deviations from quartic	85 1463	5 120	17.00 12.19	1.39	75+
quintic surface deviations from quintic					

TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

source	sum of squares	degrees of freedom	mean square	F	%confidence
first order surface deviations from first order	327 1704	2 132	163.50 12.90	12.67	99.99+
second order surface deviations from second order	367 1664	5 129	73.40 12.89	5.69	99.99+
third order surface deviations from third order	483 1547	9 125	53.66 12.89	4.16	99.9+
fourth order surface deviations from fourth order	568 1463	14 120	40.57 12.19	3.32	99.9+
fifth order surface deviations from fifth order					
source	sum of squares	degrees of freedom	mean square	F	%confidence



VARIATION OF % SILT CONTENT PROJECTED ONTO W—E VERTICAL PLANE



VARIATION OF % SILT CONTENT PROJECTED ONTO W—E VERTICAL PLANE

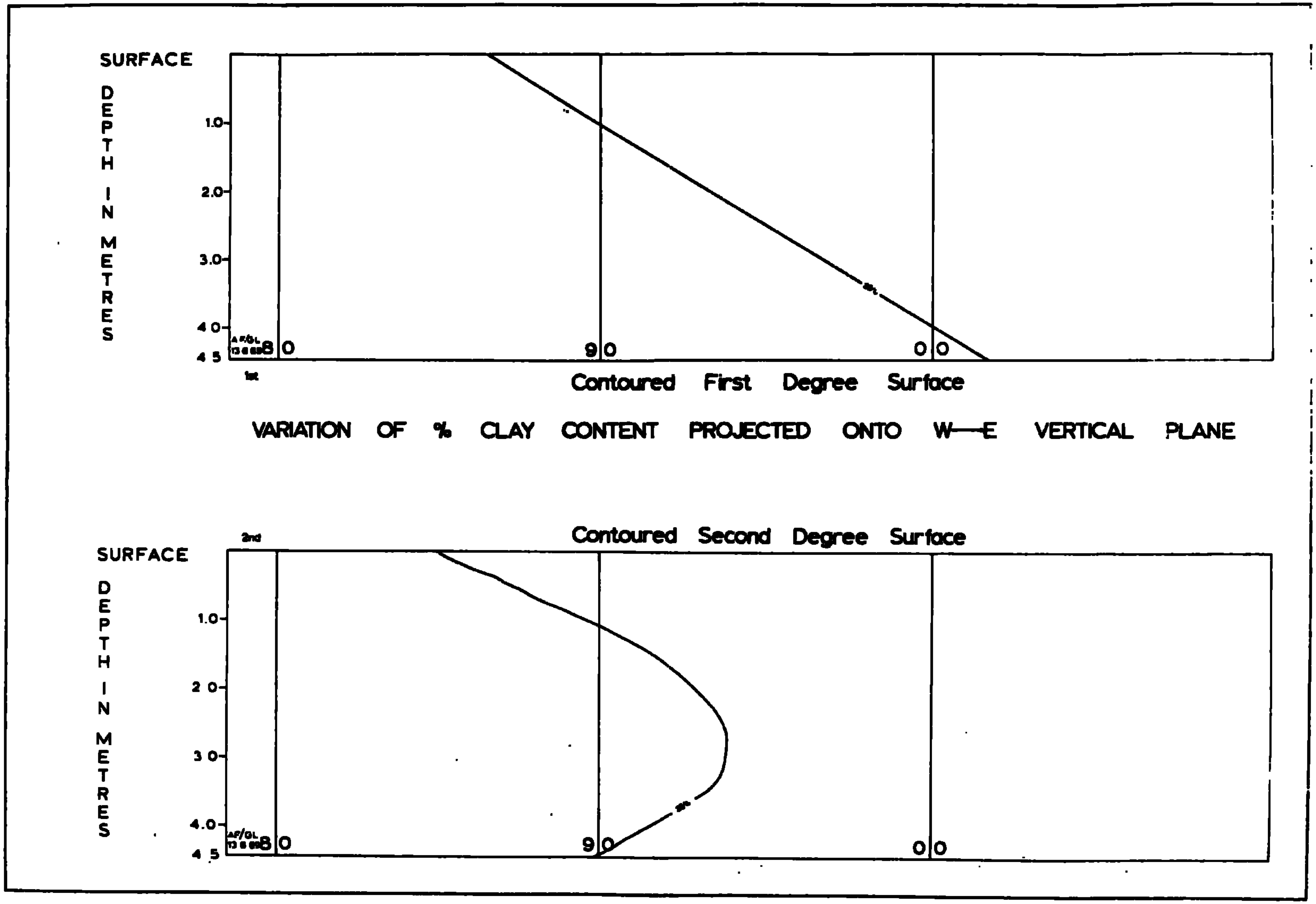
VERTICAL SURFACE DIAGRAMS OF % CLAY CONTENT

TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT
OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

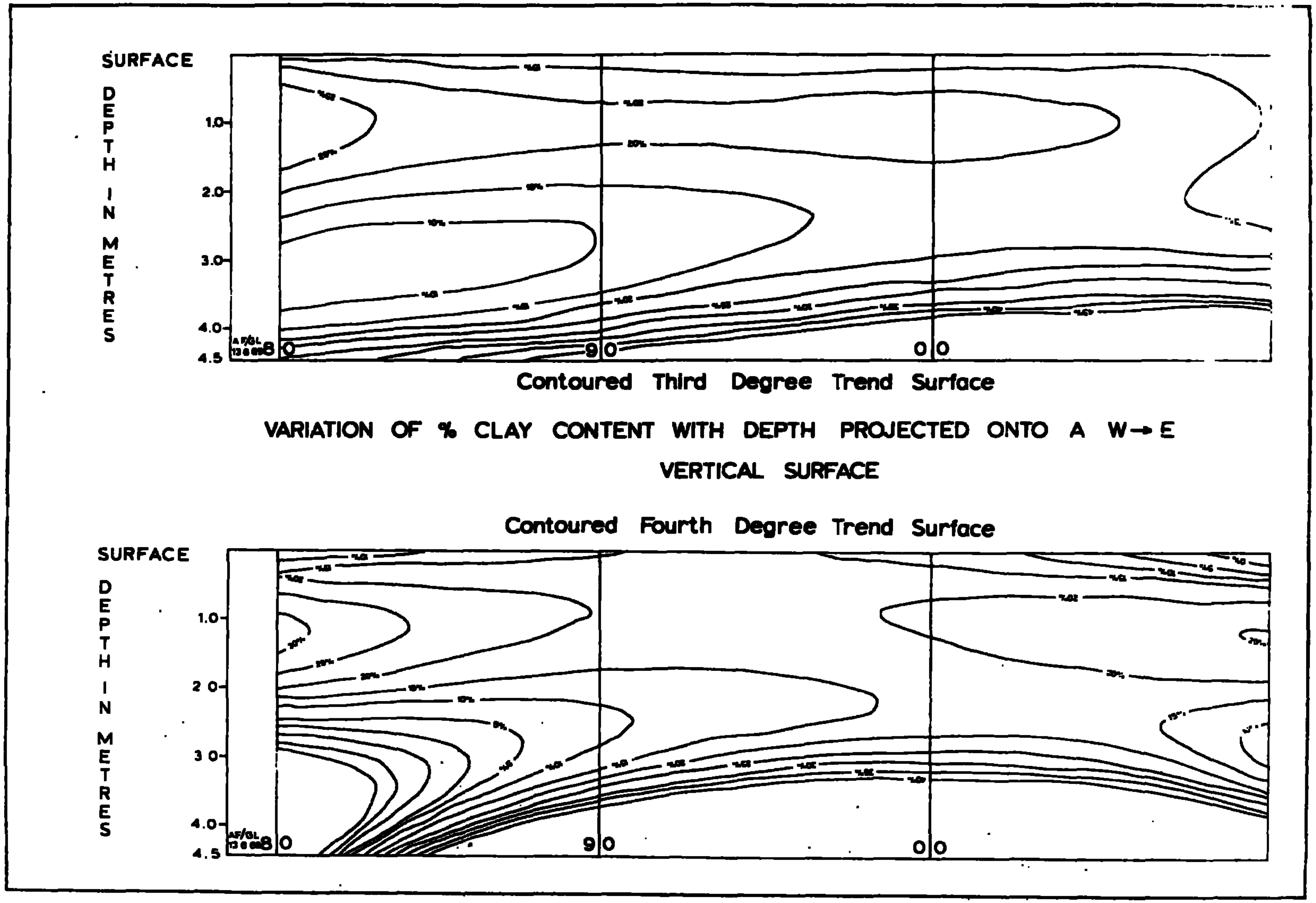
source	sum of squares	degrees of freedom	mean square	F	%confidence
linear surface deviations from above	45 1437	2 132	22.50 10.88	2.06	75+
quadratic surface deviations from quadratic	2 1435	3 129	0.66 11.12	0.06	1+
cubic surface deviations from cubic	132 1303	4 125	33.00 10.42	3.16	95+
quartic surface deviations from quartic	178 1225	5 120	35.60 10.20	3.48	97.5+
quintic surface deviations from quintic					

TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

source	sum of squares	degrees of freedom	mean square	F	%confidence
first order surface deviations from first order	45 1437	2 132	22.50 10.88	2.06	75+
second order surface deviations from second order	47 1435	5 129	9.40 11.12	0.84	25+
third order surface deviations from third order	179 1303	9 125	19.88 10.42	1.90	90+
fourth order surface deviations from fourth order	257 1225	14 120	18.35 10.20	1.79	95+
fifth order surface deviations from fifth order					
source	sum of squares	degrees of freedom	mean square	F	%confidence



VARIATION OF % CLAY CONTENT PROJECTED ONTO W—E VERTICAL PLANE



Contoured Third Degree Trend Surface

VARIATION OF % CLAY CONTENT WITH DEPTH PROJECTED ONTO A W→E VERTICAL SURFACE

Contoured Fourth Degree Trend Surface

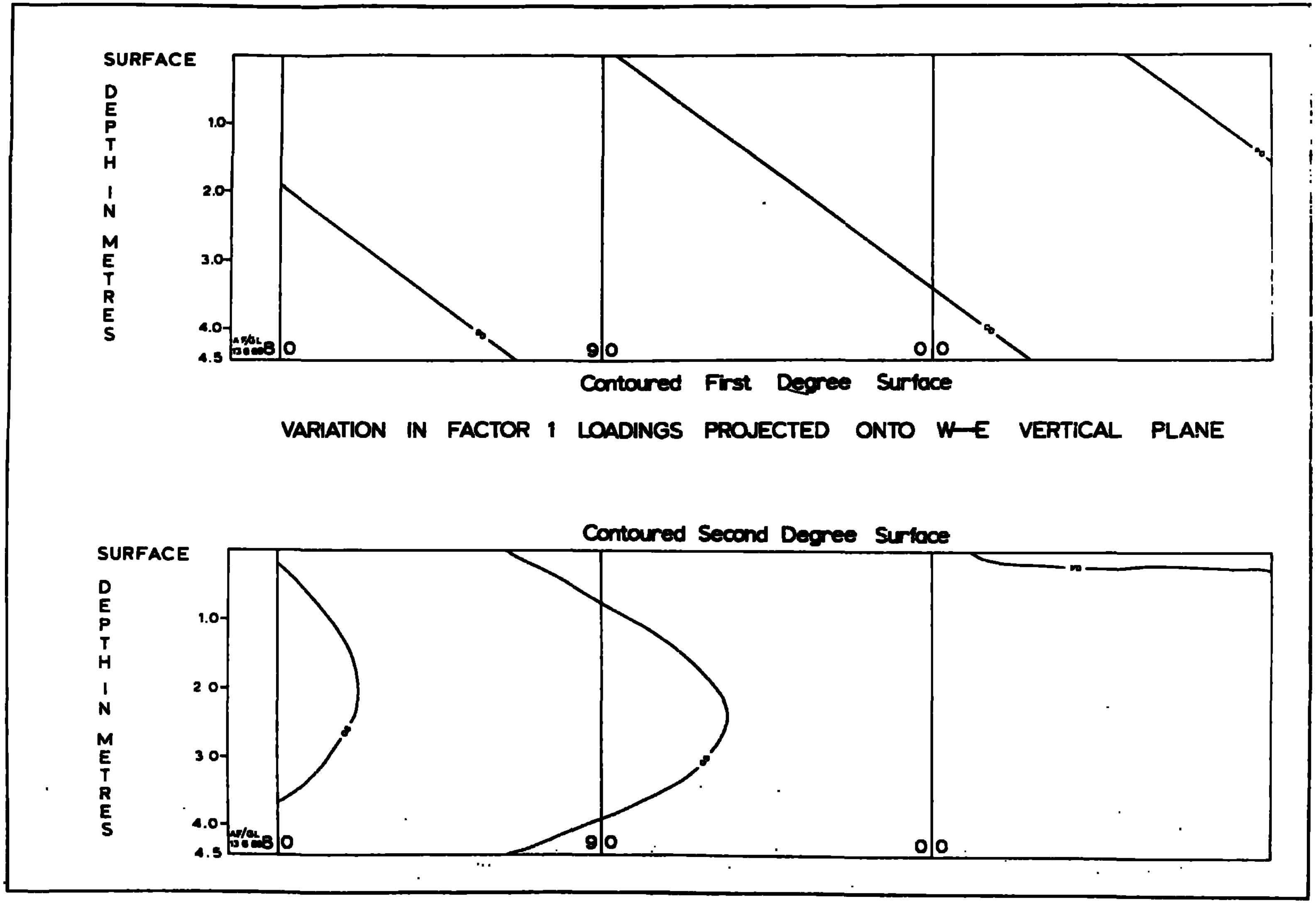
VERTICAL SURFACE DIAGRAM OF FACTOR 1 LOADINGS

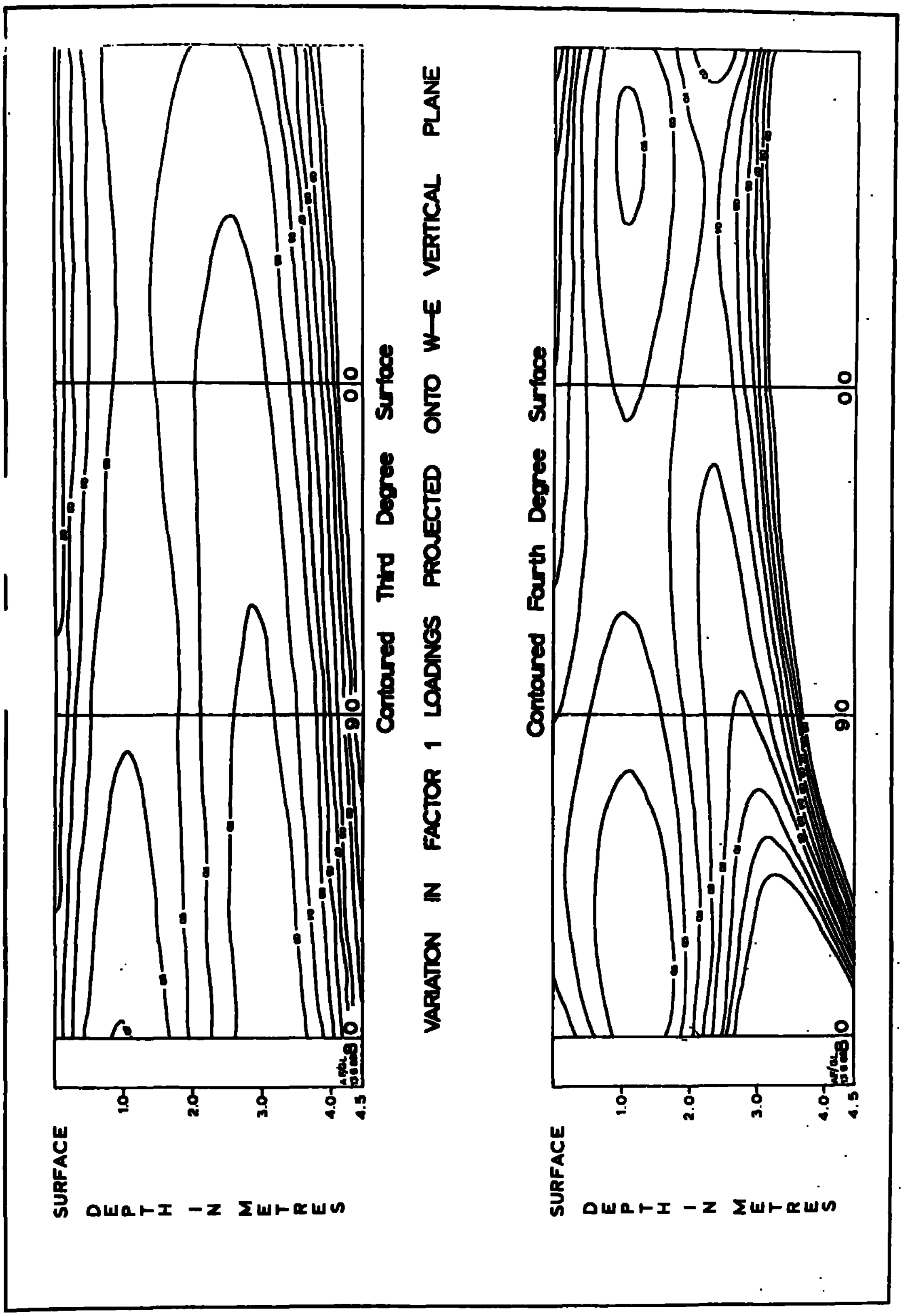
TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT
OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

source	sum of squares	degrees of freedom	mean square	F	%confidence
linear surface deviations from above	497 9271	2 132	248.50 70.23	3.54	95+
quadratic surface deviations from quadratic	66 9204	3 129	22.00 71.35	0.30	10+
cubic surface deviations from cubic	951 8254	4 125	23.70 66.03	0.35	10+
quartic surface deviations from quartic	301 7954	5 120	60.20 66.28	0.90	50+
quintic surface deviations from quintic					-

TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

source	sum of squares	degrees of freedom	mean square	F	%confidence
first order surface deviations from first order	497 9271	2 132	248.50 70.23	3.54	95+
second order surface deviations from second order	562 9204	5 129	112.40 71.30	1.57	75+
third order surface deviations from third order	1513 9204	9 129	168.11 66.03	2.54	97.5+
fourth order surface deviations from fourth order	1814 7954	14 120	129.57 66.28	1.95	97.5+
fifth order surface deviations from fifth order					
source	sum of squares	degrees of freedom	mean square	F	%confidence


SURFACE
DEPTH IN METRES
1.0
2.0
3.0
4.0
4.5
8 0
9 0
0 0
Contoured First Degree Surface
VARIATION IN FACTOR 1 LOADINGS PROJECTED ONTO W—E VERTICAL PLANE
Contoured Second Degree Surface
SURFACE
DEPTH IN METRES
1.0
2 0
3 0
4.0
4.5
8 0
9 0
0 0



VARIATION IN FACTOR 1 LOADINGS PROJECTED ONTO W—E VERTICAL PLANE

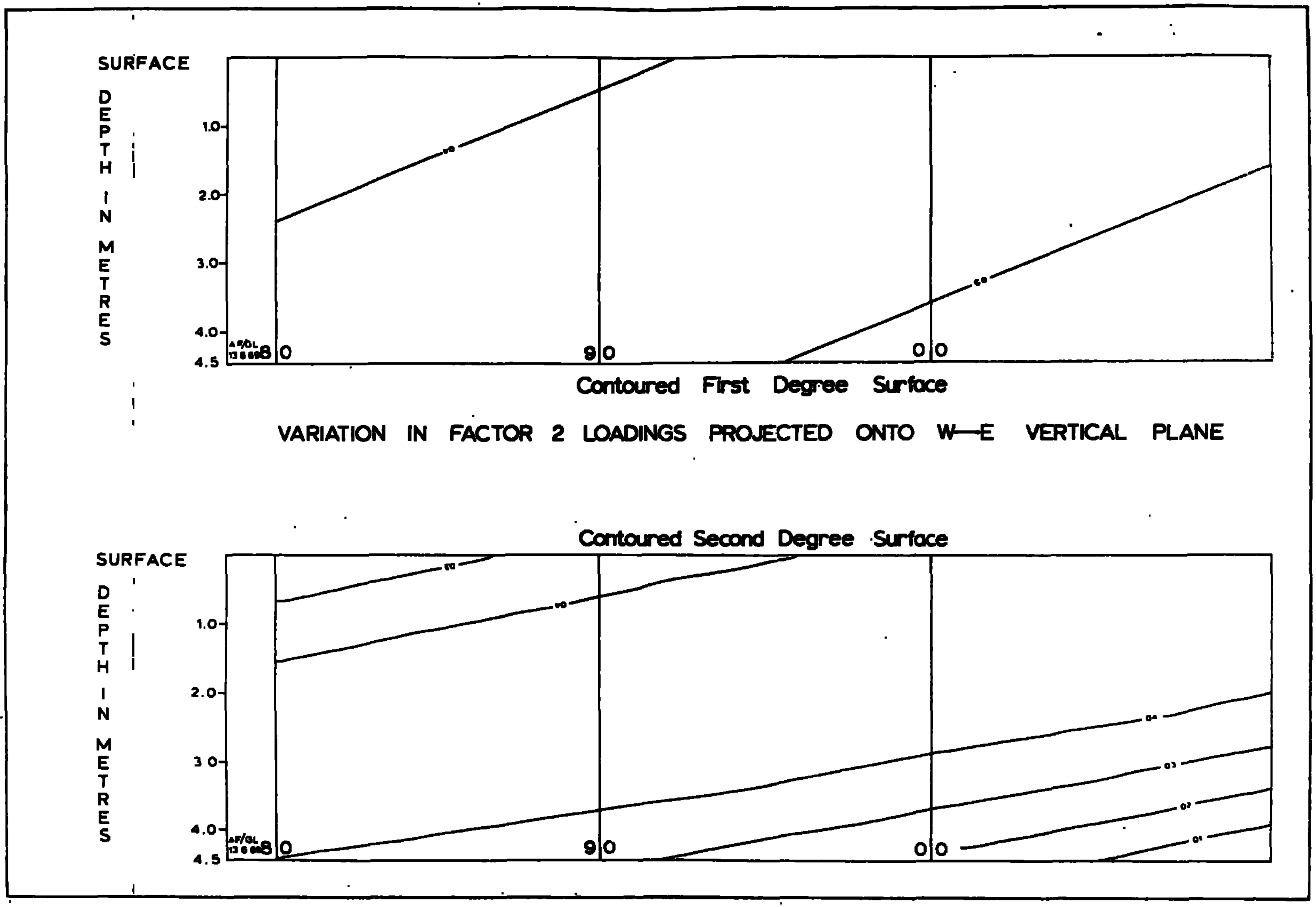
VERTICAL SURFACE DIAGRAM OF FACTOR 2 LOADINGS

TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT
OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

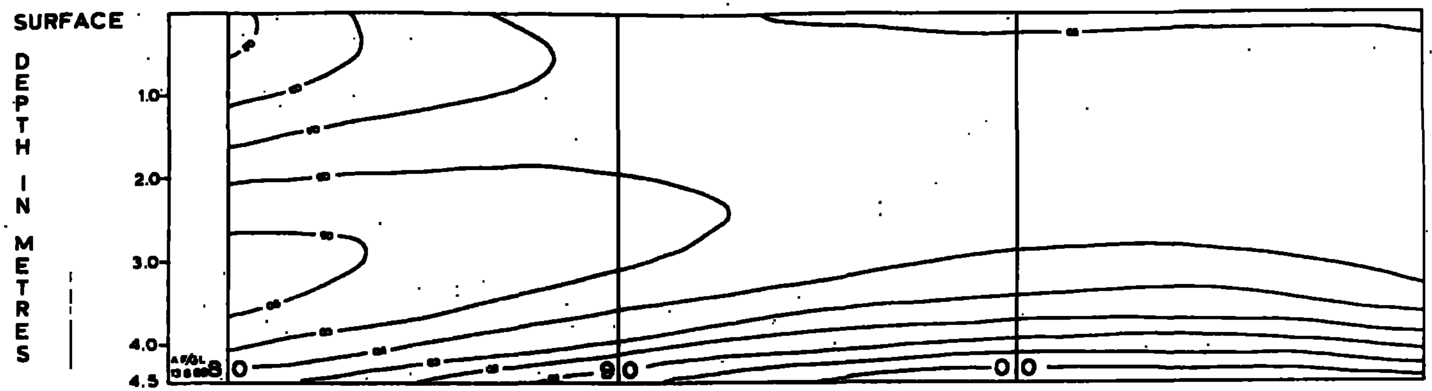
source	sum of squares	degrees of freedom	mean square	F	% confidence
linear surface deviations from above	168 7478	2 132	84.00 56.65	1.48	75+
quadratic surface deviations from quadratic	199 7279	3 129	66.33 56.42	1.17	50+
cubic surface deviations from cubic	180 7098	4 125	45.00 56.78	0.79	25+
quartic surface deviations from quartic	316 6782	5 120	63.20 56.51	1.12	50+
quintic surface deviations from quintic					

TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

source	sum of squares	degrees of freedom	mean square	F	% confidence
first order surface deviations from first order	168 7478	2 132	84.00 56.65	1.48	75+
second order surface deviations from second order	367 7279	5 129	73.40 56.42	1.30	50+
third order surface deviations from third order	547 7098	9 125	60.77 56.78	1.07	50+
fourth order surface deviations from fourth order	863 6782	14 120	61.64 56.51	1.09	50+
fifth order surface deviations from fifth order					
source	sum of squares	degrees of freedom	mean square	F	% confidence



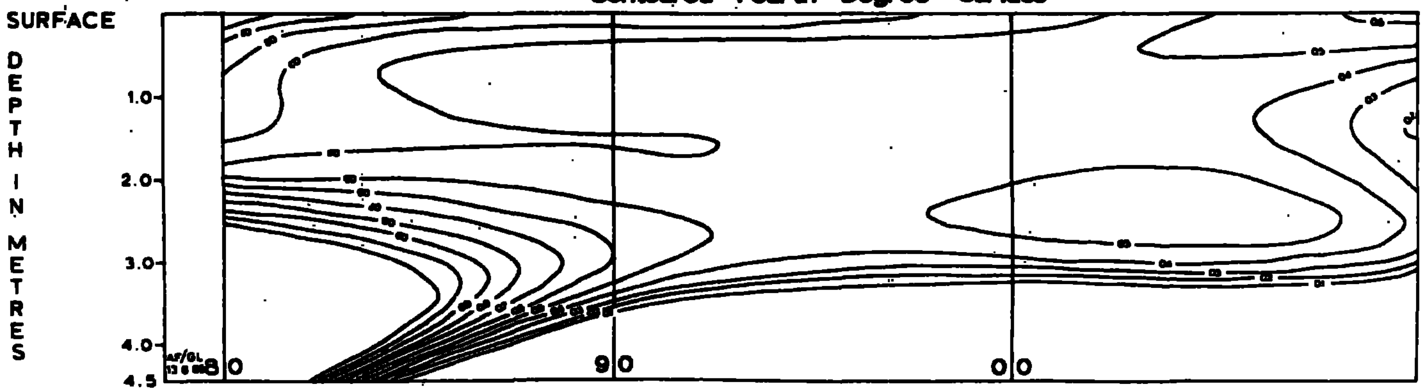
SURFACE
DEPTH IN METRES
1.0
2.0
3.0
4.0
4.5
8|0
9|0
0|0
Contoured First Degree Surface
VARIATION IN FACTOR 2 LOADINGS PROJECTED ONTO W—E VERTICAL PLANE
Contoured Second Degree Surface
SURFACE
DEPTH IN METRES
1.0
2.0
3.0
4.0
4.5
8|0
9|0
0|0



Contoured Third Degree Surface

VARIATION IN FACTOR 2 LOADINGS PROJECTED ONTO W—E VERTICAL PLANE

Contoured Fourth Degree Surface



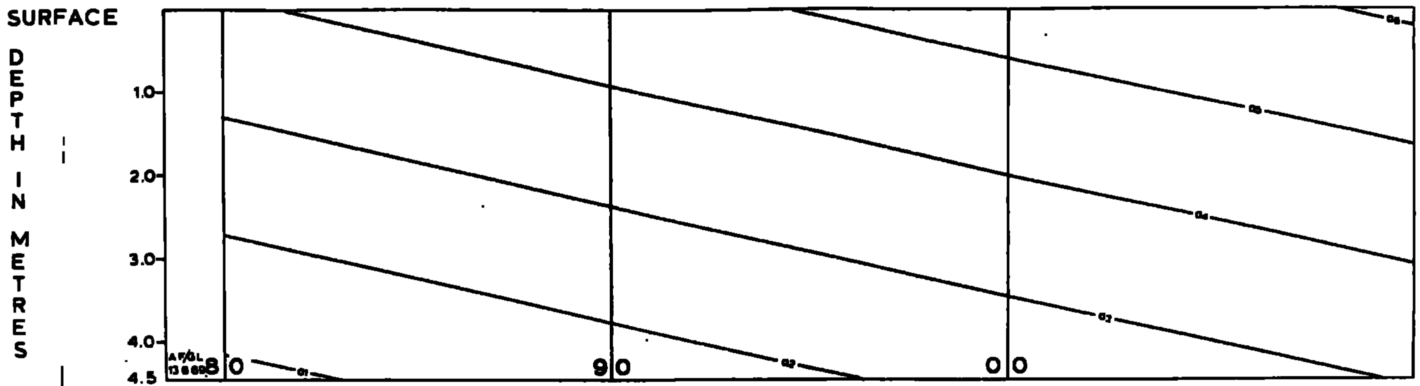
VERTICAL SURFACE DIAGRAM OF FACTOR 3 LOADINGS

TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

source	sum of squares	degrees of freedom	mean square	F	%confidence
linear surface deviations from above	1088 6071	2 132	544.00 45.99	11.82	99.99+
quadratic surface deviations from quadratic	198 5873	3 129	66.00 45.52	1.45	75+
cubic surface deviations from cubic	276 5597	4 125	69.00 44.77	1.54	75+
quartic surface deviations from quartic	170 5427	5 120	34.00 45.22	0.75	25+
quintic surface deviations from quintic					

TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

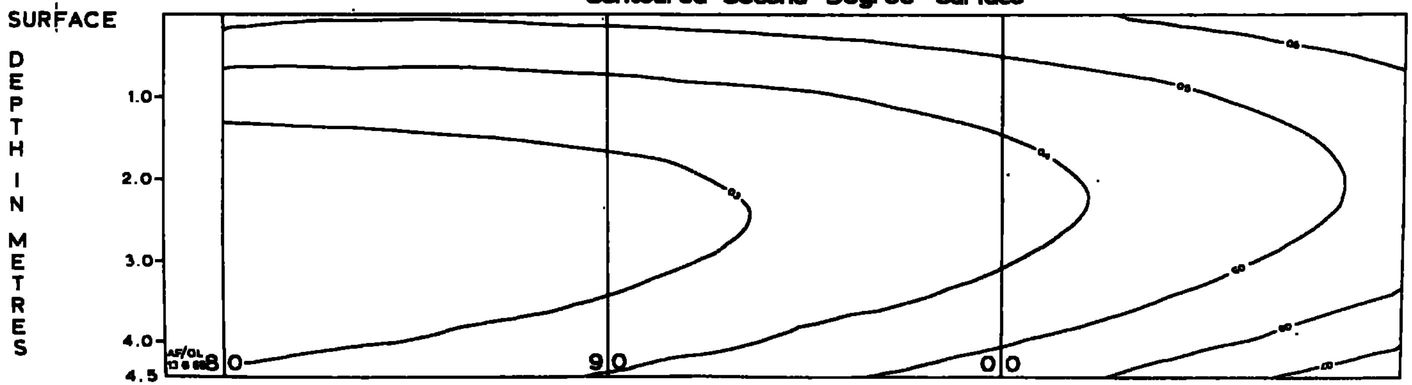
source	sum of squares	degrees of freedom	mean square	F	%confidence
first order surface deviations from first order	1088 6071	2 132	544.00 45.99	11.82	99.99+
second order surface deviations from second order	1286 5873	5 129	257.20 45.52	5.65	99.9+
third order surface deviations from third order	1562 5597	9 125	173.55 44.77	3.87	99.9+
fourth order surface deviations from fourth order	1732 5427	14 120	123.71 45.22	2.73	95+
fifth order surface deviations from fifth order					
source	sum of squares	degrees of freedom	mean square	F	%confidence

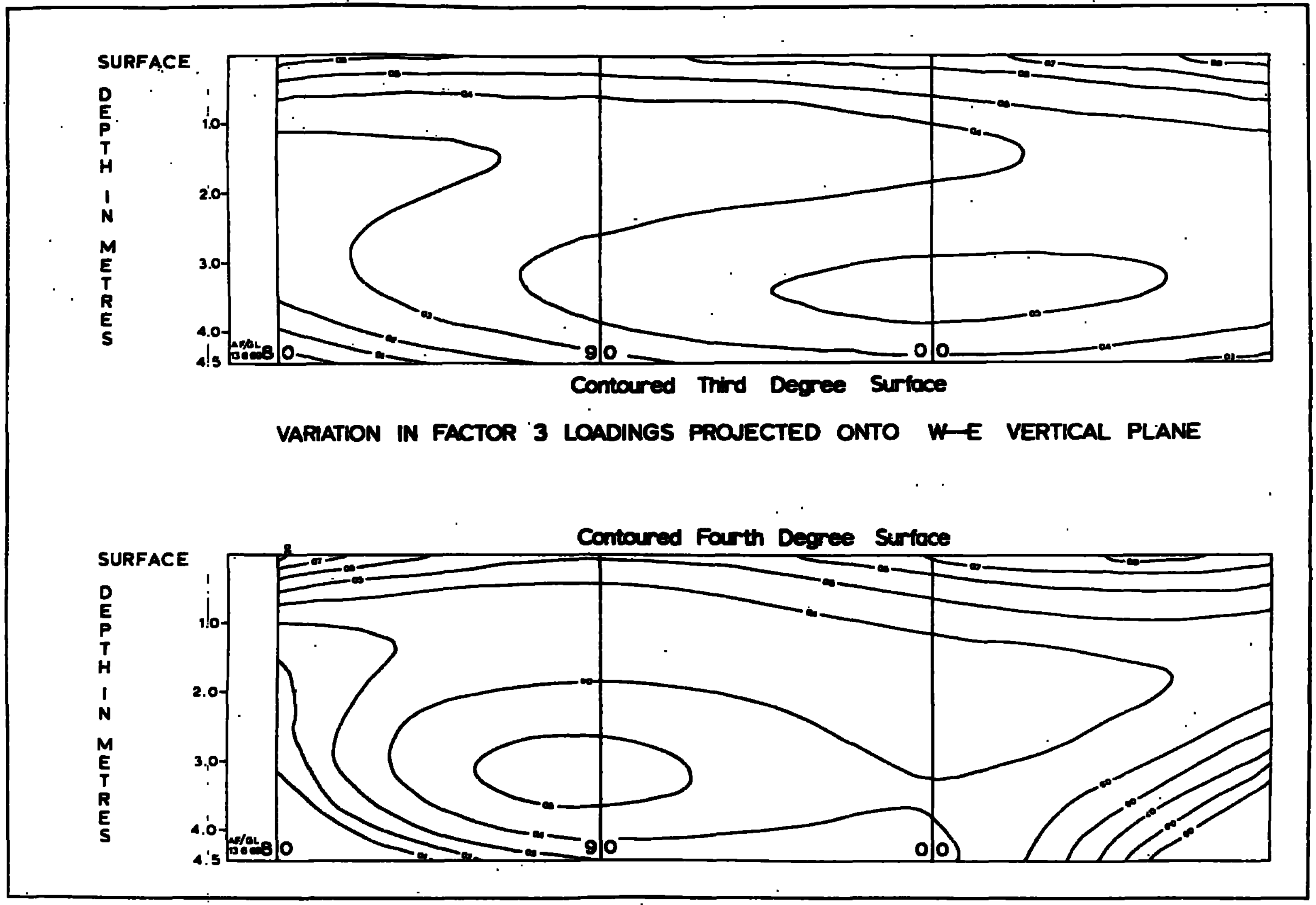


Contoured First Degree Surface

VARIATION IN FACTOR 3 LOADINGS PROJECTED ONTO W—E VERTICAL PLANE

Contoured Second Degree Surface




SURFACE
DEPTH IN METRES
1.0
2.0
3.0
4.0
4.5
80
90
00
Contoured Third Degree Surface
VARIATION IN FACTOR 3 LOADINGS PROJECTED ONTO W—E VERTICAL PLANE
Contoured Fourth Degree Surface
SURFACE
DEPTH IN METRES
1.0
2.0
3.0
4.0
4.5
80
90
00

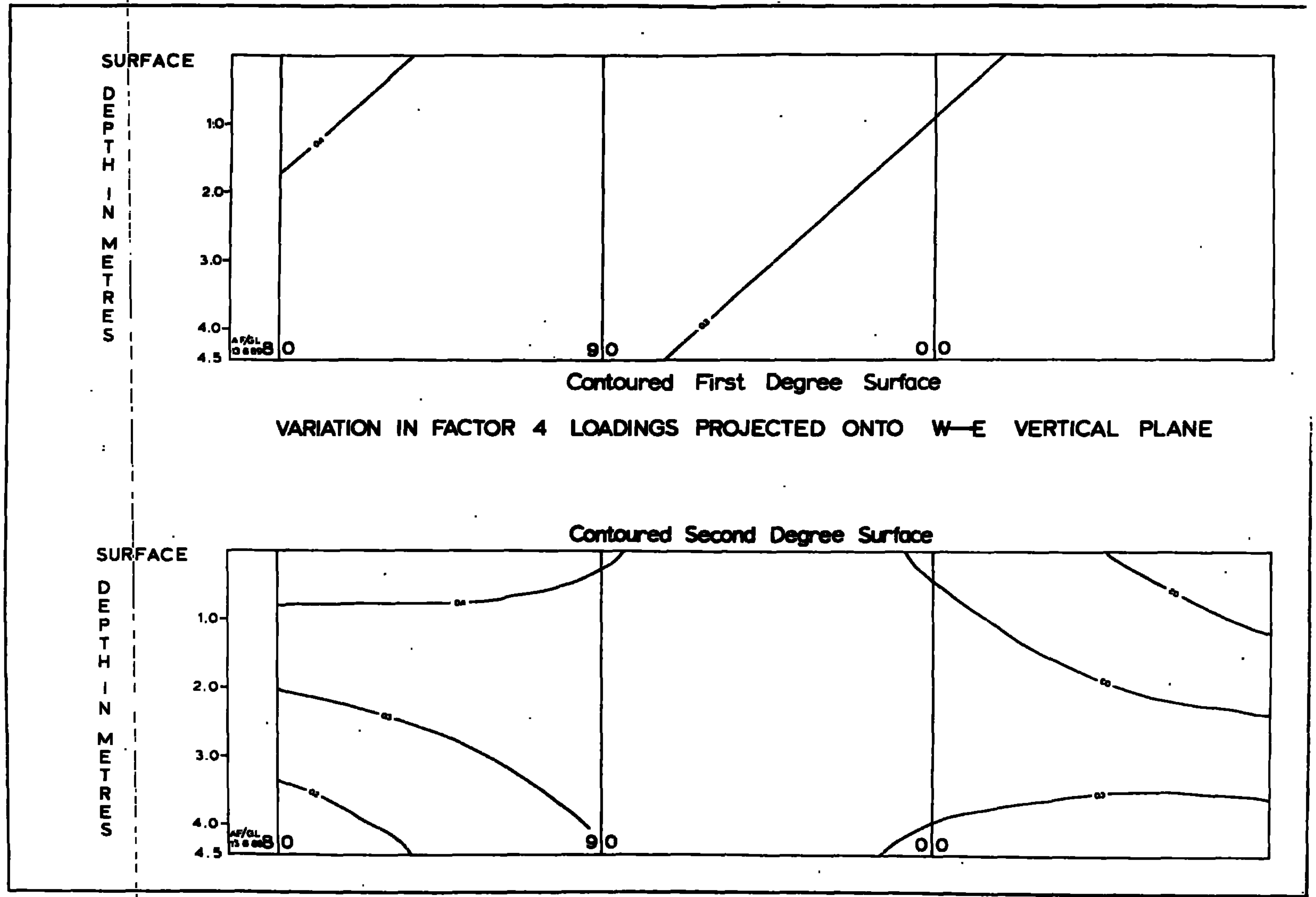
VERTICAL SURFACE DIAGRAM OF FACTOR 4 LOADINGS

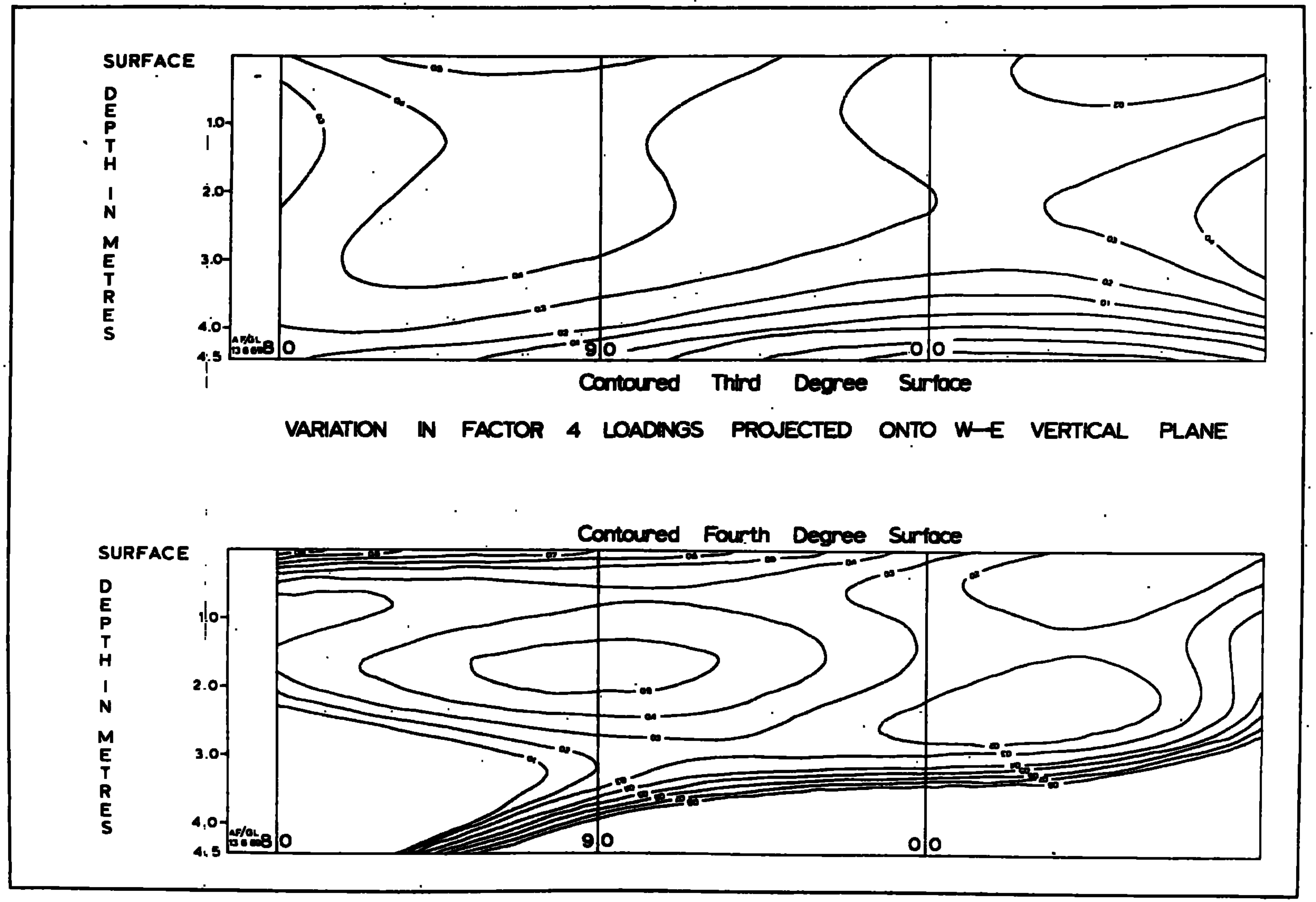
TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT
OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

source	sum of squares	degrees of freedom	mean square	F	% confidence
linear surface deviations from above	340 5023	2 132	170.00 38.05	4.46	97.5+
quadratic surface deviations from quadratic	264 4760	3 129	88.00 36.89	2.38	90+
cubic surface deviations from cubic	301 4459	4 125	75.25 35.67	2.10	90+
quartic surface deviations from quartic	499 3960	5 120	99.80 33.00	3.03	97.5+
quintic surface deviations from quintic					

TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

source	sum of squares	degrees of freedom	mean square	F	% confidence
first order surface deviations from first order	340 5023	2 132	170.00 38.05	4.46	97.5+
second order surface deviations from second order	604 4760	5 129	120.80 36.89	3.27	99.9+
third order surface deviations from third order	905 4459	9 125	100.55 35.67	2.82	99.5+
fourth order surface deviations from fourth order	1040 3960	14 120	74.28 33.00	2.25	90+
fifth order surface deviations from fifth order					
source	sum of squares	degrees of freedom	mean square	F	% confidence


SURFACE
DEPTH IN METRES
1.0
2.0
3.0
4.0
4.5
8 0
9 0
0 0
Contoured First Degree Surface
VARIATION IN FACTOR 4 LOADINGS PROJECTED ONTO W—E VERTICAL PLANE
Contoured Second Degree Surface
SURFACE
DEPTH IN METRES
1.0
2.0
3.0
4.0
4.5
8 0
9 0
0 0


SURFACE
DEPTH IN METRES
1.0
2.0
3.0
4.0
4.5
8|0
9|0
0|0
Contoured Third Degree Surface
VARIATION IN FACTOR 4 LOADINGS PROJECTED ONTO W—E VERTICAL PLANE
Contoured Fourth Degree Surface
SURFACE
DEPTH IN METRES
1.0
2.0
3.0
4.0
4.5
8|0
9|0
0|0

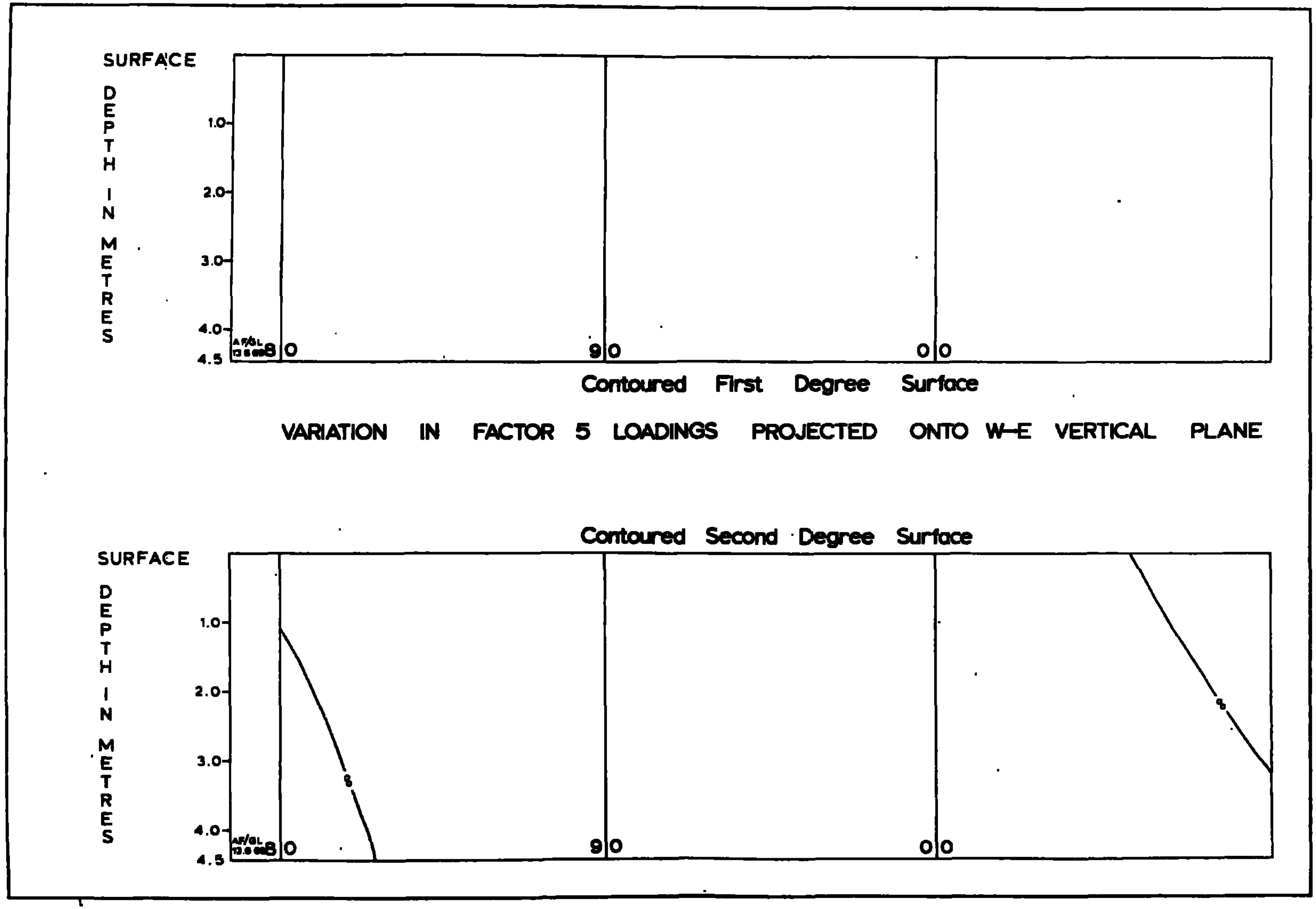
VERTICAL SURFACE DIAGRAM OF FACTOR 5 LOADINGS

TESTS OF THE SIGNIFICANCE OF EACH SUCCESSIVE UNIT OF THE POLYNOMIAL TREND SURFACES (after Allen and Krumbein)

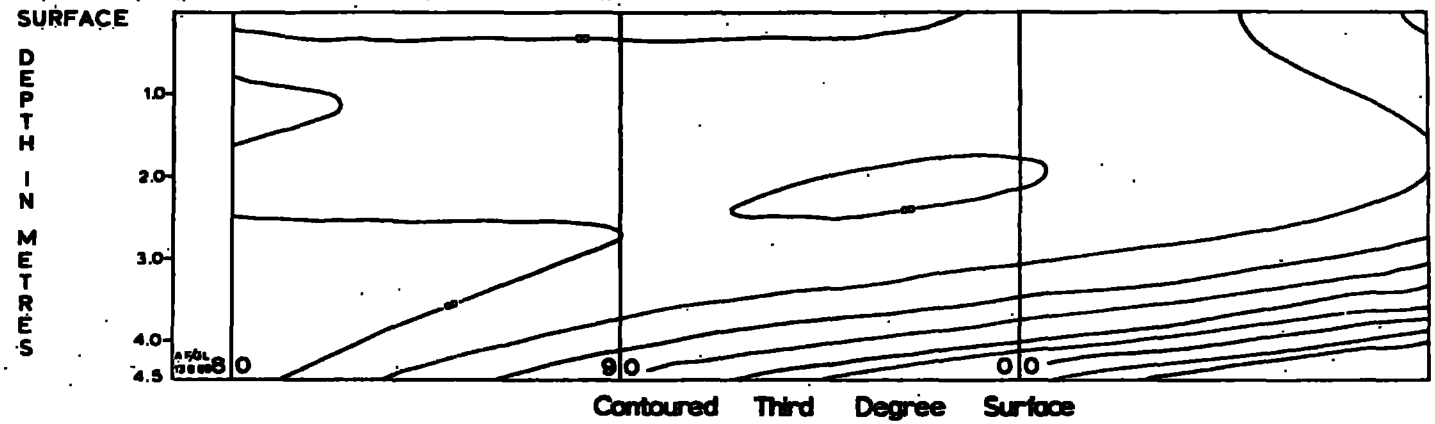
source	sum of squares	degrees of freedom	mean square	F	% confidence
linear surface deviations from above	3 4137	2 132	1.50 31.34	0.04	2.5+
quadratic surface deviations from quadratic	148 3989	3 129	49.33 30.92	1.59	75+
cubic surface deviations from cubic	79 3910	4 125	19.75 31.28	0.63	25+
quartic surface deviations from quartic	63 3847	5 120	12.60 32.05	0.39	10+
quintic surface deviations from quintic					

TESTS OF THE OVERALL SIGNIFICANCE OF EACH SURFACE

source	sum of squares	degrees of freedom	mean square	F	% confidence
first order surface deviations from first order	3 4137	2 132	1.50 31.34	0.04	2.5+
second order surface deviations from second order	151 3989	5 129	30.20 30.92	0.97	50+
third order surface deviations from third order	230 3910	9 125	25.55 31.28	0.82	25+
fourth order surface deviations from fourth order	293 3847	14 120	20.92 32.05	0.65	10+
fifth order surface deviations from fifth order					
source	sum of squares	degrees of freedom	mean square	F	% confidence



VARIATION IN FACTOR 5 LOADINGS PROJECTED ONTO W–E VERTICAL PLANE



VARIATION IN FACTOR 5 LOADINGS PROJECTED ONTO W—E VERTICAL PLANE