ANALYSIS OF GLACIAL DEPOSITS NEAR FALA, MIDLOTHIAN.

by

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Thesis presented for the degree of Doctor of Philosophy of the University of Edinburgh in the Faculty of Social Sciences, May, 1966.

ACKNOWLEDGEMENTS

I wish to express my gratitude to the many people who have helped me in the course of producing this thesis. In particular, I am indebted to my supervisors Dr. J.B. Sissons and Professor J.W. Watson for their constant encouragement and counsel. At various stages during the research I received some form of advice or help from Mr. R.L. Bennett, Dr. J.G. Burns, Mr. M.J. Burke, Dr. K.G. Cox, Dr. A.J. Crosbie, Mr. P.McL.D. Duff, Mr. D.M.L. Duthie, Mr. P.A. Furley, Mr. G.A. Goodlet, Mr. R.P. Kirby, Mr. W.A. Mitchell, Dr. W.W. Newey, Miss G.M. Randall, Mr. A.H. Seville, Mr. W. Tulloch, Dr. E.K. Walton, Mr. W.A.D. Whitfield and Dr. M.J. Wilson. To all I am indebted and record grateful acknowledgement of their assistance.

J.A.T.Y.

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Introduction

This study revolves round a 40 ft. section through a sequence of glacial deposits. The object was to find out as much as possible about these deposits, in particular their physical composition and properties by carrying out a sequence of systematic studies in the field and in the laboratory. The variations over very short distances both laterally and vertically were examined.

Initially this work began by tracing the north eastern limit of the ultimate ice advance from the Southern Uplands into the Midlothian Basin. Work by Sissons (1961) has shown that Southern Upland ice flowing north from the Eddelston Valley turned north east on reaching the Midlothian Basin and probably penetrated (Sissons, personal communication) 15 to 17 miles into the area around Fala. Chapter I explains the general background and glacial history of the area, setting the scene for the main work in one of the sections excavated during preliminary reconnaissance work. This section is unique in the area as it displays a sequence containing three units of till separated from one another by various thicknesses of sands.

Chapters 2,3,4 and 5 stand as separate systematic studies in themselves. Chapter 2 is based on work carried out in the field whilst the other three chapters present the results of laboratory analyses.

Other workers have found that the component pebbles of tills tend to be arranged with a preferred alignment that is coincident with the direction of the depositing ice. In Chapter 2 the variations in preferred pebble disposition between and within the three till units were examined at intervals separated by 2 ft. vertically; over and above, the variations laterally in four directions were studied at three different levels in one of the till units. At another level an attempt was made to isolate each of the maxima in a three-peak system that emerged/

emerged in an earlier study carried out at that level by working in a very shallow depth. Rigorous scrutinisation of the data from these short distance studies of pebble disposition was made and produced conclusions of importance generally to this type of work as well as specifically to the tills of the section.

Knowledge of the particle size distribution, mineralogy and chemical characteristics of the tills and sands permits better assessment of the provenance of the transporting ice, its path and the nature of the englacial processes (Chapters 3, 4 and 5). Samples from each of the levels of study (Chapter 2) were taken and the problem of representative sample size was considered.

Particle size analysis (Chapter 3) assesses the distribution of the component size fractions from clay to boulders and the amount of each size fraction for every till and sand sample. Under field conditions it is all too easy to estimate incorrectly the texture of a deposit; high moisture content and a high degree of compaction often give the impression of a clay whereas drier and less compact material may seem coarser and sandy.

Both micro- and macromineralogy of the samples was studied (Chapter 4). The relative proportion of the different lithologies in the pebble and cobble fractions was evaluated. Part of the fine sand fraction was separated into "heavy" and "light" portions on the basis of specific gravity and samples from each portion systematically identified under a polarizing microscope.

The pH and total soluble carbonate content of each till and sand sample was measured (Chapter 5) as simple indices of the chemical characteristics of the deposits.

Thus the study evolved primarily as an intensive examination of the physical properties of the tills and sands with a brief incursion into the chemical properties. At all stages during the investigation great emphasis was placed on accuracy and the development of a sound, objective, research technique.

Chapter 1. The Area Around Fala and Upper Keith

The area of the study is located 14 miles south east of Edinburgh and straddles the country boundary between Midlothian and East Lothian. A short distance of 1 to 2 miles further south east lies the Southern Upland fault which is a major, local topographical divide. To the south and east of the fault the ground rises steeply to heights varying between 1100 and 1750 feet in the Lammermuirs. On the other hand, to the north and west the land immediately adjacent to the scarp face of the Lammermuirs is more gently undulating between heights of 400 and 800 feet.

Geologically, the Southern Upland fault separates the older Ordovician and Silurian greywackes from the younger Central Valley Devonian and Carboniferous sediments and their contemporary igneous rocks. Structurally, the area lying between the Southern Upland fault and the Pentland Hills which are situated 15 miles to the north west is a syncline of Carboniferous sediments and is referred to as the Midlothian Basin.

Thus the locus of this study is the eastern edge of the Midlothian Basin in the lee of the Lammermuirs with particular reference to the area around Fala and Upper Keith (Figure 1.1).

The landscapes of both Midlothian and East Lothian bear a distinctive imprint of glacial activity. Since the first edition of the local Geological Survey Memoirs (Howell and Geikie, 1861; Howell, Geikie and Young, 1866) a near plethora of papers has attempted to explain the evolution of this area during the glacial period.

On the basis of the alignment of crag and tail features, the few observed striae, large grooves cut in the bedrock and erratic indicator stones it would seem that ice has passed across the southern area of the Midlothian Basin from approximately south west to north east; towards the north there is/

is a gradual change in alignment to a more west-east direction, Milne (1840), Howell and Geikie (1861), Howell, Geikie and Young (1866), Miller (1884), Geikie (1894), Kendall and Bailey (1908), Clough et al (1910), Peach, Clough et al (1910), McCall and Goodlet (1951).

There is evidence to demonstrate that both Southern Upland and Highland ice masses have been present in the Midlothian Basin. However, it is not absolutely certain what the maximum extension of each ice mass was and whether they were contemporaneous or separated by a time interval. Southern Upland greywackes have been found in the tills as far north as Pencaitland and Ormiston (Peach, Clough et al, 1910) whereas Highland schists figure prominently in the tills as far south as Tynehead (Geikie, 1894).

In 1908, Kendall and Bailey described the existence of a reddish coloured till overlying 15 feet of stratified sands and gravels that in turn overlaid a greyish coloured till in one section at Costerton in East Lothian (Figure 1.1, map reference 438631). Since this discovery, other workers have noted the existence of a reddish coloured till over a restricted area of the southern Midlothian Basin. The greyish coloured till is more widespread and often lies directly on rockhead. In all cases where both tills occur in the same section, the reddish one always overlies the greyish one and may be separated by greatly varying depths of sands and gravels. The actual thicknesses of both tills varies considerably from site to site but it would be valid to generalise that the grey till tends to be thicker than the red till.

Since the discovery of two apparently different tills separated by sands and gravels, various interpretations of fluctuation and readvance of the ice front during the final stages of the glacial period in this part of Scotland have been made. For instance, Charlesworth (1926) favoured a major advance by Highland ice/

ice that partially retreated and later readvanced. On the other hand, Eckford (1952) suggested that the source of the last major advance was the Highlands with a later minor advance from the Southern Uplands. Kendall and Bailey (1908) themselves and later Wright (1937) believed that both the Southern Upland and Highland ice masses were coterminous having joined forces in the Ayrshire plain and spread out north east and south west. The north easterly component penetrated into the Midlothian Basin and oscillations of the ice front were postulated to explain the stratigraphical sequence described.

Evidence of some form of glacier oscillation has been suggested by Sissons (1958a, 1963) and Tulloch and Walton (1958) from the till infillings of glacial drainage channels that must have been cut, at the latest, during some earlier phase of the ultimate glaciation.

The most detailed studies of the deglaciation of this area have been made by Sissons (1958a,b, 1961, 1963) and have clarified the general nature and manner of ice dissipation. Towards the end of the glacial period the Midlothian Basin was filled with ice. The Lammermuirs in the south east and the Pentland Hills to the north west stood up above the general level of the ice as nunataks. Finally, the thinning ice turned stagnant and downwasted in situ cutting systems of drainage channels and building up great quantities of outwash and Kettle and Kame topography, particularly in the areas of the ice margin.

There is now no doubt that Southern Upland ice extended north and north east into the Midlothian Basin from the Eddelston Valley and probably other valleys further south west during the final phases of glacial advance (Sissons 1958b, 1961). The actual limits of ice penetration north and north east from the Eddelston Valley have never been properly defined.

The/

The foothill area of the Moorfoot-Lammermuir range from the Eddelston Valley to Dunbar can be divided into two on the basis of the landforms developed (Sissons, 1961). North east of Blegbie (Figure 1.1, map reference 481618) an intricate system of channels and Kame terraces indicates how ice pressing against the edge of the hills gradually downwasted in situ. Sissons has suggested that this particular ice had its source in the Highlands. To the south west of Blegbie almost no channels and Kame terraces are found running along the north west facing slopes although eventual stagnation of the ice has been interpreted from the long esker systems and general Kame and Kettle topography.

The first object of the current research was to investigate the area around Fala and Upper Keith and attempt to trace the north easterly limits of the Southern Upland ice penetration. Morphological mapping yielded no worthwhile results as the surface expression of the drift is almost monotonous with moderately deep dissection by glacial and post glacial streams; that is, there is no semblance of any features akin to end moraine. An attempt was then made to build up a complete picture of the stratigraphy over the area by hand auguring. It was found impossible to penetrate the ground more than a few inches with a hand augur. Therefore it was necessary to resort to a detailed examination of the sections exposed in the river banks of the area.

The headwater tributaries of the East Lothian Tyne have cut down deeply into the deposits of this area and many sections of the stratigraphical sequence have been exposed. It was thus decided to dig away the slumped material from all the available sections and record accurately the sequence of deposits, their thicknesses and colours using a Munsell chart.* The relative distribution of the sites is shown in Figure 1.1.

* Colours assessed under field conditions.

Site Descriptions

Site 1. Section exposed in the Cakemuir Burn west of the A.68 road (424608).

Not less than 10 ft. dark grey (5 YR 4/1) till containing coal fragments and larger pieces of quartz, greywacke, Carboniferous sandstone and tuffs. Upper part of section obscured by slumping off slope.

Site 2. Section exposed in Partridge Burn. (430602).

(a) 4 to 4½ ft. reddish brown (5 YR 4/3) till with upper 24 to 30 ins. including present day soil profile. Underlain by (b) not less than 4 ft. dark grey (5 YR 4/1) till. Coal fragments and pieces of Carboniferous sandstone and greywackes common to both tills.

Site 3. Section exposed in Partridge Burn. (429604).

(a) 2½ ft. present day soil profile underlain by (b) 4½ ft. reddish brown (5 YR 4/3) till containing coal fragments and larger pieces of Carboniferous sandstone, greywacke and tuffs.

Site 4. Section exposed in Partridge Burn. (427608).

At least 20 ft. dark grey (5 YR 4/1) till containing coal fragments and larger pieces of Carboniferous sandstone, greywacke and limestone. Upper part of section obscured by slumping.

Site 5. Section exposed in Cakemuir Burn between A.68 road and Fala Dam. (428615).

(a) 4 ft. dark reddish brown (5 YR 3/2) till underlain by (b) not less than 3 ft. very dark grey (2.5 YR 3/1) till. Coal fragments and larger pieces of Carboniferous sandstone and greywacke common to both tills.

Site 6. Section exposed in Cakemuir Burn between Routing Glen and Fala Dam. (431617).

Not less than 10 ft. very dark grey (5 YR 3/1) till containing coal fragments and larger pieces of greywacke, Carboniferous sandstone and limestone.

Site 7. /

<u>Site 7.</u> Section exposed in Cakemuir Burn between Fala Dam and Routing Glen. (432617).

(a) 4 to 5 ft. dark brown (7.5 YR 4/2) till overlying (b) not less than 20 ft. dark reddish brown (5 YR 2/2) till. Coal fragments, greywacke and Carboniferous sandstone common to both tills.

<u>Site 8.</u> Section exposed in Routing Glen. (436614).

(a) 4 to 5 ft. dark brown (7.5 YR 4/4) pebbly sand overlying (b) 20 to 25 ft. very dark grey (7.5 YR 3/1) till. Sporadic coal fragments in sand becoming larger and more frequent in till. Greywackes and Carboniferous sandstones found in both till and sand.

<u>Site 9.</u> Section exposed in Fala Dam Burn between Routing Glen and East Water. (436620).

Not less than 4 ft. dark grey (5 YR 4/1) till containing coal fragments and larger pieces of greywacke, Carboniferous sandstone and limestone. Upper parts of section slumped and overgrown.

<u>Site 10.</u> Section exposed in Fala Dam Burn between Routing Glen and East Water. (437623).

Not less than 3½ to 4 ft. dark brown (7.5 YR 4/2) till containing occasional coal fragments and larger pieces of greywacke and Carboniferous sandstone. Upper part of section overgrown.

<u>Site 11.</u> Section exposed in East Water south of Woodcote Bridge. (449601).

10 ft. very dusky red (7.5 R 2/4) stoney and unconsolidated debris overlying purple, weathered conglomerate; included stones solely rounded greywackes.

<u>Site 12.</u> Section exposed in East Water north of Woodcote Bridge. (450604).

2 ft. very dusky red (7.5 R 2/4) stoney and unconsolidated debris overlying purple, weathered conglomerate; included pebbles solely rounded greywackes.

<u>Site 13</u>. /

Site 13. Section exposed in East Water between Woodcote Bridge and East Water Bridge. (451608).

At least 20 ft. till exposed in section, erratics including greywacke, Carboniferous sandstone and coal fragments.

(a) 3 ft. reddish brown (5 YR 4/3) till overlying (b) 7 ft. dark reddish brown (5 YR 3/4) till overlying (c) 10 ft. dark reddish brown (5 YR 3/2) till. At 19 to 20 ft. from ground surface discontinuous 2 to 4 inch bands of dusky red (10 R 3/4) clay included in lowest till level.

Site 14. Section exposed in East Water between Woodcote Bridge and East Water Bridge. (451609)

At least 20 ft. till exposed in section. Erratics found included coal fragments and larger pieces of greywacke, Carboniferous sandstone, Old Red sandstone and limestone. (a) 18 ft. reddish brown (5 YR 4/4) till overlying (b) 2 ft. dark reddish brown (5 YR 3/4) till with included dusky red (10 R 3/4) streak bands overlying (c) not less than 2 ft. currently bedded reddish brown (5 YR 4/3) sands with concentrations of coal fragments.

Site 15. Section exposed in East Water between Woodcote Bridge and East Water Bridge. (452609).

(a) 8 to 10 ft. reddish brown (5 YR 4/4) till containing Old Red Sandstone, Carboniferous sandstone and greywacke erratics and coal fragments overlying (b) 4 ft. currently bedded reddish brown (5 YR 4/3) sands overlying (c) 6 ft. dark reddish brown (5 YR 4/2) till containing larger pieces of Carboniferous sandstone, greywacke and Old Red sandstone and fragments of coal overlying (d) 1 ft. currently bedded reddish brown (5 YR 4/3) sands overlying (e) not less than 10 ft. very dark grey (5 YR 3/1) till containing coal fragments and larger pieces of limestone, Carboniferous sandstone and greywacke.

Site 16./

Site 16. Section exposed in East Water between Woodcote Bridge and East Water Bridge. (452611).

(a) 10 ft. reddish brown (5 YR 4/4) till containing Old Red sandstone, Carboniferous sandstone and greywacke erratics and coal fragments overlying (b) 4 ft. dark reddish brown (5 YR 4/2) till containing Carboniferous sandstone and greywacke erratics and coal fragments.

Site 17. Section exposed in East Water between Woodcote Bridge and East Water Bridge. (453612).

(a) 3 ft. very stoney, dark reddish brown (2.5 YR 3/4) till containing Carboniferous sandstone, Old Red sandstone and greywacke erratics overlying (b) not less than 4 ft. very dark grey (5 YR 3/1) till containing Carboniferous sandstone and greywackes. Coal fragments found in both tills.

Site 18. Section exposed in East Water between Woodcote Bridge and East Water Bridge. (452613).

(a) 2 ft. dark reddish brown (2.5 YR 3/4) till containing Old Red sandstone, Carboniferous sandstone and greywacke erratics overlying (b) 2 to 2½ ft. coarse gravels (Old Red sandstone, greywacke, Carboniferous sandstone and tuffs) overlying (c) an irregular 2 to 18 inch band of very dark grey (5 YR 3/1) till containing Carboniferous sandstone, greywacke erratics and coal fragments overlying (d) an irregular convolved bedded yellowish sand containing included lumps of grey till overlying (e) not less than 4 ft. very dark grey (5 YR 3/1) till containing Carboniferous sandstone and greywacke erratics and coal fragments.

Site 19. Section exposed in East Water north of East Water Bridge. (451616).

(a) 10 ft. very sand, yellow red (5 YR 6/6) till containing coal fragments and Carboniferous sandstone overlying (b) 3 ft. currently bedded pale brown (10 YR 6/3) sand.

Site 20./

Site 20. Section exposed in East Water north of East Water Bridge. (450617).

(a) 2 ft. present day soil profile overlying (b) 1 ft. coarse gravels containing Carboniferous sandstone and greywacke pebbles overlying (c) 8 to 10 ft. dark brown (7.5 YR 4/2) till containing coal fragments, Carboniferous sandstone and greywacke erratics.

Site 21. Section exposed in East Water north of East Water Bridge. (450619).

(a) not less than 2 ft. medium to coarse gravel containing Carboniferous sandstone, greywacke and tuff pebbles overlying (b) 1ft. red (2.5 YR 4/8)sand overlying (c) 2 ft. yellowish brown (10 YR 5/4) sand overlying (d) 10 ft. dark brown (5 YR 3/2) till containing coal fragments, Carboniferous sandstone and greywacke erratics.

Site 22. Section exposed in small burn south of Fala Hall. (444617).

3 ft. reddish brown (5 YR 4/4) till containing Carboniferous sandstone and greywacke erratics.

Site 23. Section exposed in East Water near Fala Hall. (444619).

(a) 3 ft. reddish brown (5 YR 4/4) till containing coal fragments and Carboniferous sandstone and greywacke erratics overlying (b) not less than 30 ft. very dark grey (2.5 Y 3/0) till containing coal fragments and lumps, Carboniferous sandstone, greywacke and tuff erratics.

Site 24. Section exposed in East Water near Fala Hall. (440621).

(a) 4 to 4½ ft. reddish brown (5 YR 4/4) till containing Carboniferous sandstone and greywackes overlying (b) not less than 15 ft. currently bedded sands with included layers of reddish brown till near top; towards base, sand coarsens considerably to gravel with cobbles common and overlies (c) not less than 10 ft. very dark grey (2.5 Y 3/0) till containing coal fragments, Carboniferous sandstone, greywackes and limestone erratics.

Site 25. Almost vertical section exposed in East Water near junction with Fala Dam Burn. (437623).

(a) 3 to 3½ ft. dark brown (10 YR 3/3) sands containing present day soil profile at top overlying (b) 4 to 5 ft. dark reddish brown (5 YR 3/2) till containing coal fragments, Carboniferous sandstone and greywacke erratics overlying (c) 2 ft. pebbly sand overlying (d) not less than 12 ft. dark brown (7.5 YR 4/2) till containing coal fragments, Carboniferous sandstone, greywacke and tuff erratics overlying (e) 3 ft. currently bedded sands with included bands of coal fragments overlying (f) not less than 10 ft. dark grey (10 YR 4/1) till containing small lumps and fragments of coal and Carboniferous sandstone, greywacke and limestone erratics.

Site 26. Red Scar at Costerton (438631), described first by Kendall and Bailey (1908).

(a) not less than 50 ft. dark brown (10 YR 3/3) sands overlying (b) 12 to 13 ft. reddish brown (5 YR 4/3) till containing coal fragments and Carboniferous sandstone and greywacke erratics overlying (c) 10 to 15 ft. pale brown (10 YR 6/3) sands overlying (d) 30 to 40 ft. very dark grey (10 YR 3/1) till containing Carboniferous sandstone, greywacke and limestone erratics and coal fragments.

Site 27. Section exposed in Keith Water near Keith Bridge. (448638).

(a) not less than 10 ft. sands and gravels overlying (b) 8 ft. very dark grey (5 YR 3/1) till containing coal fragments and Carboniferous sandstone and greywacke erratics.

Site 28. Section exposed in Keith Water near Keith Bridge. (449638).

(a) 4 to 4½ ft. reddish brown (5 YR 4/4) till containing fragments and small lumps of coal, Carboniferous sandstones and greywackes overlying (b) currently bedded sands. A fragment of felsite (perhaps from Tinto Hill) has been found in this section (Sissons, personal communication).

<u>Site 29.</u> Section exposed in Keith Water near Keith Bridge. (450639).

(a) 6 ft. sands and gravels overlying (b) not less than 4 ft. very dark grey (5 YR 3/1) till containing fragments of coal and Carboniferous sandstone, greywacke and tuff erratics.

<u>Site 30.</u> Section exposed in old sandpit near Keith Bridge. (450640).

(a) 4 ft. dark reddish brown (2.5. YR 3/4) till containing Carboniferous sandstone, Old Red sandstone and greywacke erratics and coal fragments and lumps overlying (b) 3 to 5 ins. currently bedded, dark reddish brown (5 YR 3/4) sands overlying (c) 2 to 4 ins. dark reddish brown (2.5 YR 3/4) till containing coal fragments, greywackes, Old Red sandstone and Carboniferous sandstone overlying (d) not less than 35 ft. currently bedded sands with discontinuous bands of coal fragments.

<u>Site 31.</u> Section exposed in burn near Borland Cottage. (475614).

8 ft. dark red (2.5. YR 3/6) sandy till containing coal fragments, Old Red sandstone and greywackes.

<u>Site 32.</u> Section exposed in Blegbie Burn near Blegbie Farm. (479619).

(a) 6 ft. weathered and very stoney till-like material containing Old Red sandstone, Carboniferous sandstone and greywackes overlying (b) 2 to 3 ft. currently bedded sands containing thin bands of coal fragments.

<u>Site 33.</u> Section exposed in Humbie Dean. (469623).

2 to 3 ft. dark reddish brown (10 YR 4/1) till containing coal fragments, Old Red sandstone Carboniferous sandstone and greywackes.

<u>Site 34.</u> Section exposed in Humbie Dean. (466625).

(a) 4 ft. dark reddish brown (5 YR 3/2) till heavily charged with coal fragments and also Old Red sandstone, Carboniferous sandstone and greywackes overlying (b) 1 ft. currently bedded sands overlying (c) not less than 10 ft. very dark grey (5 YR 3/1) till containing Carboniferous sandstone and greywackes with sporadic coal fragments.

<u>Site 35.</u> Section exposed in Birns Water near Ewingston Farm. (489646).

(a) 2 ft. sands and gravels overlying (b) not less than 3 ft. dusky red/

red (10 R 3/4) till containing coal fragments, Old Red sandstone, Carboniferous sandstone and tuffs.

Site 36. Section exposed in Birns Water near Ewingston Farm. (488650).

4 to 5 ft. dusky red (10 R 3/4) till containing coal fragments, Old Red sandstone, Carboniferous sandstone and tuffs.

Site 37. Section exposed in Birns Water near Gilchriston Farm. (477652).

Not less than 2 to 4 ft. dusky red (10 R 3/4) till containing coal fragments, Old Red sandstone, Carboniferous sandstone and tuffs.

Site 38. Section cut back into railway cutting in Saltoun Big Wood. (467654).

3 to 4 ft. reddish brown (2.5 YR 3/4) till containing coal fragments, Old Red sandstone, Carboniferous sandstone and tuffs.

Site 39. Section exposed in How Burn. (496664).

(a) 3 ft. dark brown (7.5 YR 4/4) sand overlying (b) not less than 18 ins. pinkish grey (5 YR 6/2) sand. Both sands contain bands of coal fragments.

Site 40. Section exposed in old quarry near Cross Roads School. (436654).

(a) 4½ ft. weathered greyish brown (10 YR 5/2) till containing very dark greyish brown (10 YR 3/2) flecks, coal fragments, limestone, Carboniferous sandstone and greywackes overlying (b) 10 ins. yellow red (5 YR 4/8) sticky clay overlying (c) 18 to 24 ins. dark grey (5 YR 4/1) weathered limestone on in situ limestone bedrock.

Site 41. Section exposed in Peaston Quarry. (428644).

4 to 5 ft. weathered, greyish brown (10 YR 5/2) till gradually giving way to dark grey (5 YR 4/1) till at base and overlying limestone bedrock. Coal fragments, Carboniferous sandstone, limestone and greywackes found in till.

Site 42. Section exposed in old quarry near Peaston Quarry. (420642).

4 ft. weathered greyish brown (10 YR 5/2) till with dark grey (5 YR 4/1) flecks /

flecks and containing coal fragments, Carboniferous sandstone, limestone and greywackes overlying limestone bedrock.

Site 43. Section exposed in old quarry near Hope Farm. (409630).

3 to 4½ ft. weathered, greyish brown (10 YR 5/2) till containing coal fragments, Carboniferous sandstone, limestone and greywackes overlying limestone bedrock.

The descriptions of the 43 sections show how rapidly and radically the stratigraphy in this area changes over short distances. It would be impossible to construct an isopachyte map of any clarity for any one strat~~a~~-um from the results obtained.

Bedrock is hidden beneath varying thicknesses of till and stratified drift that is deepest in the valleys and depressions. In the north west of the area (Sites 40 to 43) a ridge of limestone lies only 4 to 5 ft. from the ground surface. South east of Sites 31 and 32 the greywacke bedrock appears at and near the surface with only a thin veneer of weathered greywacke debris.

From the site investigations it would seem that a dark grey till (absolute colour varying slightly from point to point) underlies the greater part of the area. It is suggested that the greyish brown till capping the limestone ridge (Sites 40 to 43) is a weathered form of the dark grey till and not an admixture with the dark reddish brown till found immediately to the south east.

It would seem that a reddish brown to dark reddish brown till, often found overlying the dark grey till, is maximally developed south east of the limestone ridge (Sites 40 to 43) and north west of Sites 31 and 32 which lie in the immediate lee of the Lammermuir fault line scarp. North east of a line from Site 30 to Site 33 the character of the till is sandier and less compact, no greywacke erratics are found and the colour becomes dusky red in contrast

to/

to a reddish brown further south west. No south western limit of the dark reddish brown till was found during the present study.

It was decided to develop the foregoing work by examining and analysing one of the 43 sections already described in the greatest possible detail according to the facilities available. Site 25 near the junction of the East Water and Fala Dam Burn was selected because a vertical sequence exposing three units of till each separated from one another by lesser thicknesses of sands and gravel had been noted and the site was readily accessible. The detailed diagram (Figure 1.2) of Site 25 shows the thicknesses of the various strata, their relationship to one another and the levels of investigation (Chapters 2,3,4 and 5) with the Munsell chart colours of each level.

LOCATION OF SITES INVESTIGATED

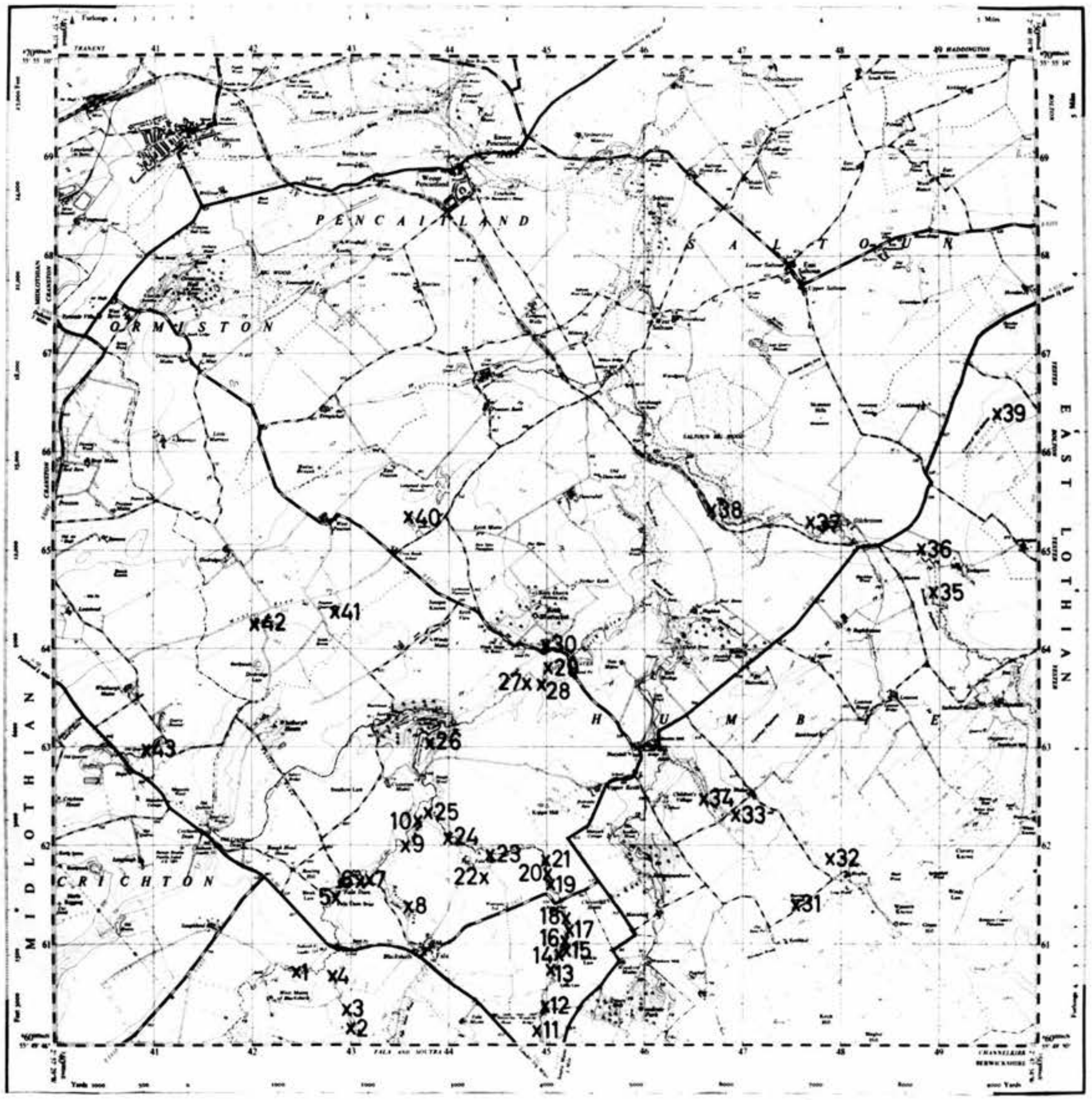
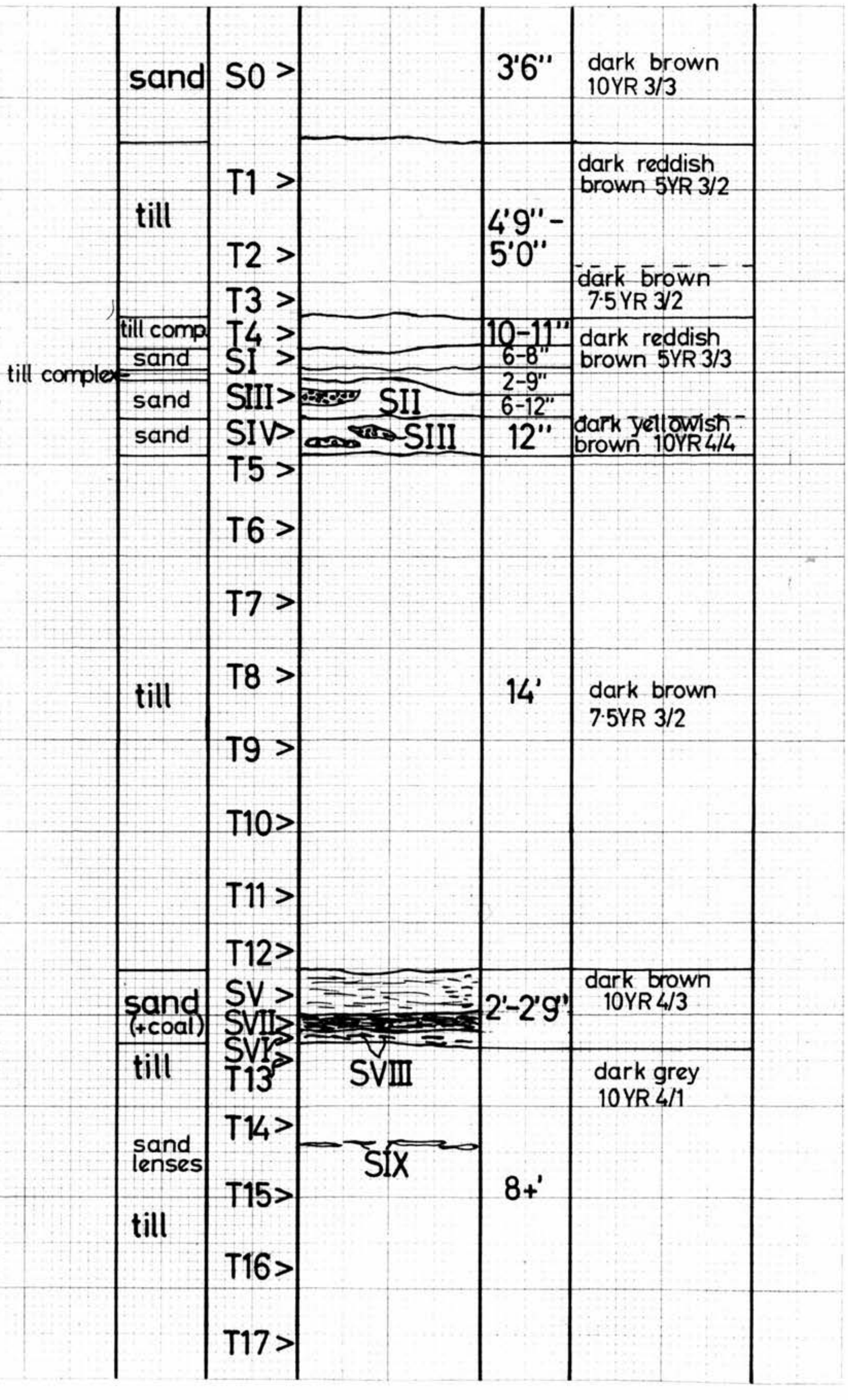


FIGURE 1.1

FIGURE 1.2 - MAIN SECTION ANALYSED



Chapter 2. Orientation and Dip Analysis of the Till Macrofabric.

Orientation and dip analysis involves measurement of the azimuth and plunge of the long axis of pebbles. It is common to find a resulting preferred alignment of these pebbles over a narrow arc.

The results obtained in this type of analysis have been used for three different purposes. Firstly, Holmes (1941), Dreimanis and Reavely (1953), Kaiser (1962) and Stewart and Mac Lintock (1964), in America, Virkkala (1951) in Finland, West and Donner (1956) in England and Kirby (1961) in Canada have assessed regional ice movement. Secondly, Holmes (1941), and Harrison (1957b) in America and Andrews (1963b, 1965) in Canada have tried to explain the manner in which till has been deposited. Thirdly, Hoppe (1952, 1957) in Sweden, Wright (1957) in America and Andrews (1963b,1965) in Canada have postulated the genesis of various landforms composed of till.

West and Donner (1956) found variations extending over an arc of 60° in three analyses separated vertically by 1.5 m. and 4 m. in a single layer of till 8 m. thick. They also examined lateral variation in four instances and found differences up to 25° at the same level. Their conclusions were that the horizontal variation was small in comparison with the vertical variation and did not hinder their objective of differentiating the three major East Anglian episodes of ice advance.

The work of Harrison (1957b) represents the most detailed study of orientation and dip analysis to date. At two sites 750 ft. apart, he showed that in four till units separated by lake silts or sand and gravel, the variation in orientation was 21° to 48° at approximately the same level, whilst the range of variation vertically within the two sections was 134° and 73° respectively. Although the till units were 5 ft.,20 ft., 8 ft. and not less than 10 ft. thick, he only carried out one investigation per till unit at each site. Within a single till/

till sheet, Harrison found differences of 20° between analyses separated by $6\frac{1}{2}$ ft. vertically and 9° between analyses separated by 3 ft. horizontally. He concluded that there was considerable variation in orientation between individual till sheets, lateral variation over 750 ft. was considerable and over a very short distance, horizontal variation in pebble disposition at a given level was less than vertical variation between levels.

Although the literature bears evidence of detailed work by West and Donner (1956) and Harrison (1957b), no worker has yet directed his whole research solely to the examination of short distance variations in pebble disposition. Accordingly, it was decided to examine intensively the variations, if any, in pebble disposition over very short distances both laterally and vertically within the three till units of the section (Figure 1.2). The three till units were 5 ft., 14 ft., and not less than 8 ft. thick and were separated from each other and also capped by various thicknesses of sands and gravel. In the first instance, it was decided to work at depths 2 ft. apart vertically, as close to the base of the upper and middle till units and as near to the top of the middle and lower till units as possible. T1 was sited 1 ft. below the top of the upper till unit since the upper 9 to 10 inches contained small concentrations of cracks and evidence of rootlet penetration which might have seriously affected the true positions of the stones. The work was always carried out at least 3 ft. in from the face of the scar, again to ensure freedom from subaerial disturbances.

Theory of till deposition. It is necessary to discuss the manner in which till has been laid down in order to appreciate the properties yielded in orientation and dip analysis. Hubbert (1937) believed that the glacier base was constantly at pressure melting point and continuous deposition of the basal load took place. Since then, observations made at the ice margins of contemporary glaciers by various/

various workers have added to the understanding of glacial deposition. However, it is still not known exactly what processes do take place under the ice.

As a result of work in Baffin Island, Ward (1952) confirmed that extensive deposition of glacial debris took place below the ice as the debris was released by "ablation of the ice and shearing of more active ice over less active or dead ice". Carey and Ahmad (1961), on the basis of work carried out in Antarctica, Tasmania and Alaska, have shown that basal melting was the most important cause of deposition and that this could only take place to any extent beneath "wet base" ice. Okko (1955) has investigated till being actively deposited in Iceland and has described the newly released material as "water-soaked and porridge-like". There seems to be general agreement that quantities of water are associated with the laying down of till although no obvious indication of water action is apparent in the deposit (Holmes, 1949).

Any body in a flow will tend to align itself in a position of minimum drag provided that it has some suitable axis about which it can rotate. (J.G. Burns, personal communication). That is, within the ice there is a tendency for elongate debris to take up a preferred alignment either parallel or at right angles to the direction of flow of the ice. The component particles of the future till deposit thus inherit the characteristic flow of the glacier and on deposition, this englacial flow fabric is preserved as the till builds up. Not only the pebbles but also the lesser size fractions assume a preferred alignment as has been demonstrated by Sitler and Chapman, (1955), Harrison (1957b) and Ostry and Deane (1963) in their analyses of the component micro particles of tills. "Kinematic analysis" of the macro particles by Harrison (1957b) showed that much of the orientation and dip pattern was inherited from the "transportational environment."

There are two antagonistic viewpoints which attempt to explain the

manner/

manner in which till has been built up. In the first instance, Holmes (1941) has suggested that the till was deposited in a series of thin laminae and continuously "plastered-on"; the constituent pebbles were "lodged" or "glided" into the till matrix during deposition without loss of their original alignment. A minority of the stones was found transverse to the main concentration and these stones were postulated to have been rotating about their axes when thrust into the already deposited till.

Laboratory work by Glen, Donner and West (1957) supported Holmes' theory and added that secondary alignments of the stones were not found in the early stages of movement when only one preferred alignment was apparent. With time and perhaps due to collision between particles, this trend was upset. Holmes (1949) presented additional arguments for his earlier theory and found support from Zeuner (1954) and Flint (1957).

On the other hand, Harrison (1957b) has suggested that deposition of till was almost entirely confined to the deglaciation phases when the debris melted out slowly from the stagnant basal zones of the ice. This was not a new idea and was propounded in not dissimilar form by Goodchild in 1875. Fervent adherence to total deposition through basal under-melting of the ice has been recorded several times by Carruthers (1939, 1940, 1953). In 1953 a seminar was held by The Glaciological Society under the chairmanship of the late Sir J.M. Wardie and the nature of till deposition was discussed. The participants accorded strong approval for the concept of continuous build up of till under active ice and equally strongly dismissed the pleas of Carruthers.

The evidence available indicates that there is a preferred alignment of the macro and micro particles comprising an undisturbed till deposit. The preferred arrangement of the particles may have been inherited from the transporting glacier/

glacier and may represent the direction of flow of the ice which deposited the particular till.

Classification of tills. A simple, tripartite, genetic classification of tills has been suggested. Flint (1957) recognised the existence of lodgment till, ablation till and a third type that had been reworked since its initial deposition.

Lodgment till was deposited at the glacier base by slow melting out of the debris included in the ice and was continuously plastered on to the subglacial floor in successive thin laminae. The component particles tended to retain the preferred alignment imparted by the moving ice when lodged. Due to the weight of the overhead ice, this type of till was very compact and sometimes exhibited a fissile structure. With time, lodgment till might build up to considerable thicknesses.

Ablation till is much less compact, does not build up the same thicknesses of deposit and is believed to have been let down out of the melting ice rather than plastered on. The large amounts of water associated with downwasting of the ice may have flushed out much of the finer clay and silt fractions. Whilst the large stones may have retained their preferred orientations parallel with the direction of ice movement, the smaller grades may have been reorientated during deposition. Glen, Donner and West (1957) have also suggested that when deposition took place from stagnant ice, the dips of the particles in the debris were seriously altered from their original preferences.

Thirdly, reorientated till has been mentioned in the literature. Chamberlin (1894) may have been the first to recognise this reworked till. More recently, attention has again been drawn to this by Hoppe (1952, 1957) in Sweden, Gravenor and Kupsch (1959) in America and Stalker (1959) and Andrews (1963b, 1965) in Canada. In order to explain certain ridged landforms composed of till they have/

have envisaged movement of the already deposited and water-soaked till into subglacial crevasses and holes in the ice by the pressure produced as a result of the weight of the overlying, stagnant ice. The orientation and dip measurements of the pebbles in these deposits are completely unrelated to the ice which originally laid down the till and cannot be correlated with the original ice movement. MacClintock and Dreimanis (1964) have further noted reorientation of existing till by later overriding ice in the St. Lawrence Valley. They recorded disturbances to a depth of 35 ft. below the top of the till and observed the existence of drag folds and "lesser deformation" to a depth of 65 ft. to 70 ft.

Field Methods. It was necessary to work down through the section (Figure 1.2) in a series of six steps as the original face was nearly vertical at the top and declined in gradient towards the stream where it was covered in the lower parts by the material that had fallen down from the upper parts. The lowest site (T17) was at a level below which accumulation was so great that it would have been necessary to clear at least 10 ft. to 12 ft. laterally before the face of the section could have been reached; it was considered impractical to work below this level.

Seventeen different sites approximately 2 ft. apart vertically were predetermined and yielded four studies in the upper till unit, eight in the middle till unit and five in the lower till unit (Figure 1.2).

Analysis of the orientation and dip of the macro particles involved cutting a horizontal platform approximately 2 ft. by 2 ft. and digging out stones not less than 1 cm. long that had a length to breadth ratio not less than 3:2. The actual thickness of till from which the stones were taken was approximately 6 inches at each level. A Finnish Suunto compass, specially manufactured for measuring both orientation and dip was used to measure the alignment and plunge of/

of 100 stones to the nearest 5°. Stones touching one another were rejected. The longest, acceptable pebbles found were 8 cm. to 10 cm. long although the great majority were in the range 1 cm. to 5 cm. The maximum error in measurements of this type has been assessed at 8° in orientation and 6° in dip by Harrison (1957b) and 5° in both orientation and dip by Andrews (1965).

Data plotting. The data were plotted on polar equidistant projections (Figures 2.1 to 2.10), having firstly allowed 10° for each orientation measurement as a correction of magnetic variation west of true north. Orientation is represented by the circumferential scale and dip by the radial scale. The principal ordinates north-south and east-west are drawn in and the radial scale increases in 10° units from horizontal (0° dip) at the perimeter to 60° at the innermost circle. Each stone is represented by a dot on these polar nets and when more than one stone occurs in the same position, a proportionally larger dot is used according to the scale shown in Figure 2.6. Horizontal stones (0° dip) were plotted symmetrically on either side of the projection when they totalled an even number and when an odd number, the additional stone was placed in the hemisphere with the greater number of stones. These diagrams thus show the true spatial position of the pebbles in the tills.

A more rapid, visual impression of the total distribution of the pebbles is afforded by the inner rose shape produced by grouping the observations in 36 x 10° units: this corresponds to the dot distribution. The relative number of stones in each grouping can be judged by the distance of each peak from the centre of the diagram.

The right hand rose diagrams in Figures 2.1 to 2.10 were drawn by rearranging the orientation results symmetrically in each hemisphere. This produces a generalisation of the inner rose shape of the left hand diagrams but affords/

affords a rapid impression of the total alignment of the pebbles. Since the projections are not equal in area, there is an exaggeration of the included area outwards from the centre in both plots.

A value for the preferred orientation and strength of this value in percentages was calculated using vector analysis (Curray, 1956). The orientation trend and strength values are shown for each diagram. Vector analysis gives results that are independent of any a priori reference direction or origin unlike chi-squared testing used by Harrison (1957a,b) and Kirby (1961). For a confidence level of 95% when 100 stones are measured, the strength (vector magnitude) must be greater than 17.3%.

The left hand diagrams all carry three pairs of barbs, marked on the outside circles. The long barb corresponds to the line of preferred orientation and the two shorter barbs to the limit of the arc 45° on either side of the calculated alignment. Thus the two small barbs delimit an arc of 90° across the main concentration of stones; this area will be referred to hereinafter as the main quadrant and is twinned on either side of the plot. The 90° arc between the two parts of the main quadrant will be referred to as the minor quadrant.

Results. The results of the sequence of vertical analyses (T1 to T17) are shown in Figures 2.1 to 2.6 and in Appendix II.I. Excepting T9 and T11, the orientation plots give a reasonably clear and swift general impression of the preferred alignment. This preference varies considerably from level to level as does the strength value. It is apparent that the greater the concentration of stones close to the calculated preferred orientation, the greater is the strength; conversely, the greater the dispersion of stones about the preferred orientation, the lesser is the strength. Also, the greater the number of stones outside the area of the main quadrant (± 45° on either side of the preferred alignment), the lower is the strength. For example,/

For example,

No.	Strength %	No. of ° on either side of pref. ortn...				
		5	10	15	20	45
T7	67	21	38	52	59	90
T17	50	16	32	36	44	79
T10	40	10	15	38	48	72
T4	30	11	15	27	34	69

The data in the above Table and in Appendix II.I may be compared with the results of Wright (1957) who recorded that an average 84% of the stones measured in drumlins lay within ± 40^{o} of the trend (preferred alignment) of these features and 10% to 25% lay in the minor quadrant.

The differences in orientation and strength values within the same till unit are considerable. T1, T2, T3 and T4 show no tendency to any consistent alignment although the range in depth covering them is only 4 ft. T1 and T2 are 33^{o} apart, whilst the range from extremes T3 and T4 is 120^{o} from E30N/W30S to N/S. Strength values vary from 30% to 51%.

The upper 6 ft. of the middle till unit (T5,T6,T7 and T8) yield preferred alignments varying over only 12^{o} from W27N/E27S to W39N/E39S with strength values from 29% to 67%. T9 produces a near amorphous pattern whose strength of alignment is only 8% and therefore no preferred orientation can be judged to exist statistically. T10, T11 and T12 all show more constant alignment in the lower 4 ft. of this till unit, varying over 32^{o} from W35N/E35S to N23W/S23E and strength value range 12% to 40%. However, T11 like T9 has a strength value less than 17.3% and although calculation shows that the preferred alignment would fall between the calculated values for T10 and T12, this is not significant.

In/

In the lower (grey) till unit, very comparable orientation values are found in the upper 4 ft. (T13, T14 and T15) and are followed by a gradual change in direction through T16 to T17. T13, T14 and T15 all fall in a narrow band of 8° from N25W/S25E to N17W/S17E with strength values ranging from 38% to 56%. T16 swings towards north and a value of N4W/S4E is recorded; this swing is continued and the T17 value is N23E/S23W. T16 and T17 have strength values of 51% and 50% respectively. The strength values of the orientations in the lower till unit are consistently higher than in the other two till units excepting T13 which only produces a value of 38%.

The shapes of the orientation plots vary as much as the alignment and strength values. The range is from the smooth, propellor-like T7 to the multi-peaked and fragmented T9. Between these there is a range exhibiting intermediate fragmentation where many of the plots produce a moderately high strength of alignment. For example, T14 - 56%, T10 - 40%, T13 - 38%.

<u>Cross peaks.</u> In all seventeen plots lesser peaks are found in the area of the minor quadrant. Closer inspection indicates a tendency for the peaks of the minor quadrant to be fragmented to the same extent as the fragmentation of the main quadrant peak. For example, T14 has three peaks in the main and minor quadrants, T4 - three, T5 - three and T7 - two.

Observation of a cross peak at right angles to the main peak is no new phenomenon. However, it is surprising to find that where there are several parts to the main peak, there is usually an equal number in the cross peak. If the several peaks in the main quadrant are paired with those in the minor quadrant a difference of approximately 90° is often found. For example,/

For example,

No.	Main Quadrant	Minor Quadrant	Difference (°)
T5	280/100	180/0	100
	300/120	200/0	100
	320/140	240/60	80
T7	350/170	260/80	90
	310/130	220/40	90
T13	330/150	230/50	100
	180/0	270/90	90
T14	350/170	260/80	90
	190/10	280/100	90
	330/150	250/70	80

Horizontal variations. It was decided to examine the variation horizontally at the levels T1, T2 and T3, by carrying out analyses both along and also into the working face of the section. These analyses all fall in the upper till unit.

The section faces approximately due east and the studies into and along the section have been designated accordingly W, N and S after the number of the level, e.g. T2(N). The original study at each level falls between the N and S studies across the face and nearer the outside of the scar than the studies designated W. The horizontal distance between the original analysis and the three extension studies at each of the three levels was 2 ft. to $2\frac{1}{2}$ ft. The results are given in Figures 2.7 to 2.9 and in Appendix II.I.

The three additional analyses at level T1 produced two - T1 (W) and

T1(S)/

T1 (S) - with preferred pebble alignments within ± 4° of the original N37W/S37E; strength values were 60% and 39% compared with 51%. T1(N) showed little similarity with the others and was approximately 50° different in calculated orientation with a strength value of 35%.

T2(N) and T2(S) produced values covered by +5° from the original W20N/E20S of T2 whilst their strength values of 55% and 49% compared with 40% T2(W) was only slightly more divergent at W35N/E35S and strength value of 31%.

The further studies at level T3 showed remarkable parity and were all within 10° of the original E30N/W30S value. Strength values varied considerably from 24% to 66%.

Vertical variations in a depth of six inches.

Normally 100 stones would be yielded from the 2 ft. x 2 ft. working platform in a depth of 5 inches to 6 inches. At level T14, it was decided to try and work in as shallow a depth as possible by exposing the pebbles through gentle scraping instead of by gouging. It was also hoped that it might be possible to isolate each of the triple peaks of the original T14 analysis.

It was found that 100 acceptable stones could be obtained in a depth of 1 inch to 1½ inches. After levelling off this working, the process was repeated twice enabling three analyses to be made in the normal depth required for one. The results T14(A), T14(B), and T14(C) are shown in Figure 2.10 and Appendix II.I.

The attempt to isolate the triple peaks failed. In T14(A) triple main and cross peaks, approximately at right angles to each other were found; T14(B) yielded double sets of peaks whilst T14(C) produced a triple main peak with a double cross peak. All three calculated orientations were within ± 20° of the original T14 value although the strength value range was 24% to 56%.

Strict objectivity in method was practised throughout all 29 analyses. In the case of the latter 12 comparative analyses, the data were not plotted until all/

all the analyses at each level had been completed. Accordingly, the results seem more than coincidence.

One main problem was the continued evidence for clear fragmentation in the analyses at the T14 level. Flow can only take place in a medium in one direction at one time (J.G. Burns, personal communication). That is, three different lines of flow which would align particles in each of the three positions cannot take place in the same medium at the one time. Yet it is obvious that in three cases out of four that this pattern emerges from the investigations.

Statistical analysis of the multiple peaks. The chi-squared test of goodness of fit devised by Pearson (1922) was applied to the four T14 analyses to help discern whether the fragmented orientation plots were real or simply part of a more composite and general lobe.

In order to have as many classes as possible, the 5° groupings were used. The arc across the main peak was divided into the same number of parts as there were fragmentations; the mean (expected) number of stones at each interval within each part was calculated. The difference between this and the actual number at each interval was found and squared; the sum total for each part was noted and divided by the calculated mean. Addition of the values for each of the parts of the main peak gave the chi-squared value for the arc.

$$X^2 = \frac{\sum (0 - E)^2}{E}$$

where

E = expected value.

0 = observed value.

This calculated value was compared with those in Tables (Fisher and Yates, 1938) to determine whether it was significant at the 95% level of probability. If it had been, this would have suggested that the arc being examined did not correspond to the several calculated means and was not significantly fragmented. In all four instances a non-significant result was found.

A/

A converse attempt to approximate the data to one mean (one peak) also produced values ~~now~~ not significant at the 95% level of probability. In other words, the peak could not be shown to be either significantly fragmented or significantly one.

Comparative plotting and calculation. In all 29 analyses the rose shapes of both the left and right hand diagrams in Figures 2.1 to 2.10 were produced by grouping the original data in 10° classes. The reason for this generalisation was to take into account any possible error in measurement of orientation which Harrison (1957b) and Andrews (1965) have assessed at a maximum of 8° and 5° respectively.

The grouping system practised throughout Figures 2.1 to 2.10 involved plotting stones in the arc 5° before to 4° after each 10° value at the 10° position. For example, 0° = all the stones from 355° to 4°: in the case of the right hand diagrams, 0° = 180° = all the stones from 355° to 4° + all the stones from 175° to 184° divided by two and plotted symmetrically at 0° and 180°.

The four orientation diagrams T14, T14(A), T14(B) and T14(C) were redrawn using a 10° grouping of 4° before to 5° after each interval and are compared with the original diagrams in Figure 2.11. It can be seen that the basic fragmented form is approximately the same in three cases out of four. In the case of T14(A) one of the peaks in the minor quadrant has been absorbed in the replotting: the two peaks that have merged when replotted were only separated by an arc of 20° in the original plot. The recalculated orientations varied 3° to 6° from the original values and the strength values were exactly the same in two cases out of four.

Figure 2.12 was constructed using the absolute 5° groupings for the same four analyses as Figure 2.11 and also T1(W) and T7 which are two of the strongest and most concentrated results. Again, the rose shape is basically the same as the original 10° plots although it varies in detail of fragmentation. Calculated/

Calculated orientation and strength values show only small differences when compared with the 10° groupings.

If 20° groupings are used (Figures 2.13, 2.14), much of the fragmentation in the rose diagrams disappears although both strength and orientation value remain close to the original 10° figures. Two types of 20° plot were made for the four T14 studies, comparing groupings 10° before to 9° after the interval with those 9° before to 10° after the interval.

When the 400 measurements at the T14 level were added together and redrawn in rose diagram form, the pattern obtained in Figure 2.15 emerged. Whilst fragmentation still existed, it was noticeable that the main composite peak was spread over an arc of 60° and was being filled out by the additional data.

The results of the various grouping studies are compared in Appendix II.II. Only a few degrees difference in orientation and strength values results from the various plotting exercises although the shapes of the rose diagrams (Figures 2.11 to 2.15) become less fragmented as the groupings increase in size. It is thus obvious that too much emphasis should not be placed on the minor details of these rose diagrams, particularly when the fragmented parts are only separated by narrow arcs.

<u>Sample size.</u> Since the work of Holmes (1941) it has been standard practice to measure 100 stones in each orientation and dip analysis. Occasionally, individual workers have carried out studies using fewer stones. For example, Wright (1957) and Hoppe (1952) usually measured 50 stones in all their analysis whilst West and Donner (1956) also measured 50 stones when a preferred orientation was "well marked". In one instance, Harrison (1957b) measured 410 stones and concluded that any randomly chosen three increments of 25 consecutive measurements were sufficient to define the direction of preferred orientation; successive increments/

increments of 25 stones only changed the shape of the plot but not the position of the preferred alignment. Harrison's work was the only study found which began to investigate the problem of representative sample size in orientation studies.

Six plot sets of data were recalculated using the first 5, 10, 25 and 50 stones measured in each case (Appendix II.III). The selection was made to include two of the strongest, two intermediate and two of the weakest (most dispersed) plots. In the case of the two strongest plots, T1(W) and T7, one of the intermediate plots T15, and one of the most dispersed plots, T5, there is virtually no difference in calculated orientation although strength values vary more when 25,50 or 100 stones are used. T2 produces slightly greater variations in orientation whilst strength values are nearly constant; the 100 and 50 calculations of T3(N) are comparable, with greater divergence appearing when only 25 stones are measured.

If the first five or ten stones are used, a good approximation of the alignment found when 100 stones are used can be obtained in the case of T1(W), T7, T15, and T5. 10 stones still produce comparable results in the case of T2 whilst T3(N) yields no trend consistent with the 100 and 50 values.

Twelve further composite recalculations were made (Appendix II.IV). The three most comparable sets of results of the four analyses at levels T1, T2 and T3 are compared with the original values and the sum total of all four sets of data. Orientation and strength values vary over a range not greater than ± 10° and ± 10% respectively from the first available figures.

The other analyses (Appendix II.IV) chosen for recalculation were either from the same horizon or show similar alignment in the original 29 studies. Values obtained are closely comparable with the individual component plots.

Analysis/

<u>Analysis of dip.</u> Andrews (1965) has drawn attention to the lack of study of the dip of the pebbles measured in macrofabrics analysis. For the present investigation, the dip values obtained from the field measurements were plotted in histogram form (Figure 2.16 and Appendix II.V). It is immediately apparent that there is a concentration in the low value areas. The median value is 5° on 13 occasions, 10° on 15 occasions and 15° once in the 29 analyses.

Modal analyses showed that 5° was most common in 24 instances, 10° in 4 instances and horizontal (0°) once.

Neither median nor modal values succeed in distinguishing the individual peculiarities of the several levels apparent in the histograms. Examination of the mean dip (Appendix II.VI) produces subtler differences with a range from 7.5° to 17.5° and an overall mean value of 11°. This range compares with a mean value of 11° found by Holmes (1941), 10° by Hoppe (1952), 14° by West and Donner (1956) and 23° found by Wright (1957). The same four workers found that an average of 74%, 77%, 62% and 34% of all stones measured dipped at angles of 10° or less (n.b. Hoppe worked in moraines and Wright in drumlins). These values compare with an average of 66% found dipping 10° or less in the present study. The assertion by Holmes (1941) that the number of stones found with dip values greater than 20° is a minority and falls off with increasing degree of dip is also borne out (Appendix II.V).

There is a noticeable increase in the dip of the pebbles at the top (T5) of the middle till unit compared with the values found in the upper till unit. With one exception (T7), all the mean values obtained in the middle till unit are greater than those in the lower till unit. The twelve studies in short distance variation at the same level show little similarity with the original analyses at each of the four levels T1, T2, T3 and T14.

Holmes/

Holmes (1941) believed that the dips of the stones in the minor quadrant were greater than in the main quadrant. This point was examined and yielded results in general agreement with Holmes' statement. In 25 cases out of 29, the mean dip in the minor quadrant was $1\frac{1}{2}$ to 2 times as great as the dip in the main quadrant (Appendix II.VI).

734 of the 2900 stones measured in the analyses lay in the minor quadrant. Although there is a tendency to fine minor quadrant stones dipping at greater angles than main quadrant stones, it is incorrect to assume that all the steeply angled stones lie in the minor quadrant. 2 stones in 2900 dip at 60° and neither is located in the minor quadrant: 5 dip at 55° and 4 are found in the minor quadrant, 13 at 50°(5), 23 at 45°(9), and 42 at 40°(17). (Also Appendix II.VII).

There seems to be no association between low orientation strength value and high dip value although there is relationship between strength and the number of stones in the minor quadrant. T3(N) and T14(B) are two of the most dispersed plots with strength values of 24% and 26% respectively; although both have 32 stones in the minor quadrant, only 8 and 3 stones respectively dip more than 20°. At the other end of the strength scale, T3(W) = 66% and T7 = 60% and have 2 out of 8 and 1 out of 10 of their minor quadrant stones dipping at angles over 20°.

Dip as an index of direction of ice movement. The landscape of the area around Fala, Midlothian, bears evidence of moulding by ice which is believed to have moved in a direction approximately south-west to north-east. Burke (personal communication) has found that locally the preferred alignment of the topography is W35S/E35N. Only six (four at the same level) of the orientation studies begin to approximate to this alignment. The other 23 plots fall across the corresponding north west/south east quadrants. Orientation analysis only provides evidence/

evidence of a preferred alignment of stones in a particular direction along which the ice has flowed. In itself it does not elucidate the actual direction of movement of the ice.

It has been generally accepted since the work of Holmes (1941) that a tendency exists for a majority of stones to dip towards the source from which the ice came. Examination of the inner rose shapes in the left hand diagrams (Figures 2.1 to 2.10) shows how erratic dip disposition is even in the north west or south east quadrants. Sometimes the distribution is approximately equal and in other instances it is distinctly skew.

In the upper till unit T1 has an approximately even distribution north-west/south-east, T2 shows distinct south-east bias, T3 a north-east tendency and T4 a more due south trend. The three supplementary analyses at the T1 level are all approximately even in their distribution north west/ south east; T2(N) and T2(W) tend towards south-east like T2 but T2(S) is disposed distinctly towards north-west. T3(N) and T3(W) produce symmetrical patterns whilst T3(S) is very heavily biased north-east like T3.

T5, T7 and T9 in the middle till unit display an even arrangement although T6 and T12 fall south-east, T8 and T10 tend north-west and T11 leans towards south-west. In the lower till unit, T13 trends south-east, T14 and T15 north-west, T16 due south and T17 north-east. T14(B) and T14(C) fall dominantly south whilst T14(A) is approximately even in disposition.

The foregoing evidence shows a lack of consistency in preferred direction of dip even at the same level in the section. When there was reasonable parity in orientation at successive levels such as T5, T6, T7 and T8 or T13, T14 and T15, the preferred dip direction was inconsistent. These observations force the conclusion that in this study dip analysis is too erratic to help determine the actual direction of ice movement.

Interpretation/

Interpretation and Conclusions. The foregoing investigations have provided evidence of some greater or lesser degree of order among the elongate pebbles included in the three till units. Variability in preferred orientation was considerably greater vertically than laterally over the short distances worked: in fact variation within the same till unit was often greater than variation between units. Although strength values were good measures of concentration or dispersion of the stones about the preferred alignment, differences between strength values at the same level were too large, even when the orientation values were comparable, to make use of these figures as differentiating criteria. Obvious changes in orientation between levels were not reflected in the strength values.

Peaks transverse to the main preferred alignment were found in all cases. There appeared to be a tendency for these minor quadrant peaks to be disposed at right angles to the peaks in the main quadrant. Fragmentation of both main and minor quadrant peaks was noted in 5° and 10° plotting and although the visual impression suggested multiple main peaks with matching minor peaks, the nature of the data was not adequate to withstand statistical examination which might have confirmed or disproved this trend; the difference in magnitude between the topmost and lowest points in the fragmented arcs was not great enough when only 100 stones were used.

When all 400 stones measured at the T14 level were added together, fragmentation was still apparent although much more composite peaks were beginning to emerge in both main and minor quadrants. This might suggest that if many more observations had been available a single, composite peak would have resulted in both quadrants. It was also found that caution should be exercised when interpreting the shapes of the rose diagrams.

Orientation and dip analysis has developed based on aximatic-like adherence/

adherence to the measurement of 100 stones. The present investigations show that 50 stones would certainly have provided very comparable values and that 25 stones might have yielded almost as good results. Even measurements of 5 or 10 stones could be sufficient in some cases. At the other end of the scale, no really different result was found when all four analyses at the same level were added together. When vector analysis was used to calculate preferred orientation and strength values, the method of grouping the data and size (up to 20°) of these groupings made little difference to the final orientation and strength values when they were compared.

These findings are important as they show that comparable results could have been obtained in much less time. This means that the research output over a given period could be doubled theoretically and perhaps increased by as much as a factor of four. Since it takes 4 to 6 hours to obtain 100 suitable stones for analysis and a further 2 hours to plot the data and calculate orientation and strength values, knowledge that 50 stones are adequate and that 25 stones will produce a good approximation of the same trend is important.

The full usefulness of measuring the dip of the pebbles was left unanswered by the analysis. Assessment of the mean dip produced best comparative results. The differences between mean dip at any one level where there were several studies were more often as great as the differences between levels. The middle till unit stands out from the upper and lower till units on this basis. If the number of stones dipping at angles greater than 20° is counted (Appendix II.V), it can be seen that sharp increases occur at the top and in the lower 4 ft. of the middle till unit. Stones in the minor quadrants dip more steeply than the stones in the main quadrants.

Preferred/

Preferred direction of dip has been used to determine the direction from which the ice came in some published studies. In 10 of the 29 analyses of the present investigation there was no preferred direction. Where multiple analyses were undertaken at the same level, inconsistencies of preferred dip between these existed in three cases out of four. In this study dip analysis provided no adequate aid to interpretation of the possible direction of ice movement whose trend was indicated by the preferred orientations.

However, mean dip measurements are comparatively homogeneous and seem to indicate that the tills investigated belong to the lodgement category. The average dip of 100 stones at any one level was accomodated in the range 7.5° to 17.5° and 11° was the mean value of the 2900 stones measured. 66% of all stones measured dipped at angles of 10° or less and above 20° the number of stone decreased considerably. In ablation till much higher dip averages would be expected and certainly more than 2 stones in 2900 would be expected to dip at angles of 60° or more. Reorientation of deposited till has only been suggested for moraine-like ridges in the literature; since the section in which the analyses were carried out was not in such ridges the possibility of reorientation after deposition was ruled out.

Stone orientation analysis carried out in tills by Holmes (1941), Virkkala (1951), Dreimanis and Reavely (1953), West and Donner (1956) and Kaiser (1962) has confirmed the existence of a preferred alignment of the constituent pebbles in the direction of suspected former ice movement. In 27 of the 29 analyses of the present investigation a statistically significant number of stones showed a preferred orientation and it is believed that these various directions are evidence of former ice flow which varied very considerably in direction as the till units were built up. No regular or consistent rate of change with depth was discernible.

Other workers have suggested that much of the landscape of this part of East Lothian near Fala was affected by ice moving south-west/north-east. This in no way/

way excludes the possibility of ice also having moved in other directions across the area and having deposited tills bearing evidence of such a movement. It has been noted that 23 of the 29 studies show movement to have been common at approximately right angles to a south-west/north-east direction.

It was felt that since preferred dip analysis yielded such inconsistent results, no real dependence could be made on it. Accordingly, on the diagrams and in the appendices, orientation has been shown as a trend, e.g. N30W/S30E; the system adopted was to quote the value with "north" in it first.

The results clearly demonstrate the limitations in the interpretation of orientation and dip analysis. No attempt is made to deny that each analysis in the present study indicates former flow of the ice associated with building up of the particular level of the till at which the analysis was carried out. There may be several alignments discernible in a single till unit only a few feet thick and no one analysis can be accepted as representative of a till of any thickness.

FIGURES 2.1 - 2.16

2.1-2.10	Orientation and dip diagrams.
2.11	Comparative orientation rose diagrams based on 10° groupings of the stones.
2.12	Comparative orientation rose diagrams based on 5° groupings of the stones.
2.13-2.14	Comparative orientation rose diagrams based on 20° groupings of the stones.
2.15	Composite orientation based on 400 stones.
2.16	Histograms of dip frequencies.

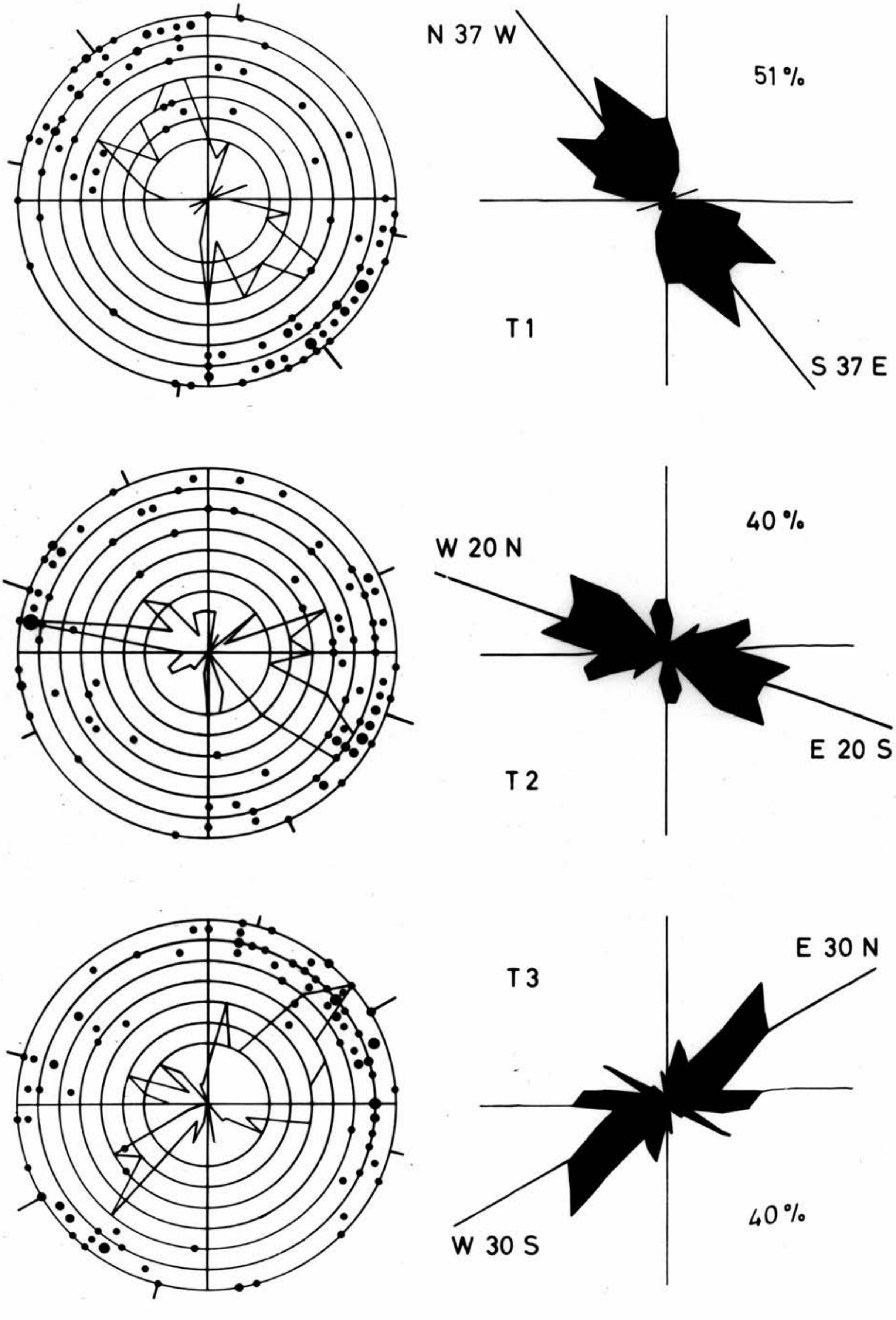


FIGURE 2.1

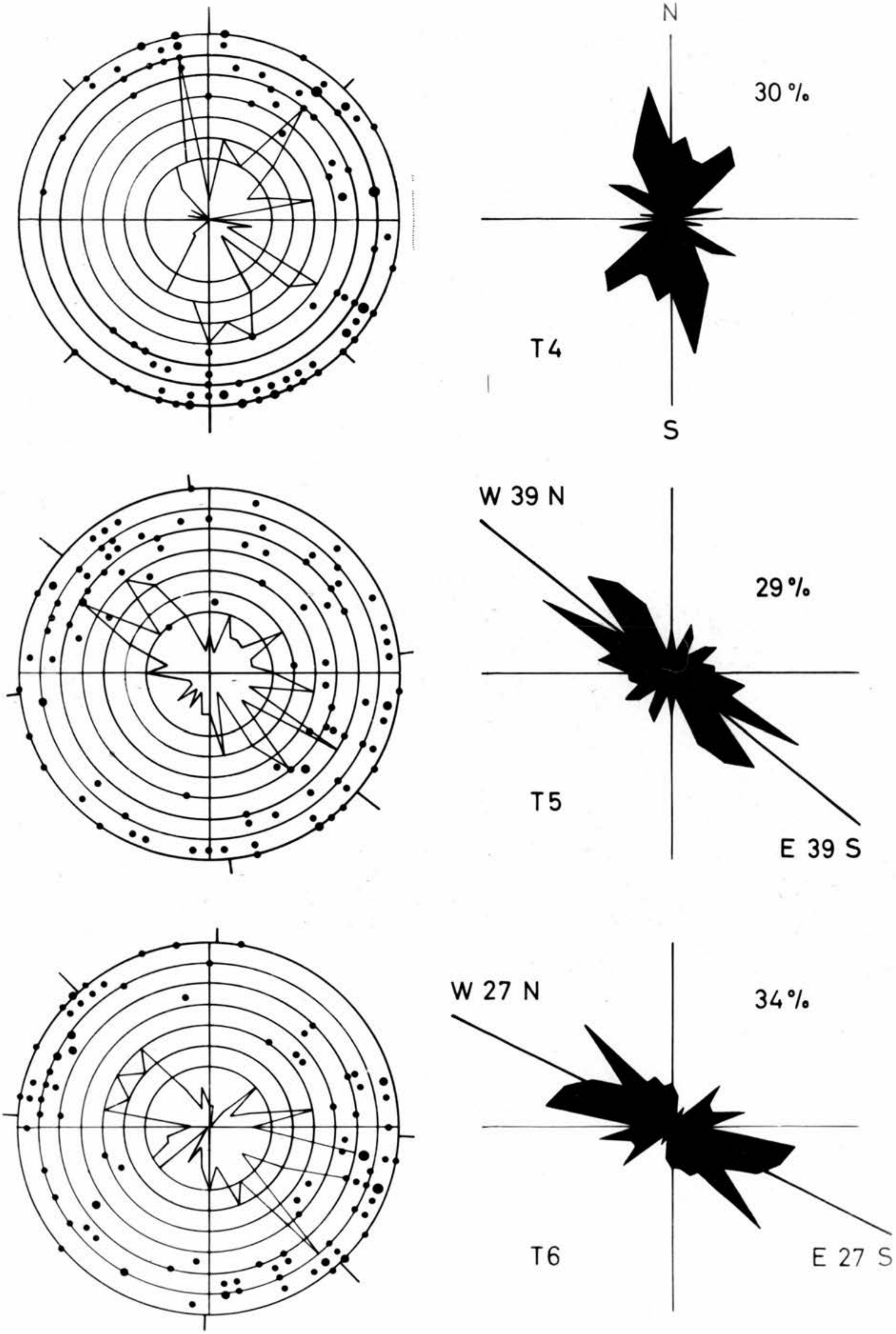


FIGURE 2.2

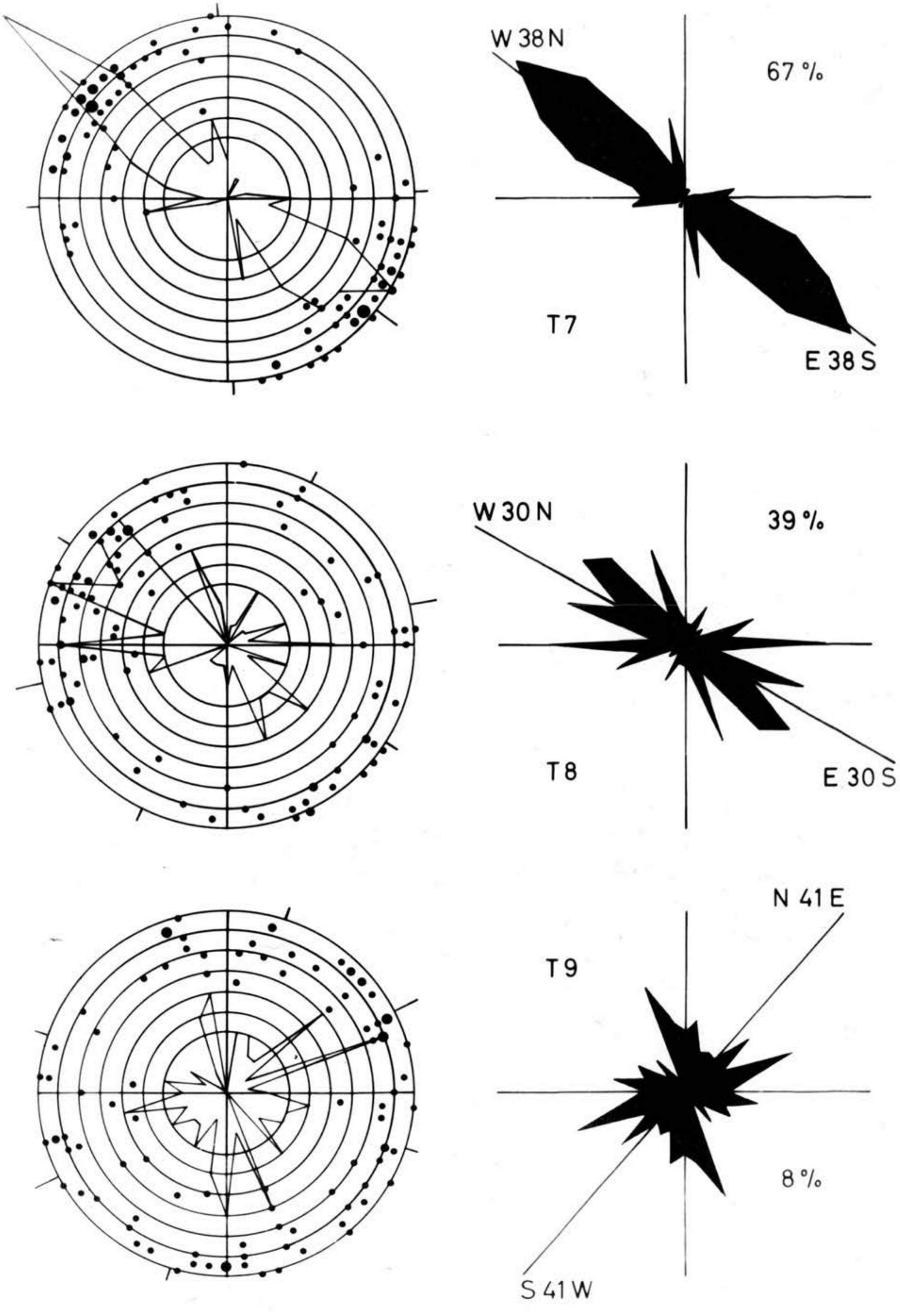


FIGURE 2.3

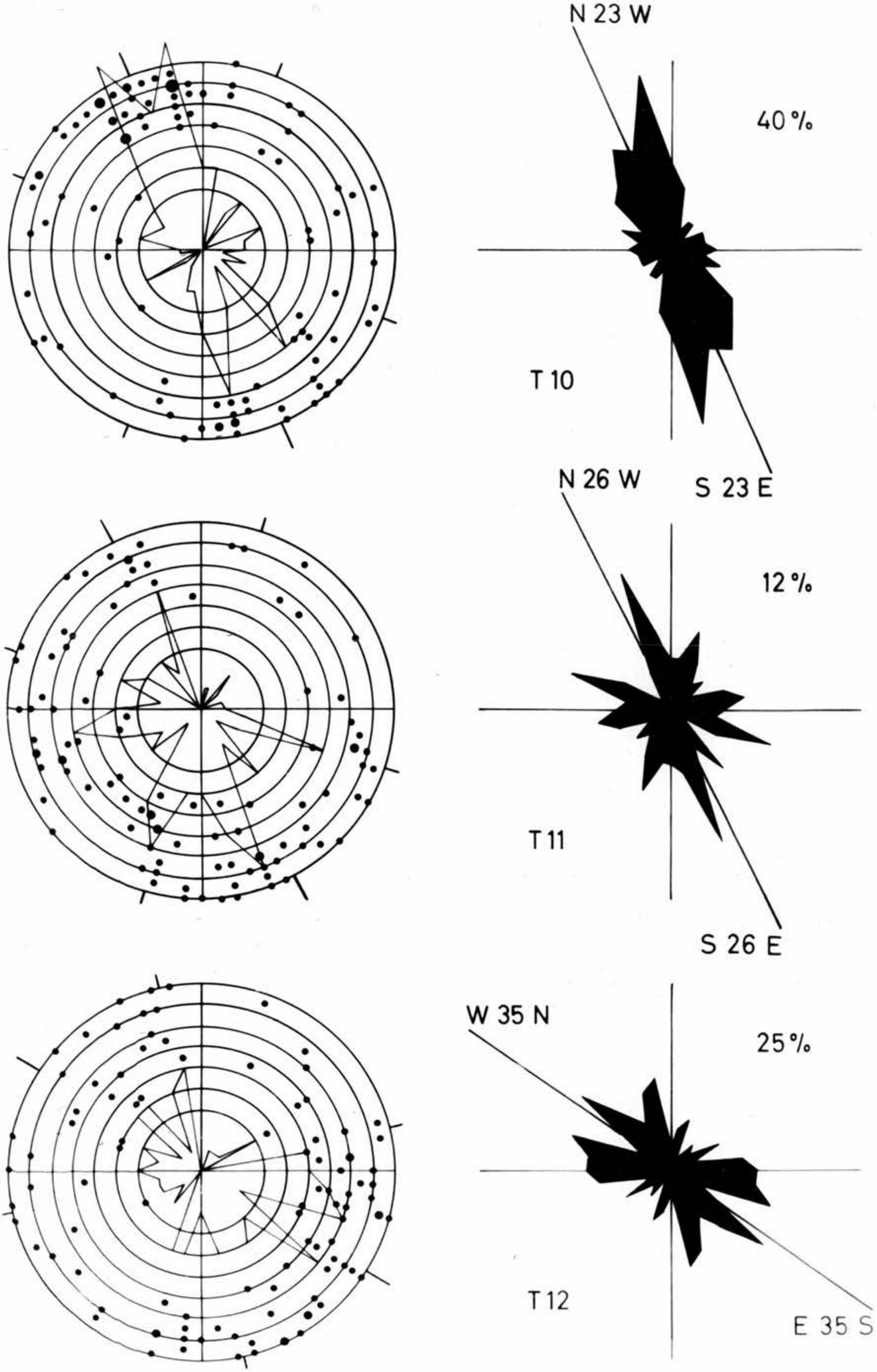


FIGURE 2.4

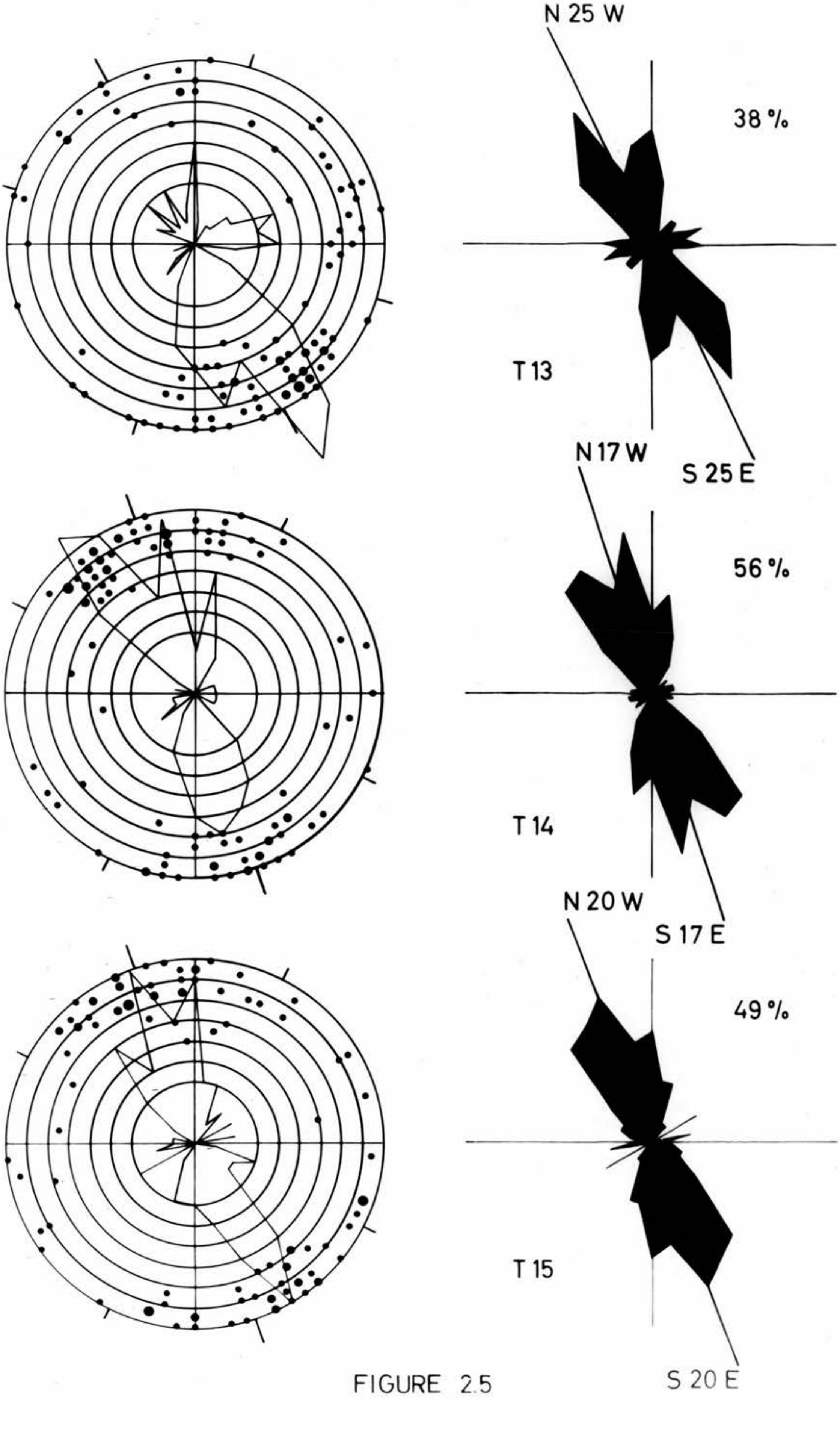


FIGURE 2.5

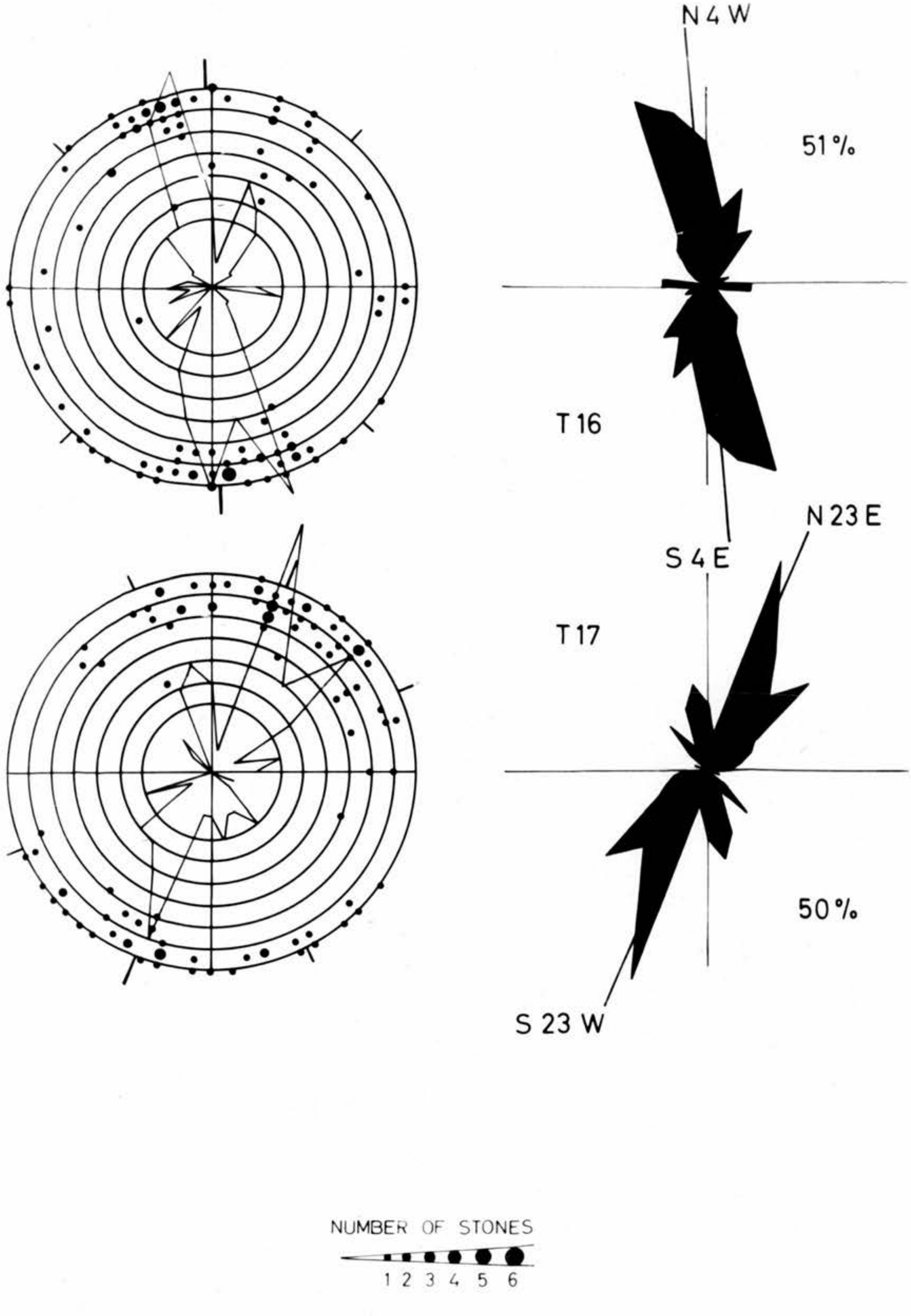


FIGURE 2.6

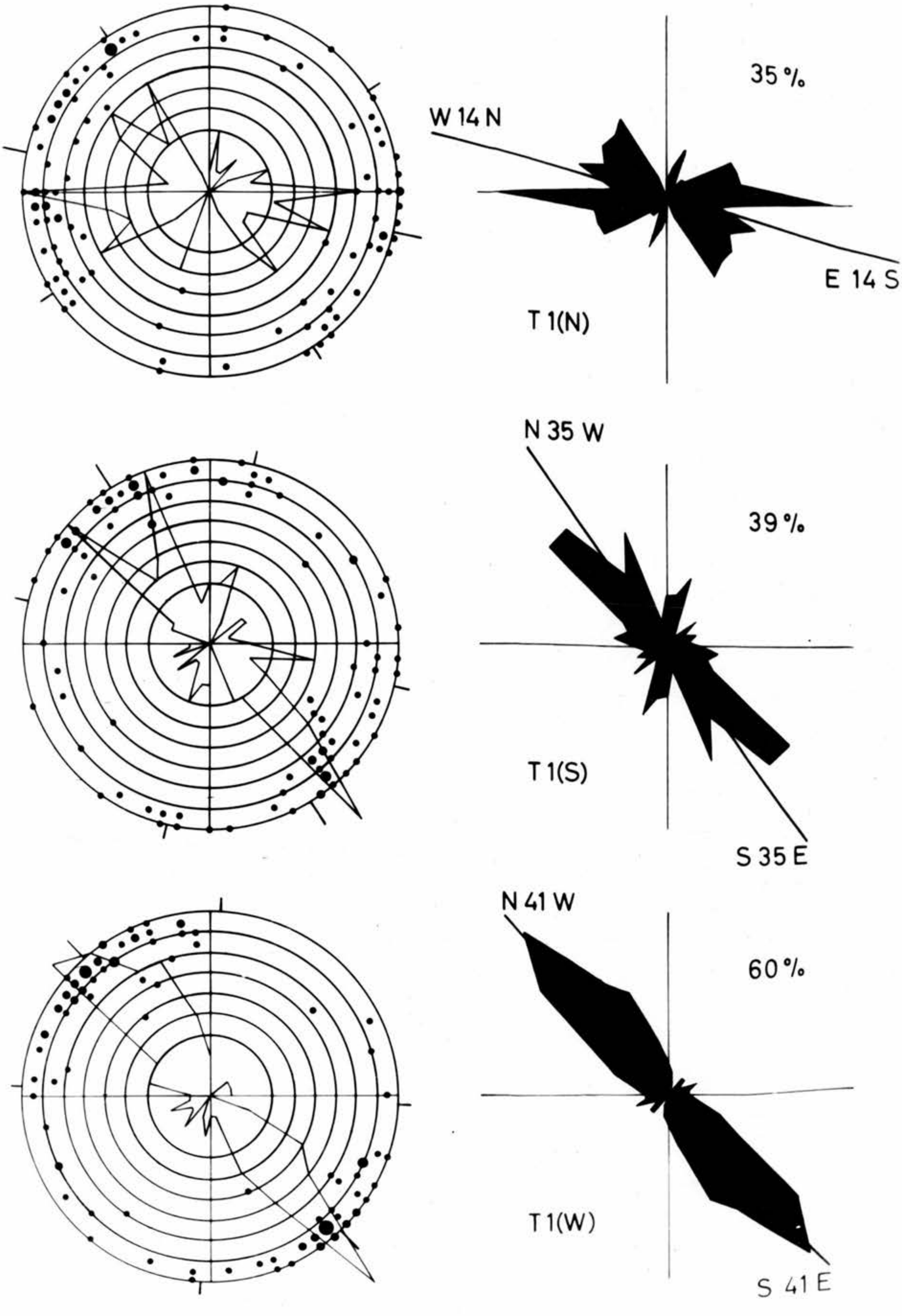


FIGURE 2.7

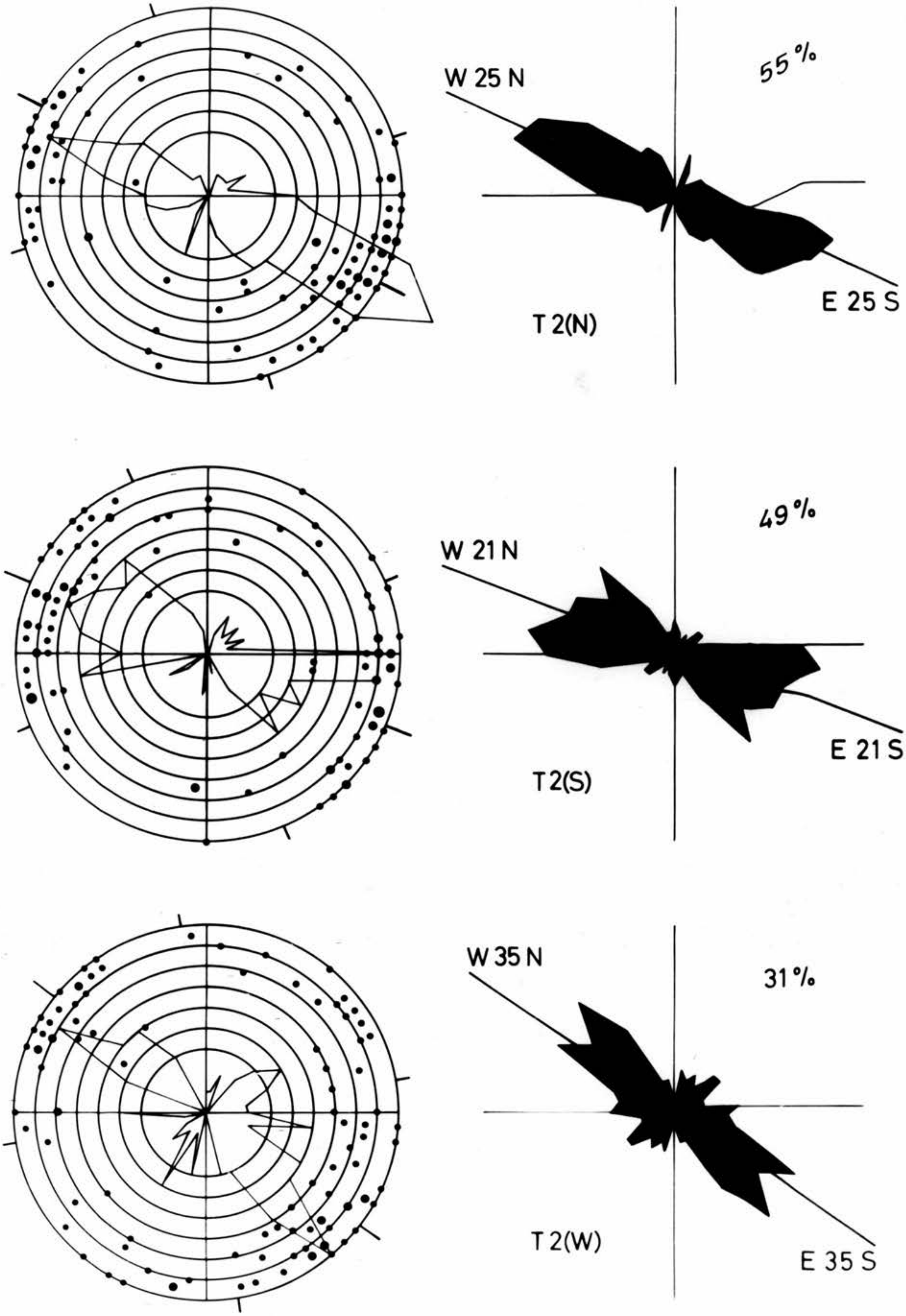


FIGURE 2.8

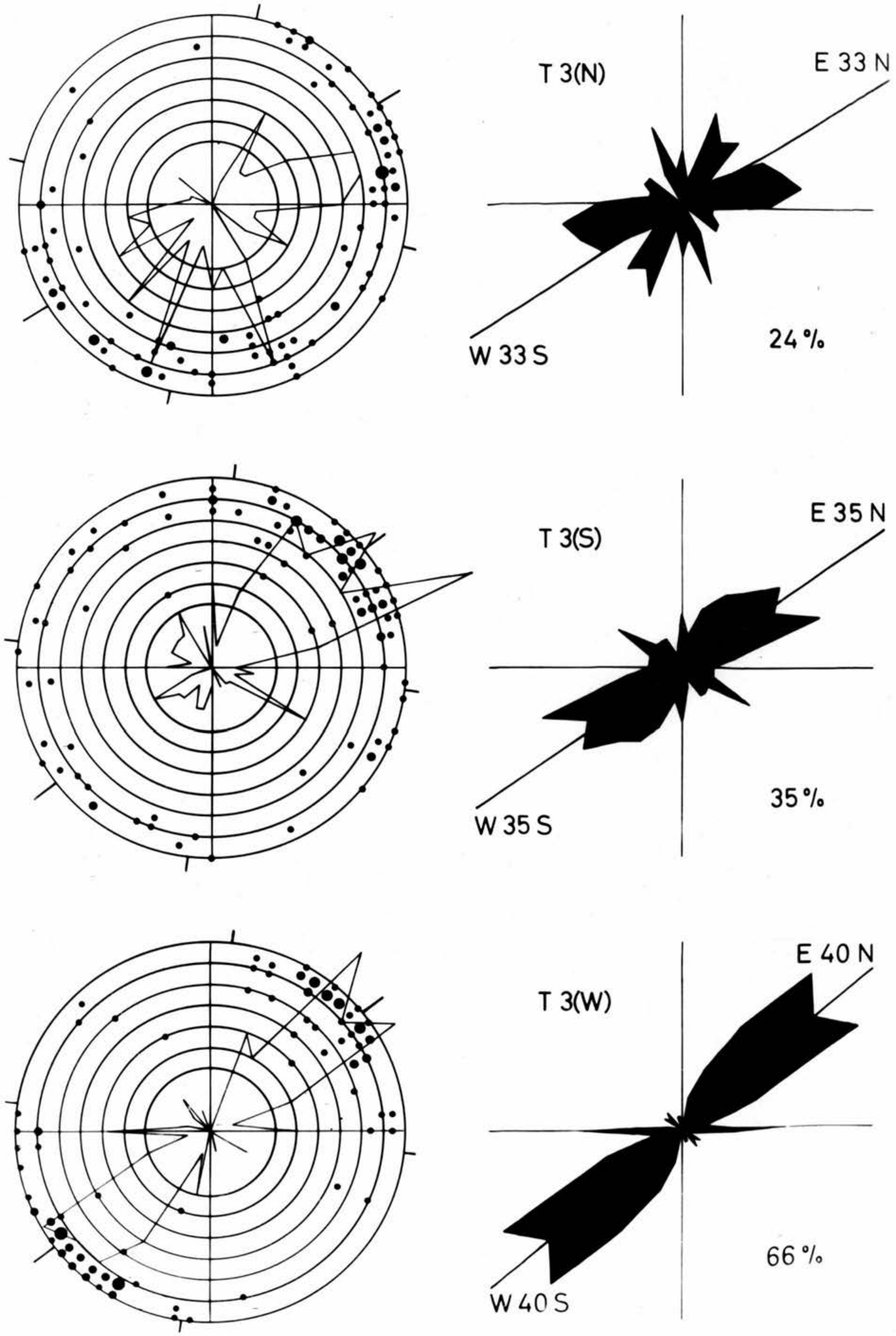


FIGURE 2.9

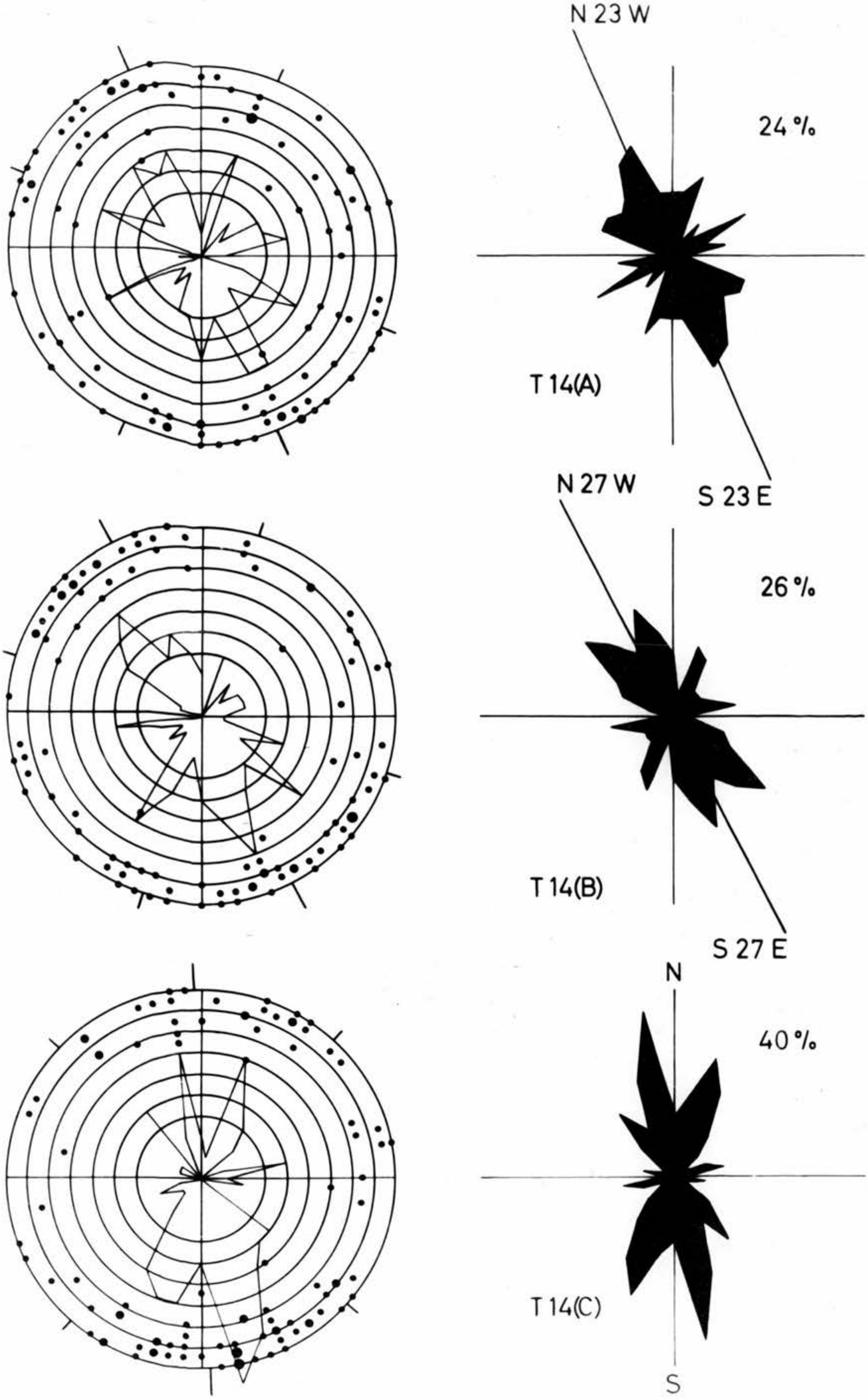


FIGURE 2.10

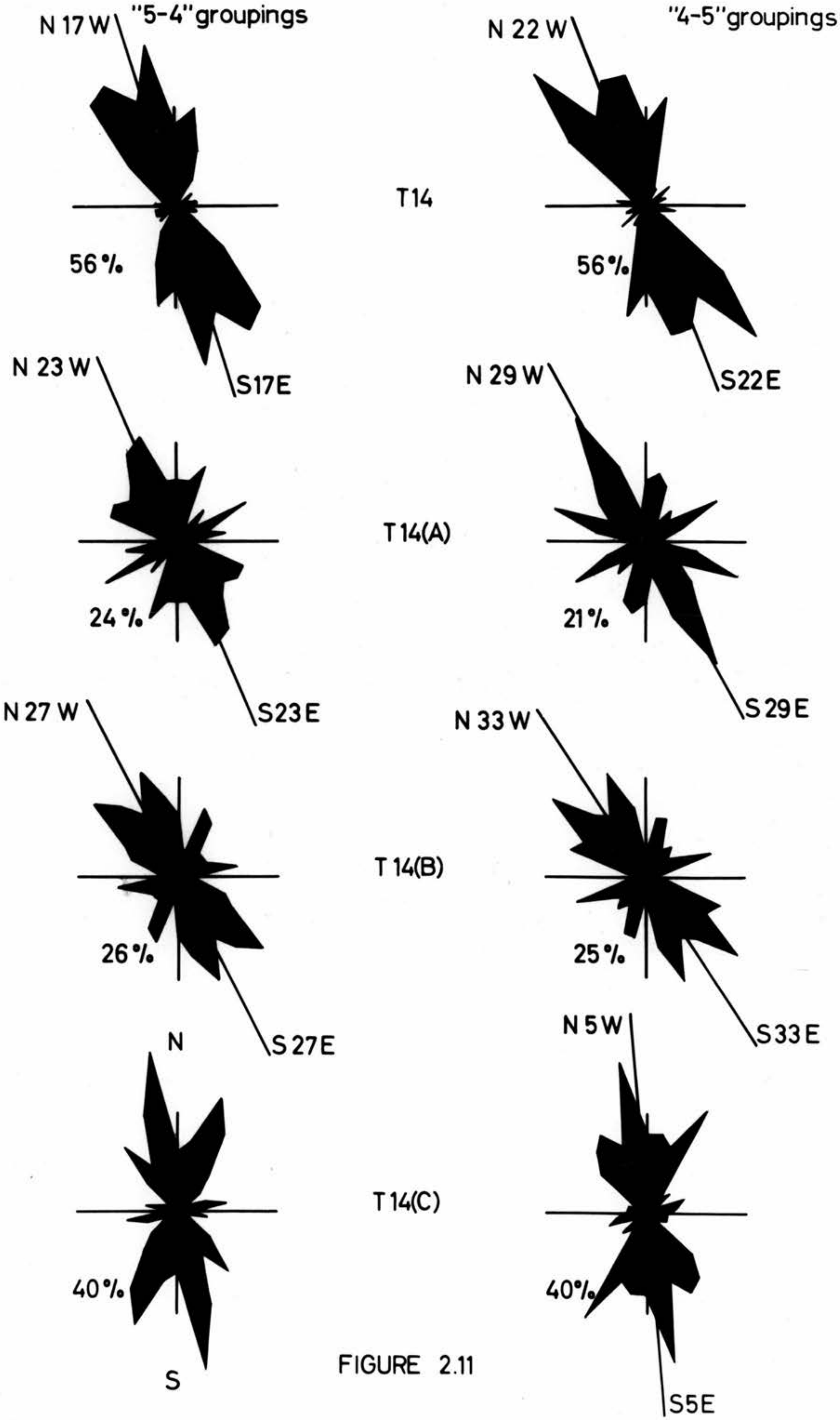

"5-4" groupings
"4-5" groupings
N 17 W
S17E
56 %
N 22 W
S22E
56 %
T14
N 23 W
S23E
24 %
N 29 W
S 29 E
21 %
T 14(A)
N 27 W
S 27E
26 %
N 33 W
S 33 E
25 %
T 14(B)
N
S
40 %
N 5 W
S5E
40%
T 14(C)

FIGURE 2.11

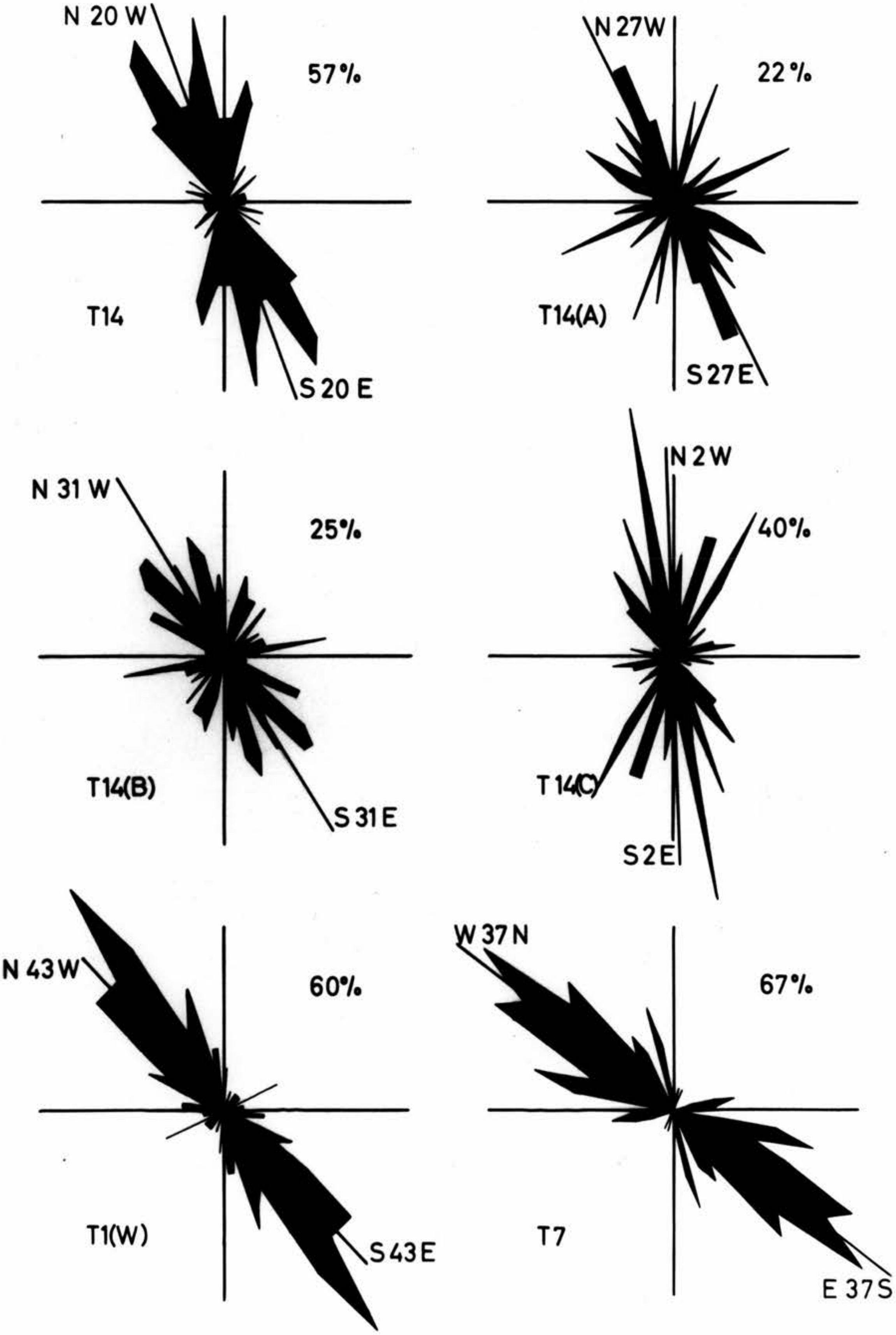

N 20 W
57%
T14
S 20 E
N 27W
22%
T14(A)
S 27E
N 31 W
25%
T14(B)
S 31 E
N 2 W
40%
T 14(C)
S 2 E
N 43 W
60%
T1(W)
S 43 E
W 37 N
67%
T7
E 37 S

FIGURE 2.12

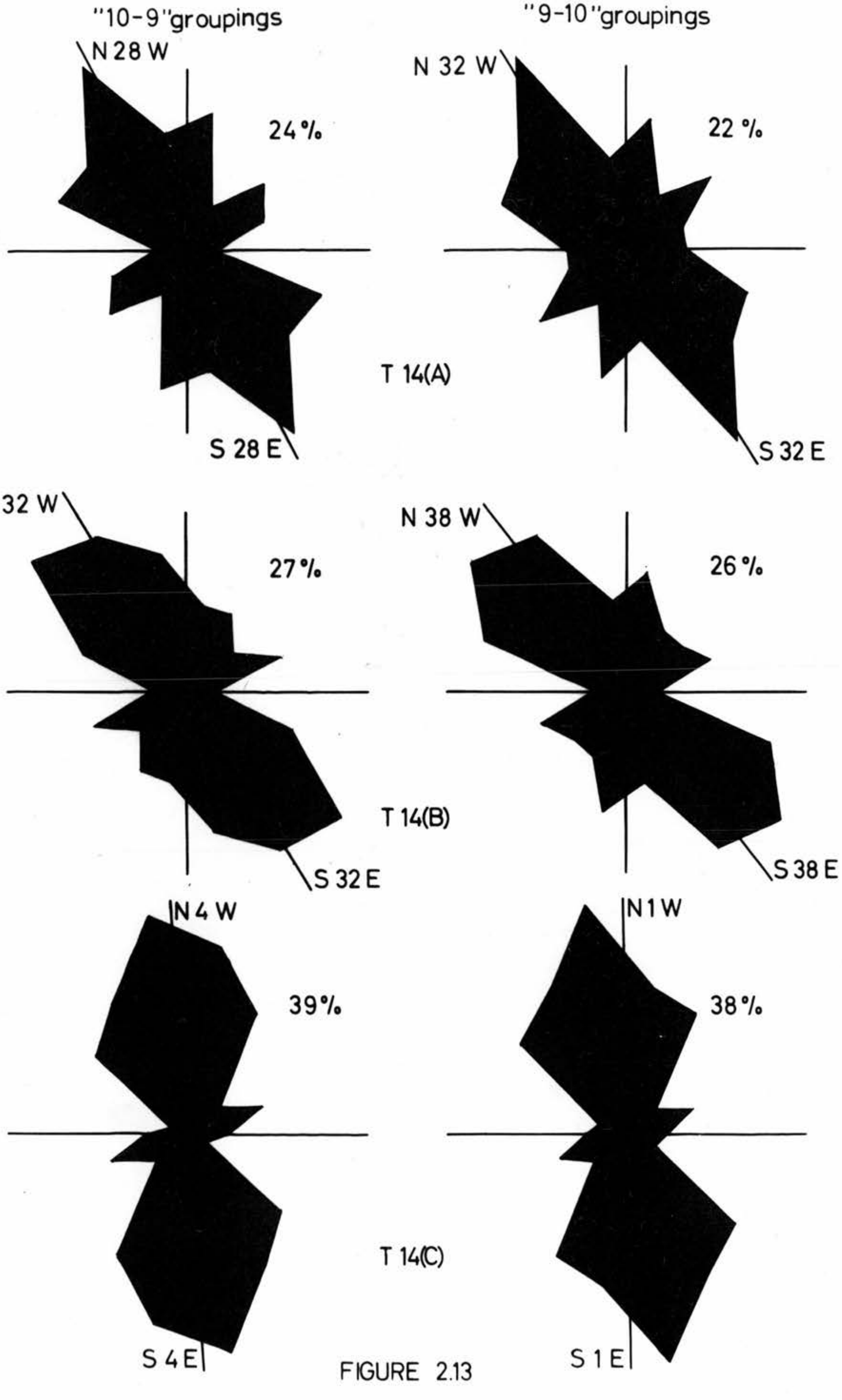

"10-9"groupings
"9-10"groupings
N 28 W
24%
S 28 E
N 32 W
22 %
S 32 E
T 14(A)
N 32 W
27%
S 32 E
N 38 W
26 %
S 38 E
T 14(B)
N 4 W
39%
S 4 E
N 1 W
38%
S 1 E
T 14(C)

FIGURE 2.13

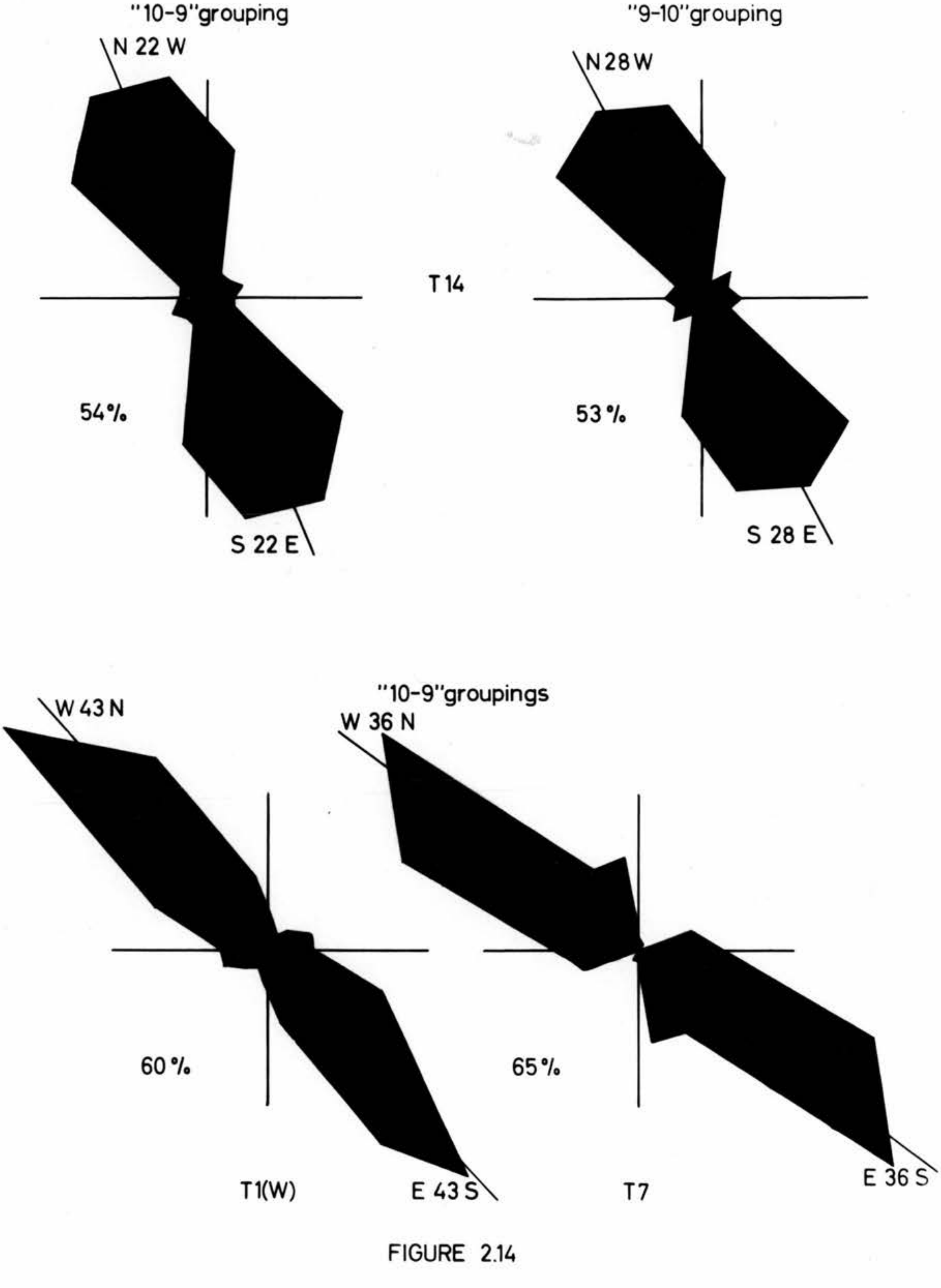

"10-9"grouping
N 22 W
S 22 E
54%
T 14
"9-10"grouping
N 28 W
S 28 E
53 %
"10-9"groupings
W 43 N
E 43 S
60 %
T1(W)
W 36 N
E 36 S
65 %
T7

FIGURE 2.14

COMPOSITE ORIENTATION BASED ON 400 STONES

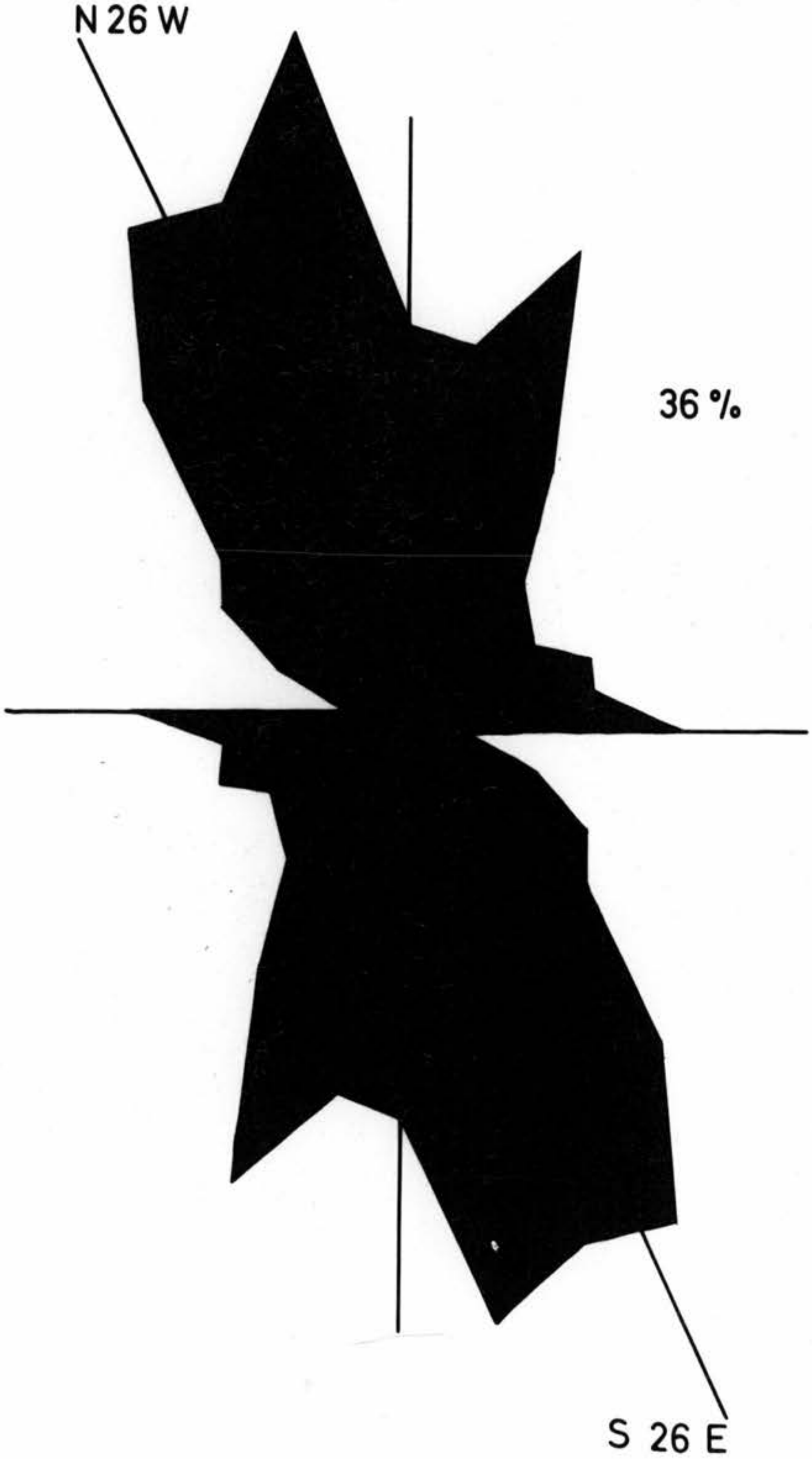
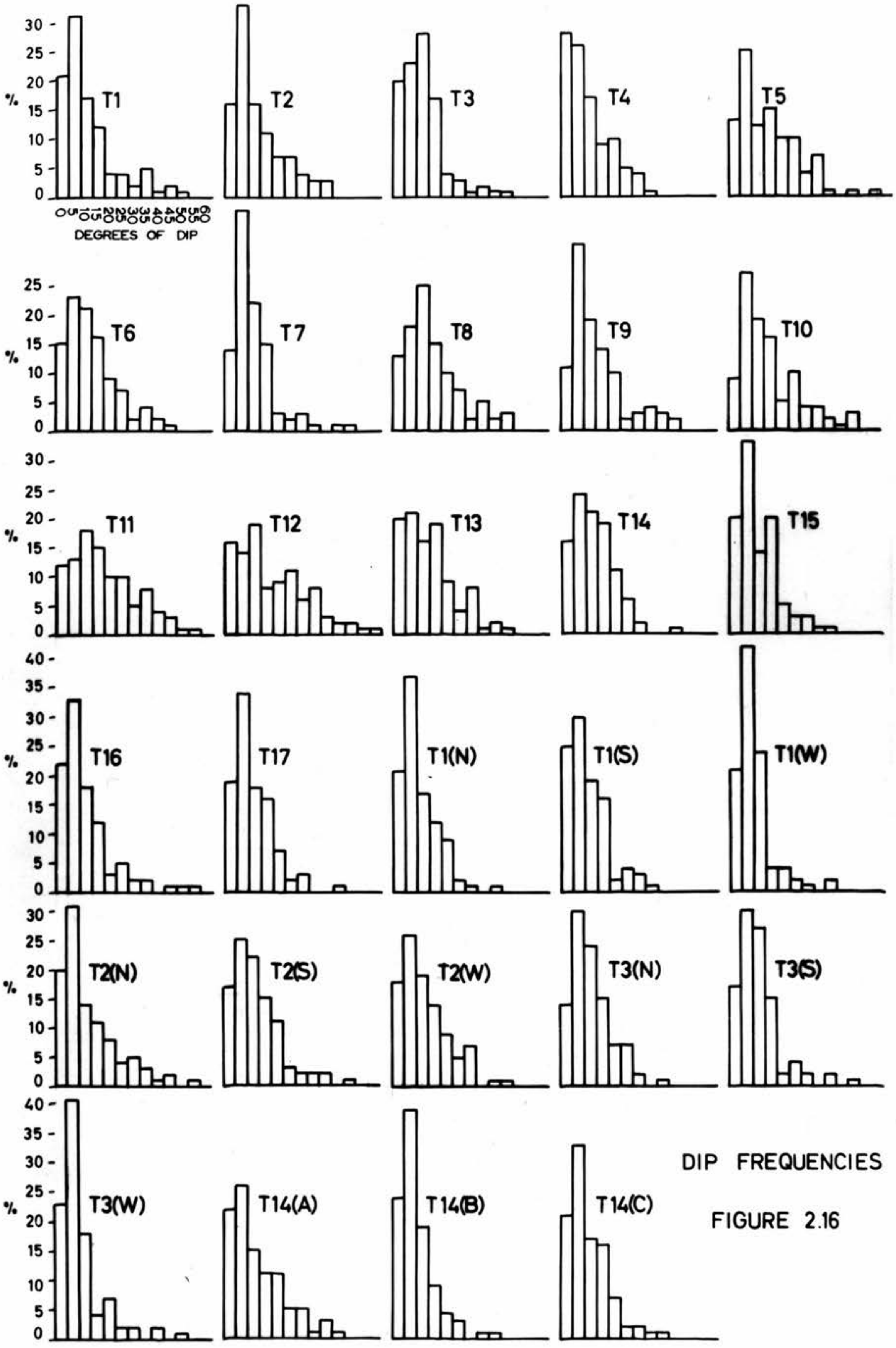


FIGURE 2.15



DIP FREQUENCIES

FIGURE 2.16

Chapter 3. Particle Size Analysis.

Particle size analysis determines quantitatively the relative proportion of the various sizes of the particles present in a sediment. Primarily, it allows expressions in numerical terms of the sorting by size of sediments. Clays, silts sands, pebbles, cobbles and boulders all have a predetermined range of size limits and each category except boulders and cobbles, can be further divided into fine, medium and coarse grades.

Under field conditions it is all too easy to assess incorrectly the texture of a deposit. High moisture content and a high degree of compaction often give the impressions of a clay whilst drier and less compact material may seem coarser and sandy.

Knowledge of the particle size distribution of the tills and sands together with the mineralogy (Chapter 4) and chemical characteristics (Chapter 5) permits some assessment of the source (provenance) of the ice that transported the debris, its possible path and also the nature of the processes to which the included debris has been subjected within the ice.

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 (1953), Shepps (1953, 1958), Shaffer (1956), Arneman and Wright (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 differences between tills although other criteria analysed suggested that the tills examined were strikingly different.

An/

An apparent and completely qualitative impression of the texture of the tills was obtained during the period of fieldwork that was carried out in the section (Figure 1.2). The upper till unit, lower 5 ft. of the middle till unit and all the lower till unit were highly compacted and very difficult to excavate; the tills of those levels all felt distinctly clayey although the presence of coarser material was easily discernible. In the process of digging down through the section, semblance of an approximately horizontal structure that was not visible on inspection was found in all three till units, excepting the upper 8 ft. to 9 ft. of the middle till unit. As a contrast, the upper 8 ft. to 9 ft. of the middle till unit were more easily dug, felt much coarser texturally and possessed no apparent structure or bedding. In the field, there thus appeared to be two distinctly different types of till on the basis of apparent textures.

The purpose of carrying out particle size analysis of the samples taken from the various till and sand levels was to find out the distribution of their component size fractions and the amount in each of these predetermined fractions for every sample.

<u>Sampling.</u> Milner (1962) has noted that sampling is a complete study in itself upon which all later laboratory analysis depends. It is of the utmost importance to ensure that a sample is representative of the body from which it is taken. In private conversation most field scientists admit the need to take as large a sample as possible although in practice they may only take a "small bagful".

In the literature that is concerned with the type of work carried out in this Chapter and in Chapters 4 and 5 it is common to find either no reference to sample size or statements that can be typified by the example, "samples/

"samples were collected in polythene bags" (Virgo, 1964). There is seldom any attempt to discuss whether the sample is representative. However, work does exist where some effort has been made to try and study this problem.

As early as 1926, Wentworth suggested that a sample of 32 Kg. was adequately representative. Hörner (1944) discussed this problem fully and concluded that a 50 Kg. field sample that was reduced by coning and quartering to 1500 g. was the minimum size that would be suitable; Järnefors (1952) concurred with the views of Hörner. Holmes (1952) considered that a sample weighing 15-20 lbs. when air dry would be large enough. In contrast, Dreimanis and Reavely (1953) only used 1-2 lb. samples for their studies. Shepps (1953) published evidence to show how the tills of north east Ohio could be differentiated and correlated solely on the basis of particle size analysis; the original size of his field samples was 1,500 to 2,500 g. More recently, work carried out by Davis (1958) and Block (1960) in the U.S.A. involved collecting samples of 100 to 150 lbs. and 50 lbs. respectively.

One of the basic properties of till is its apparent lack of size sorting in comparison with the size sorting of stratified drift (Flint 1957). If only a small field sample of till is taken this can range, in effect, from one stone to a bagful of smaller debris with a number of small stones. A small sample will only be representative of a few cubic inches around the point at which it is taken. On the other hand, if a large sample covering greater extent both laterally and vertically is taken its bulk makes it representative of a larger volume at a particular level.

It was decided to take samples of the tills from the same levels at which orientation and dip analysis was carried out (Chapter 2) and also from the included stratified sand and gravel layers discernible in the section. (Figure 1.2). Dip and orientation studies were carried out at 17 different levels through/

through the three till units. Each study was made in a volume of till measuring approximately 2 ft. horizontally x 2 ft. laterally x $\frac{1}{2}$ ft. vertically. Accordingly a sample of approximately the same dimensions was taken immediately adjacent to the 17 different levels at which orientation and dip analyses were executed. Because stratified sand and gravel has been sorted and does not contain the same range of size fractions, a much smaller sample was considered to be representative. Samples of the sand and gravels were taken from each apparently different level of sand and gravel in the section. Thus 17 till samples and 10 sand and gravel samples were brought back for laboratory analysis. Hereinafter, the samples taken from the sand and gravel levels of the section will be referred to as sands.

Preparation of samples. The samples were air dried until their moisture content was approximately 1% (range 0.8% to 1.1%), when they were weighed. The range in weight of the till samples was 100 lbs. to 120 lbs. and the range of the sands was 4 lbs. to 12 lbs. Sand samples varied in size depending on whether the sample was taken from a narrow, discontinuous lens or from a thicker, continuous band of sand.

All the pebbles and cobbles were extracted from the till samples by hand and any adhering material carefully brushed off and retained. The residual smaller debris was broken down in a mortar using a pestel covered with a latex sleave to protect the composite rock aggregates from crushing. Each sample was screened through a 2 mm. e.s.d.* B.S. sieve and the material retained on the sieve inspected. Rock granules were removed before the fraction that had been retained on the sieve was lightly ground in a mechanical grinder for approximately 5 minutes. If any small rock particles greater than 2 mm. e.s.d. were left after grinding, they were removed and retained. The material less than 2 mm. e.s.d. that was yielded by grinding was added to the material less/

---

* equivalent spherical diameter.

less than 2 mm. e.s.d. from the initial screening and retained. Thus all the material greater than 2 mm. e.s.d. was separated from all the material less than 2 mm. e.s.d. The relative proportions expressed in percentages are shown in Appendix III.I and it can be seen that the amount of material less than 2 mm. e.s.d. was greater than the total amount greater than 2 mm. e.s.d. in all cases, varying from 62% to 93% of the total sample.

The greater than 2 mm. e.s.d. fraction of the samples was stored carefully for later division by screening. After extraction of the coarser material, the less than 2 mm. e.s.d. fraction still weighed 80 to 100 lbs. and was reduced to approximately 1500 g. ($3\frac{1}{2}$ lbs.) by coning and quartering as suggested by Hörner (1944) and Järnefors (1952). The material for the less than 2 mm. e.s.d. fraction of particle size analysis, pH and carbonate analyses was taken from this 1500 g. sample.

The samples of the sands were screened through the 2 mm. e.s.d. sieve and in 8 cases out of 10 all of the sample was less than 2 mm. e.s.d. In the other two samples (Appendix III.I) where some granules and pebbles were retained on the 2 mm. e.s.d. sieve, each sample was divided into two fractions, one less than 2 mm. e.s.d. and the other greater than 2 mm. e.s.d. Both fractions were stored with the other sand samples for further analysis.

<u>Analysis.</u> Particle size was carried out by screening the coarser material (greater than 2 mm. e.s.d.) through a series of A.S.T.M. sieves with different mesh sizes. The distribution of the material less than 2 mm. e.s.d. was determined by measuring the density of a suspension of these finer fractions in a 2% sodium hexametaphosphate solution with a hydrometer at given time intervals during sedimentation. The actual analytical procedure followed is fully/

fully detailed by Glanville (1952) in "Soil Mechanics for Road Engineers", London 1952, pp.39-65. Duplicate portions of the fraction less than 2 mm. e.s.d. of each till and sand sample were used in the hydrometer analysis. Thus all values of the fraction less than 2 mm. e.s.d. (Appendices II.I, III.II and III.III) represent the mean values of the duplicate analyses for each sample.

The material greater than 2 mm. e.s.d. was separated into different particle size fractions by screening it through 128 mm. e.s.d., 64 mm. e.s.d., 32 mm. e.s.d., 16 mm. e.s.d., 8 mm. e.s.d. and 4 mm. e.s.d. A.S.T.M. sieves. The fractions retained on each sieve and the fraction that passed through the 4 mm. sieve were weighed separately and each expressed as a percentage of the total sample (Appendix III.I).

The results of the fine and coarse fraction analyses were added together and then graphed on semi logarithmic paper (Figures 3.1 and 3.2.). The cumulative percentages of the various size fractions (ordinate) were plotted against the corresponding grain sizes (abscissa). From these particle size distribution curves the cumulative percentage of material at any level of grain size can be read off and the amount of material between any two size limits calculated.

It was decided to use the British Standards Institution classification of particle size distribution (cf. Milner, 1962) to interpret and express the amount of the component fractions of each till and sand sample in the range less than 2 mm. e.s.d. This is:

Equivalent spherical diameter (mm.).	Category
2.0 - 0.60	Coarse sand
0.60 - 0.20	Medium sand
0.20 - 0.06	Fine sand
0.06 - 0.02	Coarse silt
0.02 - 0.06	Medium silt
0.06 - 0.002	Fine silt
less than 0.002	Clay

The above classification is specifically limited to the material less than 2 mm. e.s.d. and all material greater than 2 mm. e.s.d. is classified as "gravel". Since the range of material greater than 2 mm. e.s.d. extended to a limit of 128 to 256 mm. e.s.d., it was felt that it was necessary to subdivide this and the upper part of the Wentworth (1922) classification was adopted. This is:

Equivalent spherical diameter (mm.).	Category
2 - 4	Granule
4 - 64	Pebble
64 - 256	Cobble
greater than 256	Boulder

The particle size distribution of the tills and sands expressed in percentages of clay, silt, sand, granule, pebble and cobble fractions is presented in Appendix III.II.

Histograms of the total particle size distribution were drawn for each till and sand sample (Figure 3.3). Also, the material less than 2 mm. e.s.d. was recalculated on a basis of clay, silt and sand adding up to 100%, (Appendix III.III) and plotted in triangular graph form (Figure 3.4).

Results. The particle size distribution curves (Figures 3.1 and 3.2) contrast the differences between the better size sorted sands and gravels and the little sorted tills. There is a striking lack of heterogeneity in the graph patterns for the 17 till samples. They all follow the same general alignment with three examples deviating more widely from this pattern; all three aberrant graphs form specific examples of either a greater or lesser amount of coarse material compared with the percentage of particles less than 2 mm. e.s.d. in the other 14 analyses (Appendices III.I and III.II). That is, there is greater deviation from the general trend in the upper (large size fraction) parts of the graphs.

The lowest curve in Figure 3.1 represents T14 which deviates distinctly between 0.2 and 256 mm. e.s.d. and is the only sample with any material (26%) in the fraction 128 to 256 mm. e.s.d. The other lower than average plot represents T10 which deviates most from the general trend between 0.3 and 128 mm. e.s.d. and has 17.5% of its total particles in the fraction 64 to 128 mm. e.s.d. In comparison all other till samples contain nil to 7.99% of cobbles (64 to 128 mm. e.s.d.). Above the main concentration of curves, T2 stands out from the other graphs in the range 0.2 to 20 mm. e.s.d. which is a result of this particular sample only having 6.8% greater than 2 mm. e.s.d. compared with the range for the other 16 till samples of 11.83% to 37.56%.

Apart from the specific examples of partial deviation there is no major difference between the 17 till samples texturally despite the apparent illusion of at least two different till textures in the field.

The stratified sands have a more restricted particle size distribution than the tills (Figure 3.2 and Appendix III.I) and with one clear exception (SIII) follow the same general alignment. SIII is a coarser layer with 39.83% of the total sample greater than 2 mm. e.s.d. and considerably less (13.78% compared with 27.20 to 59.40%) in the silt and clay fractions.

The histograms (Figure 3.3) are an easily visualised representation of the numerical gradings (Appendix III.I) extrapolated from the cumulative frequency curves. In all till samples there is a marked concentration in the area of the silts and sands (0.002 to 2.0 mm. e.s.d.). The fine sand grouping (0.06 to 0.2 mm. e.s.d.) stands out in all till analyses and is commonly (14 instances out of 17) the greatest single fraction present. It is also noticeable that a tendency exists for the silt grades to increase from fine through medium and coarse components on one side of the fine sand in step like manner and for the/

the histograms to decrease in similar step like manner on the other side of the fine sand grade through medium and coarse sand. Individual peculiarities, such as the large amount of coarse material in the 64 to 128 mm. e.s.d. groupings of T10 and the one very large cobble (128 to 256 mm. e.s.d.) in T14 stand out clearly.

As a contrast, the stratified sands show how concentrated their distribution of particles is in the silt and sand grades in 9 cases out of 10. The clay fraction is always low (5.30 to 13.20%). Like the till samples the sands show greatest concentration in the fine sand fraction and increase in amount through the silts on one side of the fine sand grouping and decrease down again through the medium and coarse sands on the other side.

Graphing of the material less than 2mm. e.s.d. in the texture triangle (Figure 3.4) shows how all the till samples are concentrated together approximately in the middle of the triangle. All tills would be "sand-silt-clays" on the basis of the nomenclature proposed by Shephard (1954) whilst the stratified sands fall into two groups, the lower three in the triangle being sandy silts and the upper seven being silty sands.

The results of particle size analysis show a distinct general homogeneity amongst the 17 till samples and with one exception a similar but separate uniformity exists amongst the sands. The differences between individual till samples (excepting particular concentrations already mentioned) are virtually negligible. In fact, the only striking difference in all 27 analyses is that between tills and sands.

<u>Discussion.</u> The load of a glacier when seen at its margins is concentrated in the basal parts and reflects the fact that the main source of the debris carried is the ice-rock interface (Flint, 1957). Shape and size of the individual particles of the debris are controlled by (a) the bedrock across which the/

the ice has passed, (b) the durability of the rocks in relation to glacier attrition during transportation and (c) the distance that the debris has been transported by the ice.

Holmes (1960) presented evidence to show the changes in size, shape and degree of roundness of the pebbles and cobbles in glacial drift that occurred with distance of transportation. Gradually the larger size fractions were reduced to smaller sizes that in turn disappeared from the glacier load at a rate proportional to the toughness of the rock type. Rounding and crushing continued until the stones of the till were either broken down to the smallest size fractions or were deposited by the ice.

Gilberg (1955) has shown that in Southern Sweden basal till was dense and compact and that whilst cobbles (64 to 256 mm. e.s.d.) were common, boulders (greater than 256 mm. e.s.d.) were not. In comparison, he found that superglacial till was sandier and coarser and that cobbles and boulders were always more common than in basal till. In both basal and superglacial till, fine and coarse sand were the principal constituents with approximately 40% of the total sample in the fraction 0.2 to 0.02 mm. e.s.d. and 35% in the fraction 2.0 to 0.2 mm. e.s.d. Hoppe (1953) also found that ground moraine in Iceland seldom contained boulders.

Flint (1955) indicated that in eastern South Dakota the local bedrock was the dominant macro constituent of the various drifts. Shepps (1953) showed that in the tills of north east Ohio pebbles, cobbles and boulders were moderately local whereas the sand, silt and clay fractions were more distant in origin. That is, the sizes of the constituent particles of glacial deposits depend, among other factors, on distance of transportation and Shepps suggested that the far travelled finer fractions had been ground down from larger particles inside the ice en route. At sites exposing multiple till sequences, the tills became progressively finer grained upwards through the section because the younger/

younger tills had been largely derived from the underlying older tills and the constituent particles of the younger tills had been further ground down by the later ice.

A remarkable homogeneity of till textures was found to exist for each identifiable till over a wide area by Shepps (1953) who posed the question whether tills were so highly local in origin as had been previously argued. The cumulative thickness of the tills suggested that they had been transported considerable distances within the ice in order that there could be time for adequate mixing of the constituent debris and the development of a uniform mechanical composition. Incorporation of local material was argued not to have been great enough to destroy the overall uniformity of the mechanical composition once it had been produced.

Independantly of Shepps, Krumbein (1953) pointed out that till was not so heterogeneous as previously supposed. He suggested that ice sheets tended to produce till that had a reasonably well defined frequency (particle size) distribution with a more or less homogeneous basic composition.

Hörner (1944, 1946) and Järnefors (1952) have tried to assess the effects of glacier grinding on glacial drift as a means of comparison of different tills. Where a similar degree of grinding (particle size distribution) was found to exist in seemingly different tills, Järnefors ascribed the same parent glacier to these tills.

The particle size analyses carried out in the 17 till samples do not show any distinctive differences such as those quoted by White and Shepps (1952) from north east Ohio where they distinguished three tills on a particle size basis and quoted the following figures as typical:

	Sand.	Silt.	Clay.
Till 1.	50%	35%	15%
Till 2.	30%	45%	25%
Till 3.	15%	40%	45%

Glentworth, Mitchell and Mitchell 1964) have also differentiated three tills in north east Scotland on the basis of clay content and have quoted typical clay values as (1) 20 to 30% (2) 41% and (3) 56% of the total sample.

In the case of the 10 sand samples, particle size analysis shows the effect of water sorting in the general absence of material greater than 2 mm. e.s.d. and low clay values. These sands may represent washed tills that have been released from the ice with greater volumes of water than associated with the build up of the adjacent tills.

No proof was found in either the section (Figure 1.2) or in the area around Fala (Chapter 1) of glacier oscillation. No included peat beds, weathering horizons or periglacial phenomena were discovered. In other words no unconformity could be discerned.

Although it can be shown (Chapters 4 and 5) that considerable differences do exist in the tills, they are to all intents and purposes homogeneous as assessed by particle size analysis. The degree of grinding of the debris by the transporting ice has been very similar in all cases and there is no indication solely on a particle size basis to suggest derivation of any upper till level from a lower level.

In the light of the evidence of this Chapter it would seem that all the deposits of the section (Figure 1.2) could have been laid down by the same ice which has subjected all the debris to a very similar degree of mechanical abrasion. The sands represent phases when greater quantities of water were associated with the deposition of the load from the ice. The general compactness and apparent horizontal structure found during the excavation of the section and the absence of boulders add further evidence to the belief that all the tills analysed were lodged from the basal regions of active ice and are not ablation material.

FIGURE 3.1

PARTICLE SIZE DISTRIBUTION CURVES OF TILL SAMPLES

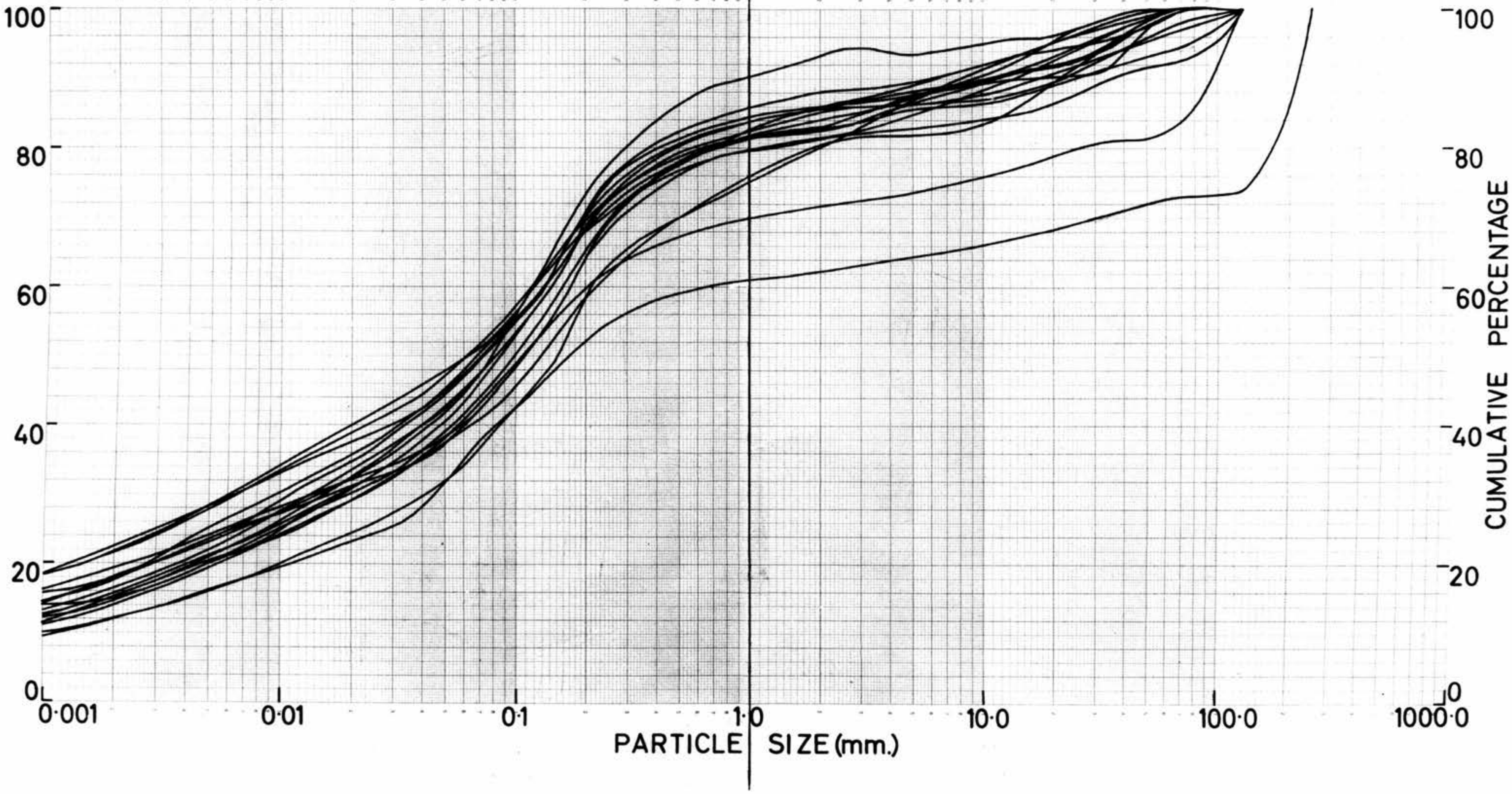
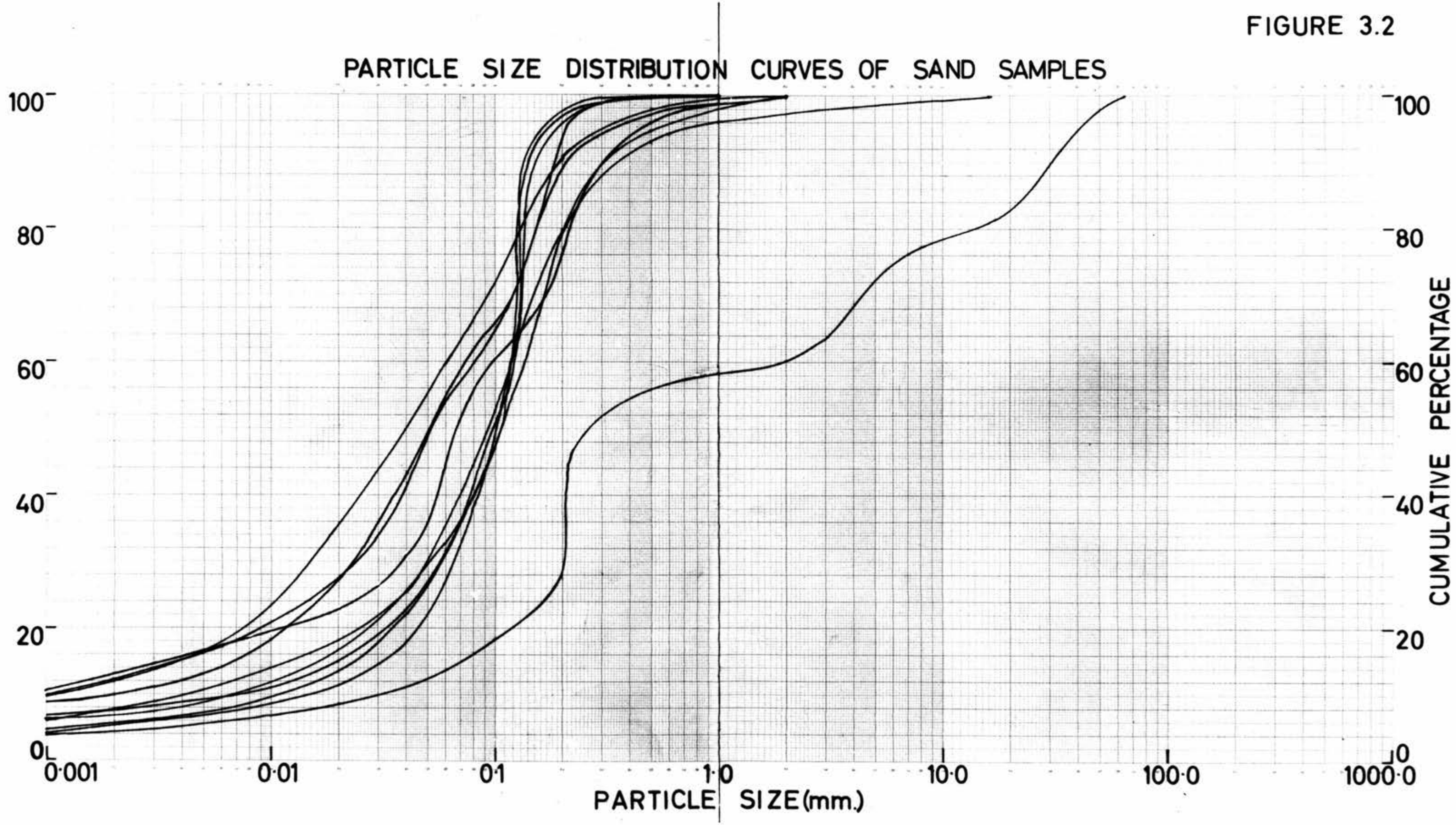
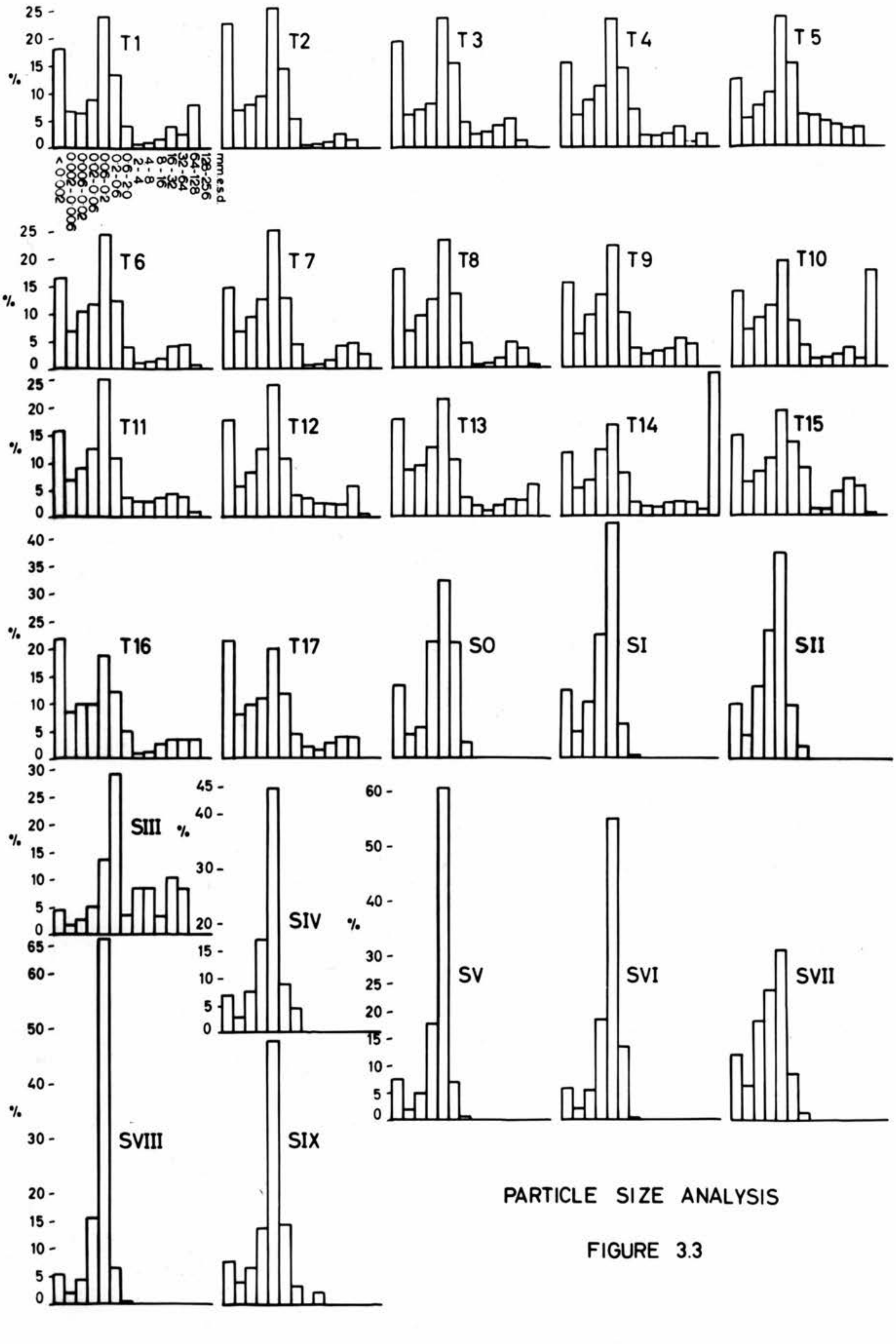


FIGURE 3.2



PARTICLE SIZE DISTRIBUTION CURVES OF SAND SAMPLES



PARTICLE SIZE ANALYSIS

FIGURE 3.3

PARTICLE SIZE DISTRIBUTION OF
MATERIAL LESS THAN 2mm. e.s.d.

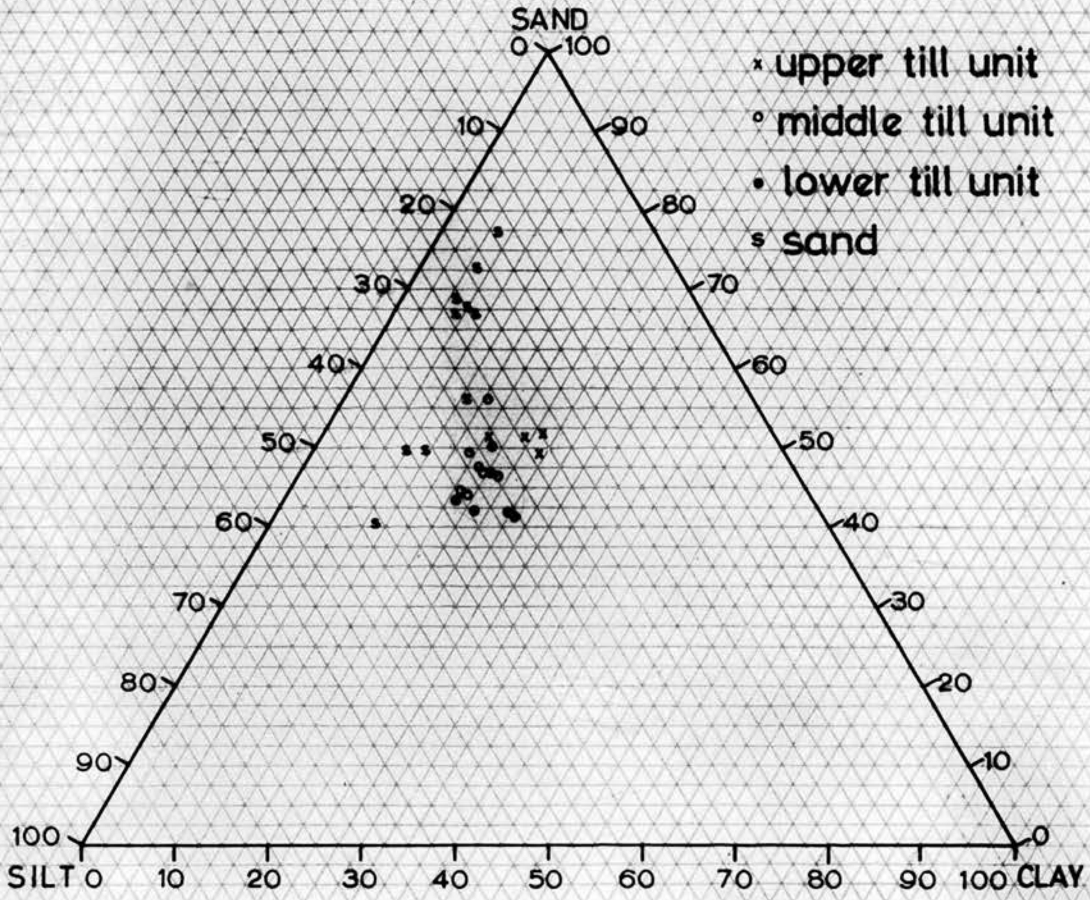


FIGURE 3.4

Chapter 4. Mineralogy

The object of examining the mineralogical composition of the tills and sands was to learn more about their provenances and also to find further particulars to aid differentiation between and within the several apparent units of the glacial deposits. The lithological constituents of glacial deposits are dependent upon the source of the ice and the composition of the bedrock across which the ice has passed. From an examination of the various included lithologies the aim was to develop evidence bearing upon the origin of the tills and sands.

Flint (1957) believed that the proportion of any rock type incorporated in glacial deposits was controlled by (a) the areal extent of the rock outcrop (b) the erodobility of the rock outcrop by ice (c) the durability of the eroded debris during transportation within the ice and (d) the distance of transportation of the debris by the ice. Thus the coarser and coarsest grades of glacial debris were usually more local in origin than the finer grades unless there were major differences in the resistances of the various lithologies to the transporting ice.

Anderson (1955) has shown that as ice passed over a bedrock outcrop the number of pebbles from a particular lithology increased to a maximum at the lee side of the outcrop. He has suggested that the distribution of any pebble fraction was influenced by (a) the extent and proximity of its provenance (b) the lithological properties of the outcrop and its resistance to erosion (c)englacial processes that the debris was subjected to and (d) the dilution of each rock type by the addition of other rock types with increasing distance of transportation and time. The same four conditions would control the percentages of any indicator lithologies.

Låg (1948) and Flint (1955) have both published evidence that showed that /

that a single till sheet could vary greatly in composition from area to area. In particular, the coarse fractions tended to reflect the complexion of the local bedrock from which they were chiefly derived. Flint (1957) pointed out that in some areas the macro constituents of till were dominantly local at the base of a deposit and the proportion of foreign debris increased upwards in the section reflecting a stirring up of the local mantle which had been followed by mixing with the already incorporated debris inside the lower parts of the ice.

Deposition of the bottom basal load took place shortly after the incorporation of the very local debris and at a later point in time the further travelled debris of the higher parts of the basal ice were deposited. Anderson (1957) has indicated that the proportion of local rocks varied greatly within and between the major Wisconsin glacial lobes in the interior of North America whereas the far travelled lithologies usually showed an even distribution throughout.

Uncertainty continues to exist in most of the literature regarding the main source of material transported by glaciers. It is generally conceded that all glacial deposits (both tills and sands) consisted almost entirely of fresh and unweathered rock before depositon from the ice (Flint, 1957) and were eroded from the in situ rock outcrops across which the ice had passed. Certain classical views still find wide acceptance. A. Geikie (1863) noted that the change in colour and erratic content of the tills of East Lothian coincided with changes in local bedrock from Old Red Sandstone to Silurian. J. Geikie (1894) also assumed that till was generally local in character and cited evidence from sandstone districts where the dominant erratics were the local sandstones. In a paper based more on theoretical considerations rather than/

than practical observations Salisbury (1900) argued fiercely that the very great bulk of "normal" till was made up of material derived locally. More recently, work typified by Gravenor (1951) has shown conclusively that in south west Ontario the finer fractions of the tills were certainly not of local origin. These two fundamentaly different views concerning the degree of local origin of the constituent materials in glacial deposits continue to exist; one viewpoint is based on qualitative observation of the larger pebbles and cobbles whilst the other is concluded as a result of quantitative analysis of the micro fraction.

In the present investigation, both the macro and micro size fractions were examined quantitatively. The several divisions of the fraction greater than 8 mm. e.s.d. and the fine sand fraction (-72 mesh + 200 mesh sieves) from the particle size analysis were studied.

Macro mineralogy. Particularly in the last 10 to 15 years, pebble counting has become a routine part of quantitative investigations of glacial deposits. However, in 1958, Davis maintained that the petrology of the pebble, cobble and boulder grades was still overlooked in comparison with the attention given to material less than 2 mm. e.s.d. Earlier than this, Leinz (1933) in North Germany, Slawson (1933) and Woodworth and Wigglesworth (1934) in North America employed pebble counting to assess the probable source of glacial deposits. Since the investigations of those workers, Anderson (1940) and McCall and Goodlet (1951) in Scotland, Järnefors in Sweden,Hyyppa (1948) and Matisto (1961) in Finland, Dreimanis and Reavely (1953) in Canada and Holmes (1952) Krumbein (1953), Anderson (1955, 1957), Flint (1955), Horberg (1956), Arneman and Wright (1959), Block (1960), Kaiser (1962) and Frye, Willman and Glass (1964) in U.S.A. have all made quantitative assessments of the macro components of glacial deposits.

Sample/

Sample size and methods. Like all other quantitative work, controversy exists regarding the minimum sample size that can be deemed representative. Most of the workers referred to in the previous paragraph believed that 100 stones provided an adequate sample. Kaiser (1962) on the other hand counted 1000 stones and Goodlet (personal communication) still believes that 300 stones are the minimum sample that should be taken.

As a result of the particle size analysis (Chapter 3) the pebbles and cobbles were divided into six groups according to size. In the largest size groups (128 to 256 mm. e.s.d., 64 to 128 mm. e.s.d. and 32 to 64 mm. e.s.d.) the number of stones in any one sample was small even though the original size of each till sample was approximately 1 cubic foot. The greatest number of stones in any one of these three largest size groups was 25.

The individual stones from the 17 till and 1 sand sample in the groups 32 to 64 mm. e.s.d., 64 to 128 mm. e.s.d. and 128 to 256 mm. e.s.d. were broken open and each stone was identified and recorded. The number of stones in the smaller groups was considerable and was reduced by splitting each sample over a knife edge until exactly 100 stones were obtained. Again each stone was cracked open, identified and recorded. It was found impossible to work with the smallest pebble group (4 to 8 mm. e.s.d.) as the constituent stones were difficult to break open without completely crushing the less resistant lithologies; identification of the smallest pebble group was also rendered very difficult because of the size of the stones.

The identification of each stone was made with the naked eye and in cases of uncertainty a hand lens was also used. On this basis, five separate lithologies were recognised. These were (a) Ordovician/Silurian greywackes (b) Carboniferous sandstones (c) Carboniferous limestones (d) tuffs and other unclassified volcanic material and (e) quartz. A more refined division of the stones would have required/

required investigation by thin section analysis. Whilst the rocks of category (d) were dominantly tuffs a minority might have been medium grained lavas: hereinafter grouping (d) will be referred to as tuffs, grouping (a) as greywackes and grouping (c) as limestones. The results of the stone counting are shown in Figure 4.1 and Appendix IV.I.

The largest pebble and cobble fractions. It would be wrong to infer too much from the analysis of the three largest size groups (32 to 64 mm. e.s.d., 64 to 128 mm. e.s.d. and 128 to 256 mm. e.s.d.) since the number of stones in any sample was often very small. All five lithologies noted above were present. The only cobble greater than 128 mm. e.s.d. was Carboniferous sandstone. In the group 64 to 128 mm. e.s.d. tuffs were most common followed in terms of frequency by Carboniferous sandstones, greywackes and limestones; no quartz was found. More stones were found in the group 32 to 64 mm. e.s.d., greywackes being the only lithology found in all 17 till samples. Carboniferous sandstones and tuffs were present in sizeable numbers proportionately whilst only sporadic pieces of quartz were identified. Excepting T12, limestone was present in all samples from T10 to T17.

16 to 32 mm. e.s.d. fraction. The groupings 16 to 32 mm. e.s.d. and 8 to 16 mm. e.s.d. were analysed on the basis of 100 stones that were randomly selected as described earlier. In the 16 to 32 mm. e.s.d. group greywackes, Carboniferous sandstones and tuffs were found in all 17 till samples. Quartz occurred in small quantities in samples T1 to T9 inclusive and only once thereafter in both T14 and T15. Limestone was present in all samples below T9. Carboniferous sandstone was the most common constituent (41 to 57%) from the levels T1 to T5, that is in the upper till unit and at the top of the middle till unit but tended to decrease thereafter down through the section to 22% at T16 and T17. The number/

The number of greywackes was seldom as great as the Carboniferous sandstones and was more restricted, yet more consistent with a range of 23 to 43%. Tuffs formed 12 to 32% of any one sample and in only four instances amounted to more than 20% of any sample. The limestone increased in the bottom 8 ft. of the middle till unit to 22% at T11 and then decreased at the base of this unit; in the lower till unit, the limestone proportion increased again from T14 (8%) to T16 (26%) and fell back slightly at T17. That is, there was more limestone in the lower till unit than in the bottom part of the middle till unit.

<u>8 to 16 mm. e.s.d. fraction.</u> In the smallest group examined (8 to 16 mm. e.s.d.) greywackes, Carboniferous sandstones, tuffs and quartz were found in all 17 till samples. Limestone was identified in the bottom samples of the middle till unit (T10, T11 and T12) and in four of the samples of the lower till unit (T14, T15, T16, and T17). Carboniferous sandstones totalled 20 to 45% of any one sample, greywackes 30 to 50%, tuffs 8 to 25% and quartz 1 to 13%. No trend in rate of change of concentration of these lithologies could be found. Limestone increased in amount from T10 (12%) to T11 (22%) and fell off at T12 (13%) in the bottom of the middle till unit. In the lower till unit, no limestone was found at level T13 but was present in all samples below this level and was found in maximum amounts (24%) at T17.

<u>Comparison of the two finest pebble fractions.</u> Comparison of the two grades 16 to 32 mm. e.s.d. and 8 to 16 mm. e.s.d. produced evidence of several tendencies in terms of changes in stone concentration through the section. Fewer Carboniferous sandstones occurred in the 8 to 16 mm. e.s.d. fraction than in the 16 to 32 mm. e.s.d. fraction of the upper and middle till units (T1 to T11). At the base of the middle till unit and in the lower till unit (T13 to T17) the proportion of Carboniferous sandstone was greater in the 8 to 16 mm. e.s.d. fraction/

fraction than in the 16 to 32 mm. e.s.d. fraction. On the other hand, the percentage of greywackes in the 8 to 16 mm. e.s.d. fraction was the same or greater than the percentage found in the 16 to 32 mm. e.s.d. fraction in 14 instances out of 17. In 13 out of the 17 till samples, the percentage of greywackes was greater than the percentage of Carboniferous sandstones in the 8 to 16 mm. e.s.d. fraction compared with 8 instances out of 17 in the 16 to 32 mm. e.s.d. fraction. The relative proportion of tuffs tended to be lower in the samples of the 8 to 16 mm. e.s.d. fraction than in the 16 to 32 mm. e.s.d. fraction and below T12, that is, at the base of the middle till unit and in the lower till unit the tuffs decreased numerically in the 8 to 16 mm. e.s.d. fraction; no consistent trend was found from T1 to T11. Quartz tended to be more common in all the 8 to 16 mm. e.s.d. samples compared with the amount found in any of the larger fractions. Limestone was present in only the bottom of the middle till unit and the lower till unit and tended to be slightly more common in the 8 to 16 mm. e.s.d. fraction than in the 16 to 32 mm. e.s.d. fraction. In the four fractions in which limestone was found, it never occurred higher in the section than T9 and was least common at T13, that is at the top of the lower till unit, than at any other level below T9.

Only one sand sample (SIII) yielded any material greater than 8 mm. e.s.d. Except in the 8 to 16 mm. e.s.d. fraction of the grades investigated, the total number of pebbles was never as great as 100. In the 8 to 16 mm. e.s.d. fraction, Carboniferous sandstone was dominant followed in order of frequency by greywackes, tuffs and quartz. SIII was sampled from the sand complex in the section (Figure 1.2) between T4 and T5.

Broken fragments of coal were picked out of all the till and most of the sand samples in the course of particle size analysis; the actual amounts were/

were always small and can only be recorded as traces. A general examination of the smallest pebbles (4 to 8 mm. e.s.d.) under a binocular microscope showed that occasional pieces of Old Red Sandstone were present in all 17 till samples; Old Red Sandstone was never found in any of the larger size grades.

Micromineralogy. The study of minerals with a microscope forms a very sizeable subject in itself. Glacial deposits are unconsolidated sediments composed of detrital mineral fragments that have been eroded from in situ rock outcrops and broken down in transit by englacial attrition prior to deposition. Like the macro mineral constituents, the composition of any glacial deposit reflects the lithologies across which the ice has passed. However it is possible that severe crushing of mineral fragments during transportation and the presence of large quantities of water during deposition may remove less resistant and readily soluble constituents. If after deposition water can percolate freely through the deposits, further minerals may be leached out and new mineral growths develop. Any changes that have taken place during transportation or after deposition can be assessed in later analysis.

Examination of the micro mineralogy of sediments is far more routine than the study of the larger fractions. Published work specifically in the field of quantitative investigations of glacial deposits is prolific. Many of the most detailed studies have been made by North American workers like Kruger (1937), Gravenor (1951, 1954), Murray (1953), Dreimanis and Reavely (1953), Dreimanis et al (1957), Arneman and Wright (1959), Brophy (1959), Frye, Willman and Glass (1960), Frye Glass and Willman (1962, 1964), Kaiser (1962), Sitler (1963), Willman, Glass and Frye (1963) and Johnson (1964). Boswell (1916) and Solomon (1932) in England, Järnefors (1952) in Sweden and Leinz (1933)and Fiedler (1939) in Germany have all employed the same techniques in similar studies that are/

are relevant to the present investigation.

The great bulk of both the till and sand samples was less than 2 mm. e.s.d. (Chapter 3). Accordingly an examination of the mineralogical composition of part of these finer fractions was necessary in order that a better total estimation of the composition of the various deposits could be obtained. Part of the fine sand fraction (-72 + 200 mesh sieves) was chosen for the investigation; the reasons for selecting this size fraction were threefold. Firstly, it was small enough not to contain rock complexes and yielded only individual mineral grains. Secondly, the size of the component mineral grains was sufficiently large to enable easy separation in a heavy liquid and thereafter the grains could be identified under a petrological microscope without employing very high magnification. Thirdly, the fine sand grade was the largest single fraction in particle size analysis.

Methods. All the fine sand (-72 + 200 mesh sieves) from the particle size analysis of each till and sand sample was used making 27 samples in all. Each sample was divided into two parts by separation in symmetrical tetrabromoethane (specific gravity 2.95). Minerals having a specific gravity greater than 2.95 (heavy minerals) were thus divided from those with a specific gravity less than 2.95 (light minerals). The percentage of heavy minerals constituted 1.26 to 2.54% and 0.67 to 2.40% of the till and sand samples respectively (Appendix IV.II). The purpose of this separation was to concentrate the heavy mineral fraction which contains a much wider variety of minerals than the light mineral fraction and is also more diagnostic of the original rock types across which the ice has passed.

Duplicate portions of both fractions for all samples were mounted in clove oil (refractive index 1.535) and examined under a polarizing petrological microscope. Parallel traverses of each slide were made using an automatic point counter/

counter and every mineral falling on the east-west crosswire of the eyepiece was identified until 500 grains were recorded (Appendix IV.II). Whilst controversy also exists regarding the minimum size of sample that will be representative, most workers count any number between 200 and 500 grains.

In the heavy mineral fraction it was found that all samples were flooded by opaque iron oxides. This suppressed the number of non opaque grains. Accordingly, each slide was re-examined and only the non opaque grains counted; weathered fragments were not recorded in this count. It was found that 200 non opaque grains could be realised in each slide and the results are shown in Appendix IV.III.

Notes on minerals identified. A selection of certain minerals is shown in Figure 4.2.

Apatite: elongate and also more rounded prisms, colourless.

Augite: pale green to brown green grains, prismatic and also very fragmented; sometimes fresh but more commonly weathered.

Biotite: brown and yellowish brown flakes with jagged edges.

Chlorite: green, rounded flakes.

Enstatite: small, greyish white prisms with longitudinal cleavage cracks.

Epidote: pale yellow green, usually weathered and rounded.

Felspars: irregularly shaped grains of orthoclase and plagioclase.

Garnet: colourless, irregularly shaped grains often with cracks, sometimes with sieve like appearance.

Hornblende: angular, green, pleochroic crystals with uneven, frayed edges; no signs of weathering.

Hypersthene: ragged prisms with characteristic pleochroism.

Iron Oxides: always irregular in shape.

Quartz: angular grains, sometimes stained on surfaces with iron oxides and commonly/

commonly displaying fragmented pieces of iron oxide overgrowths at edges.

Rutile: deep foxy brown, sometimes pale yellow; grains tended to be prismatic with rounded edges.

Tourmaline: commonly pale brown, sometimes green or blue; crystals show complete absorption on rotation of microscope stage; prisms usually well formed.

Zircon: colourless and varies from well formed prisms to more commonly badly weathered and nearly rounded grains; inclusions of unidentified bubbles infrequently found.

Results of heavy mineral analysis. (a) Till samples: Iron oxides were dominant in all samples ranging from 79.2% to 90.2% of any one sample (Appendix IV.I). The general order frequency of non opaque minerals was augite, followed by garnet and zircon; all other non opaque minerals totalled mere traces as individual categories. The number of weathered grains was always small ranging from 0.4 to 9.9% of the samples. There was a noticeably greater amount of weathered grains in the lower (grey) till unit and in the upper till unit compared with the middle till unit. Many of the weathered grains may have been unidentifiable augite crystals as this mineral was usually weathered and frequently could only just be identified. Often the weathered grains were very similar in shape to the identifiable augite crystals, being equally highly fragmented.

When 200 non opaque grains were counted the patterns of Figure 4.3 emerged. Augite was always dominant and totalled 29.0 to 65.5% of any sample; it was most common in the upper till unit, fell off in the middle till unit and increased again in the lower till unit. Garnet and zircon were present in approximately equal amounts. Apart from the top of the middle till unit (T5), garnet never totalled less than 10% of any sample and varied from 12.75% to 19.25%. Zircon was least plentiful in the upper till unit varying from 5.5% to 11.75% /

11.75% of samples T1 to T4 and in the other two units amounted to 9.0 to 19.0% of any sample.

The other non opaque minerals totalled less of all samples compared with zircon and garnet. Except in one instance (10.75% hornblende in T7); the other minerals never individually amounted to 10% of a sample and they were present in all 17 analyses. On the other hand biotite and hypersthene were only found in very small quantities (0.25 to 3.25% and 0.25 to 1.25% respectively) in the bottom parts of the middle till unit and the top parts of the lower till unit.

(b) Sand samples: The iron oxide content (81.5 to 96.8%) was absolutely dominant in all samples. Accordingly any of the categories of non opaque minerals rarely amounted to more than traces in any sample. It was noticeable that there were far fewer weathered grains in the sands than in the tills and this also tended to coincide with fewer augite grains.

Examination of only the non opaque minerals (Appendix IV.III and Figure 4.3) showed that augite was dominant in only 3 of the 10 samples. Garnet was always more common (8.5 to 32.75%) than zircon (4.25 to 21.5%) and both were very low in SIII and fell off in SI where augite was dominant in both instances. Apatite was found in 9 samples and was the most common non opaque mineral in SI (20.25%) and SVIII (21.0%) and second most common in SV (18.75%), SVI (23.75%) and SVII (17.5%). Hornblende (6.0 to 11.25%) was common. Most of the other minerals were less common and rarely constituted such large proportions as augite, zircon, garnet and apatite.

Results of light mineral analysis. The light minerals were examined as a routine study. In studies such as the present one no published evidence was found that obtained as revealing results as heavy mineral analysis. The reason for this is that the light mineral fraction does not provide a sufficient variety of different minerals; quartz and the felspars are ubiquitous.

Quartz/

Quartz was dominant in all samples and totalled 79.6 to 90.8% of the till samples and 71.7 to 89.4% of the sand samples. Weathered grains, orthoclase and coal fragments individually totalled amounts varying from 2.5 to 8.4% of any of the till samples. In the sand samples weathered grains formed 2.6 to 8.8% of any analysis whilst the coal fragments amounted to 2.4 to 16.8% of the samples. Samples SVI and SVII contained 16.8 and 15.3% respectively of coal fragments. Plagioclase, muscovite and biotite were only found in trace amounts in certain samples. Muscovite and biotite are more commonly found in the heavy mineral fraction but in this case they represent species that have specific gravities less than 2.95.

Discussion of results. It is not possible to state precisely the provenance of the ice that laid down the deposits examined because detailed mineralogical studies of all the lithologies in the Fala area are not available. In general terms it would appear that the source area has been the Southern Uplands with later movement across part of the Central Valley, particularly the Midlothian Basin.

Erratic counting showed that greywackes and Carboniferous sandstones were the dominant constituents of the deposits. The Southern Uplands would have provided an extensive source ground of the greywackes although small inliers of these rocks are also found in the Pentland Hills. Whilst these inliers may have added to the erratic content of the deposits, the total amount of greywackes was so consistently high that it is doubtful if the inlier outcrops could have been the sole source areas. Carboniferous sandstones occur extensively in the Midlothian Basin, particularly in the south western and south eastern areas adjacent to the Southern Uplands and could be the source of the Carboniferous sandstone pebbles and cobbles identified in the tills.

Old/

Old Red Sandstone outcrops in sizeable areas very close to the section worked, yet only occasional small fragments of this lithology were found in the erratics. It would seem that the local East Lothian Old Red Sandstone was not a constituent of the glacier load. Old Red Sandstone also outcrops extensively some 15 to 20 miles south west of Fala at the southern end of the Pentland Hills, in a broader belt immediately adjacent to the Southern Uplands in the area south of West Linton and also south of the Southern Upland fault in Berwickshire and Roxburghshire. Clough et al (1910), Mitchell and Mykura (1962) and Watt (1963) have shown that in the areas of Old Red Sandstone conglomerates mentioned, the conglomerate pebbles are very dominantly greywackes. Thus the greywacke content of the deposits could have been fortified by the Old Red Sandstone conglomerate eroded from the Tweed valley or some 20 miles south west of Fala or from the southern Pentland Hills. During transportation the matrix Old Red Sandstone could have been greatly broken down to fragments never as great as 8 mm. e.s.d. whilst the greywacke pebbles withstood the glacier attrition to a higher degree.

Mackie (1928) and Walton (1955) have shown that the Upper Ordovician greywackes adjacent to the Southern Upland fault are particularly rich in augite. In certain parts of this formation, such as the Coulter area south of Biggar, very large phenocrysts of augite are found (Walton, personal communication). None of the Central Valley rocks in the Fala area are known to contain large amounts of augite. The augites identified in the heavy mineral analysis commonly displayed evidence of severe weathering that could be explained by their having been broken down from larger phenocrysts during transportation. If the source material of the depositing ice had been added to by material from as far south-west as Coulter it is surprising that none of the readily recognised Tinto felsites were found in any analysis. However, the source of the augite crystals whilst probably dominantly Upper Ordovician could well have been further north east/

east towards Fala than Coulter.

Walton (1955) has also distinguished an extensive band of the Lower Silurian greywackes that coincides with the highest parts of the Southern Uplands and is characterised by a high garnet content. The garnets commonly have a sieve like appearance. Garnets, often with sieve like appearance, were one of the most commonly occuring non opaque minerals found in the till samples. If the depositing ice had come from the Southern Uplands, any garnet rich greywackes picked up in the highest parts would be diluted by the addition of the successive rocks that the ice traversed.

The source area of the tuffs is problematic. Duff (personal communication) suggested that they might have originated in the Old Red Sandstone formations of the southern Pentland Hills rather than in the Carboniferous measures.(Clough et al. 1910) noted the presence of volcanic debris in the tills near Fala and suggested its source was the Pentland Hills. This seems unlikely because distinctive lavas are much more extensive than tuffs in the southern Pentlands and would accordingly be more common than tuffs if the source area had been the southern Pentlands. Eckford and Ritchie (1931) have shown that the Tweeddale lavas are very commonly associated with tuffs. Thus the Southern Uplands could have been a source of the volcanic rocks found in the glacial deposits.

Lack of very detailed mineralogical work in all the lithologies of the general area makes definite correlations impossible. Minerals such as quartz and zircon are quite ubiquitous and all of the minerals found might occur in small quantities in almost any of the rocks.

Coal fragments found in all deposits were probably derived from the Coal Measures or Carboniferous Limestone Series of the Midlothian Basin. Larger amounts of coal fragments tended to be found in the samples in which limestone also occurred; their presence in sizeable quantities in some of the bands is

a/

a result of their being easily washed out and transported in water since their specific gravity is low.

It is very difficult to explain the mineral assemblages of the sands. The small amount of weathered grains present and the low augite totals in many samples probably reflect washing out of the augite and weathered grains by the depositing glacial meltwaters. Frequent sizeable proportions of the easily soluble apatite may be explained by its lower specific gravity - in comparison with many of the heavy minerals - and thus possibility of transportation in waters not sufficientl swift flowing to carry other heavy minerals species. Sudden reduction in volume and termination of the transporting water supply could have lead to the concentrations of apatite. Mackie (1923) suggested that apatite and hornblende were more easily transported by water and might be completely swept out in certain instances in comparison with the heavier zircons, iron oxides and garnets.

The most striking feature of the mineralogical analysis was the presence of limestone only in the bottom part of the middle till unit and in the lower till unit. Solomon (1932) and Flint (1957) both believed that the basal part of tills deposited by the same ice tended to contain large amounts of very local bedrock as well as further travelled erratics; higher up in the same deposit, the percentage of very local material decreased and even disappeared with a proportionate increase in the percentage of more distant lithologies.

Clough et al (1910) have pointed out that appreciable quantities of Carboniferous limestone have been carried from the Midlothian Basin to the north onto the foothills of the Southern Uplands. Giant limestone erratics are found resting unconformably on older rocks at Kidlaw, Marl Law quarry and Woodcote Park. Current remapping of the area around Fala by the Geological Survey confirms that these giant limestone outcrops are not in situ outliers but erratics (Tulloch, personal/

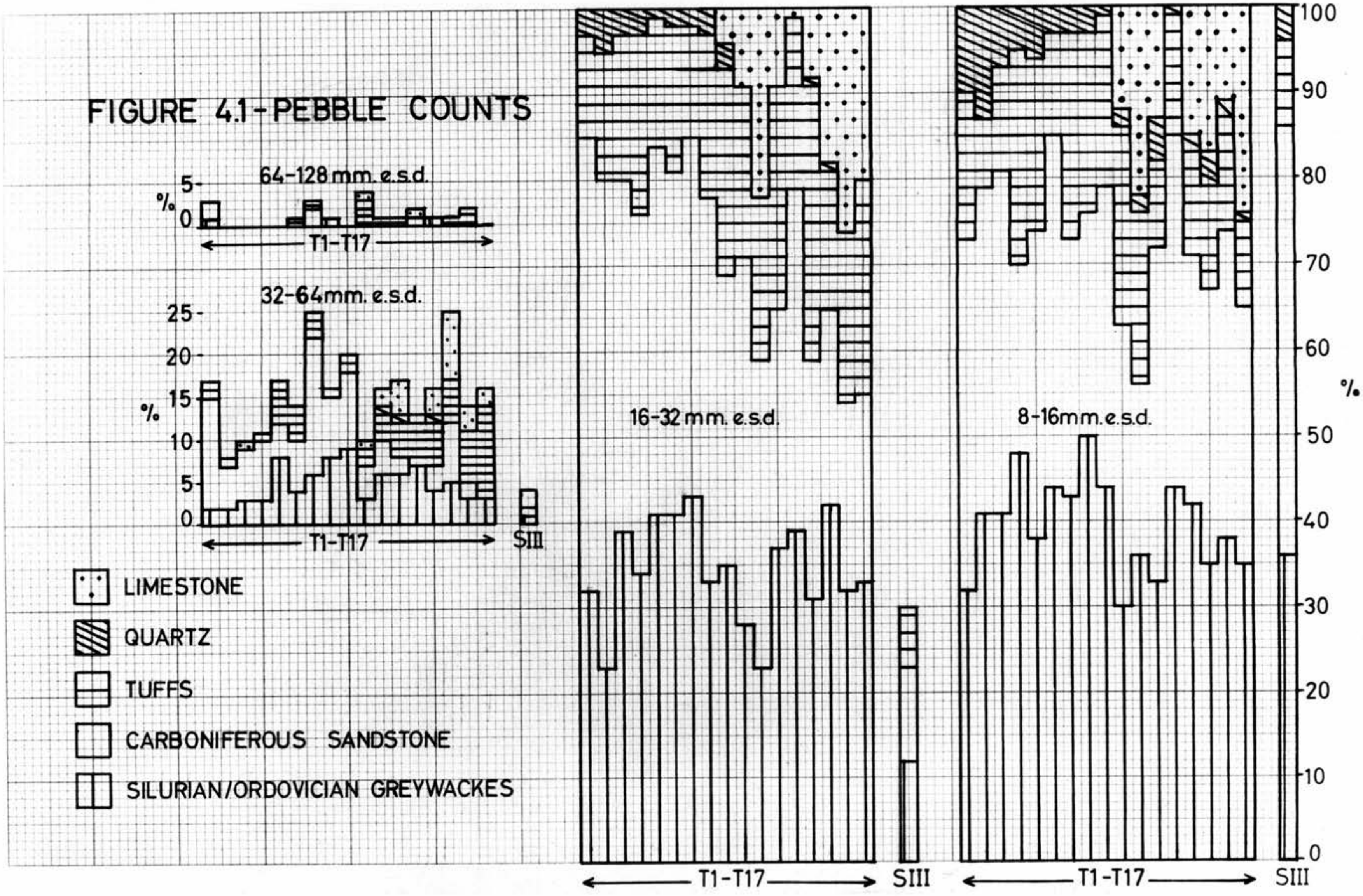
personal communication).

No identifiable Highland lithologies were found in the tills or sands. Geikie (1894) identified Highland schist erratics along the northern face of the Lammermuirs and Clough et al (1910) noted that near Tynehead they were so numerous that they figured prominently in the dry stone dykes. Anderson (1940) and McCall and Goodlet (1951) have also described the presence of Highland rocks in the tills of Midlothian.

Apart from the lower parts of the section (Figure 1.2) below T9, the macro and micro mineralogies were not dissimilar and varied only in relative amounts of the same mineralogical constituents. Examination of the micro mineralogy showed that there was no evidence of weathering surfaces in the section. The presence of such very easily weathered minerals as apatite and hornblende at all levels excepting S0 supported the conclusion that very little subaerial weathering had affected the various levels of the deposits other than the present day top sands. S0 represents the 3 ft. 9 ins. of capping sands through which soil solutions could have percolated easily and remove the readily soluble apatite.

Thus the mineralogical evidence appears to suggest that the deposits exposed in the section examined may have all been laid down by the same ice. It would seem that the ice originated largely in the Southern Uplands, flowed into the Midlothian Basin and was finally diverted south east into the Fala area before depositing the tills and sands examined.

FIGURE 4.1 - PEBBLE COUNTS



HEAVY MINERALS

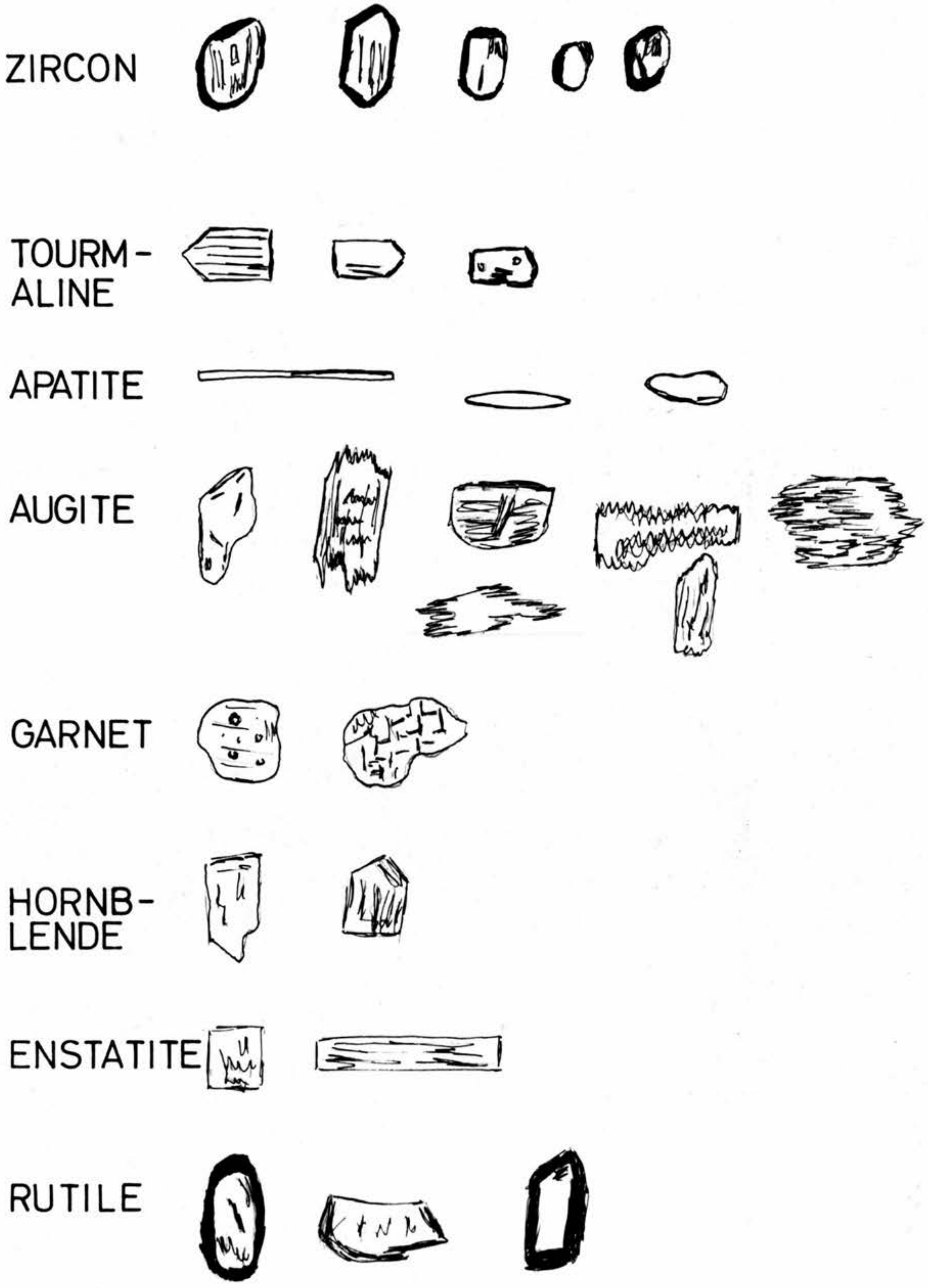
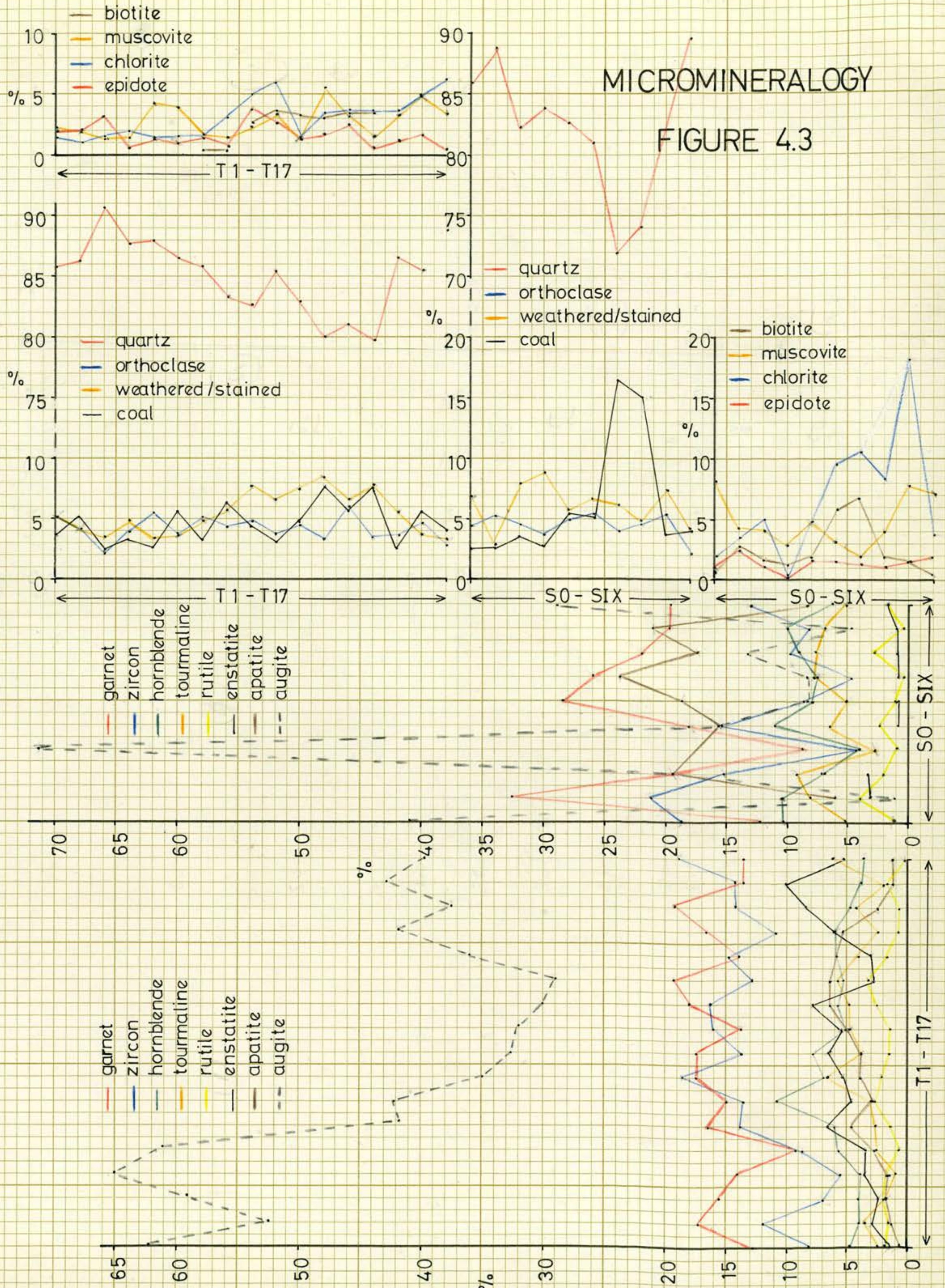


FIGURE 4.2



MICROMINERALOGY

FIGURE 4.3

Chapter 5. pH and Soluble Carbonate Analyses

pH and soluble carbonate analyses yielded evidence of the chemical properties of the tills and sands investigated. The actual methods of the analyses were both simple and rapid to carry out. A general relationship between pH and soluble carbonate content was noted and the results of these analyses produced further evidence to help elucidate the basic properties of the tills and distinguish the separate facies of the section (Figure 1.2).

The literature relevant to detailed quantitative investigations of tills bore very little evidence of any form of chemical studies. Kruger (1937) was the earliest worker found to have investigated soluble carbonate content of tills with a view to differentiating the various drifts of Minnesota. Dreimanis and Reavely (1953), Dreimanis (1960, 1962), Johnson (1964) and Andrews and Sim (1964) have all used a Chittick apparatus to measure soluble carbonate content of tills in various other parts of North America. All these workers have concluded that the results obtained greatly aided their provenance and stratigraphic studies of the various tills.

The methods of analysis used in the current investigations were standard procedures. pH was determined electrometrically using a Cambridge bench pH meter that could be read accurately to the second decimal place. Soluble carbonate content was measured using a calcimeter and the method outlines by Collins (1906) was followed. In both pH and soluble carbonate analyses, duplicate portions of each sample were used and the mean results are included in Appendix V.I and graphed in Figure 5.1.

Portions of the total fraction less than 2 mm. were used in both pH and soluble carbonate analyses. In the pH analyses, reasonable parity of duplicate portions was found whereas in the soluble carbonate analyses it was impossible/

impossible to obtain two similar results from the same sample. Dreimanis and Reavely (1953), Dreimanis (1960, 1962) and Andrews and Sim (1964) all used portions of the sample from the fraction that had passed through the 200 mesh sieve; they found that most of the soluble carbonates were present in the fine sand, silt and clay grades. Also, during analysis the rate of reaction between the soluble carbonates and the dissolving acid was comparable only when the grain size of all samples was relatively similar and small. During the present research when portions of the sample less than 200 mesh were used, comparable duplicate results were obtained in the soluble carbonate analyses. The pH analyses were repeated on the finer fraction (less than 200 mesh) and all results are shown in Appendix V.I.

The results of pH analysis of the two size fractions were comparable and within ± 0.3 with the exception of sample T13 which varied by 0.65. Where pH increased or decreased noticeably, soluble carbonate content was also seen to rise or fall with the same general pattern. The pH range was 6.00 to 8.375 in the tills and 5.20 to 7.65 in the sands; soluble carbonate range was 0.34% to 24.94% in the tills and nil to 5.49% in the sands.

On the basis of pH, samples T1 to T8, T9 to T12, T13 on its own and T14 to T17 appeared to form four separate groupings. Soluble carbonate analysis also suggested four groupings of the till samples. These groupings were T1 to T8, T9 to T11, T12 and T13 and T14 to T17.

The sand samples all have lower pH and soluble carbonate values than the adjacent till samples. With the exception of SIX, the soluble carbonate content of the sands amounted to little more than a trace. The samples were taken from four different levels (Figure 1.2). Five different groupings can be made on the basis of pH; these were S0 on its own, SI to SIV, SV and SVI, SVII and SVIII and SIX on its own.

In/

In the analyses of the tills, soluble carbonate assessments produced more dramatic differences than pH measurements between the four groups identified due to the wider range of values obtained. The sudden drop in soluble carbonate content from T11 to T12 was not reflected in pH values. Increases of 6.13% from T14 to T15 and 4.74% from T15 to T16 were not reflected in the pH values measured at these levels.

On the other hand, the pH values of the sands varied more delicately than the soluble carbonate values. The low soluble carbonate values, excepting SIX, were a reflection of the washing out of most of the soluble matter from the sand samples prior to deposition. SIX was a sample from a narrow and discontinuous lens in the middle of the lower till unit. It was obvious that SIX had not been washed to the same extent as the other identified sand levels. The very low pH value of S0 was a reflection of its capping position in the section (Figure 1.2), and the result of post depositional leaching by the surface waters down through the top $3\frac{1}{2}$ ft. of sand.

pH and soluble carbonate analyses thus provided further valuable criteria to add to the evidence of Chapters 2, 3 and 4 to enable fuller understanding of the properties of the tills and sands. There appeared to be four distinctly different tills levels that did not correspond to the three till units. The upper till unit and the top 6 ft. of the middle till unit formed one group; the remainder of the middle till unit excepting the bottom 2 ft. formed a second unit, the bottom of the middle till unit and top of the lower till unit a third group and the remainder of the lower till unit a fourth group.

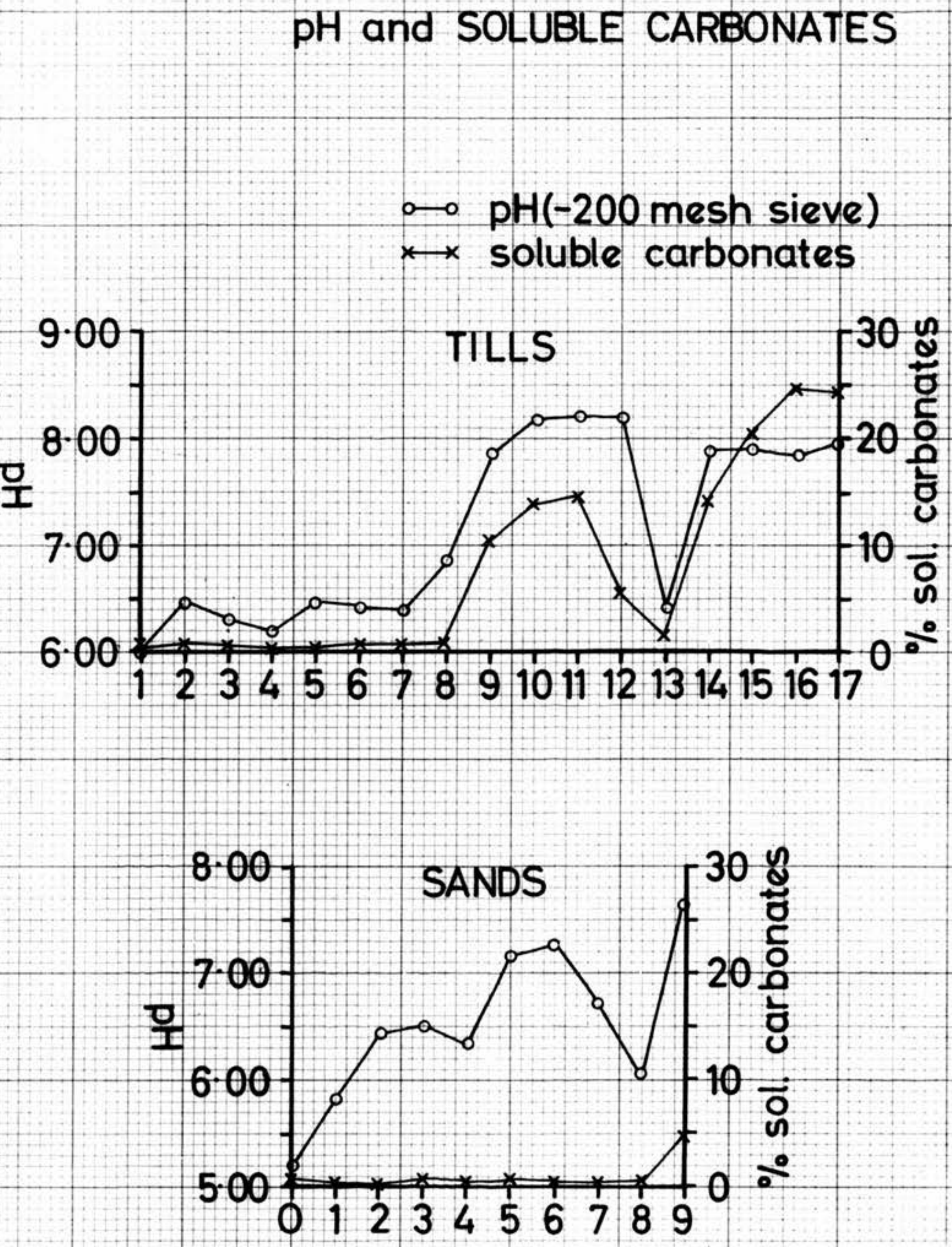

pH and SOLUBLE CARBONATES
pH(-200 mesh sieve)
soluble carbonates
TILLS
9·00
8·00
7·00
6·00
pH
30
20
10
0
% sol. carbonates
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
SANDS
8·00
7·00
6·00
5·00
pH
30
20
10
0
% sol. carbonates
0 1 2 3 4 5 6 7 8 9

FIGURE 5.1

Chapter 6. Principal Results of the Research and Conclusions

1. Rapid and radical changes are found over very short distances in the stratigraphical succession of the area around Fala and Upper Keith. A reddish brown till overlying a dark grey till, and often separated from it by currently bedded sands, is restricted to a definable tract. The approximate limits of this tract are (a) the base of the Lammermuir scarp to the south east (b) the limestone ridge running north east from Hope Farm (Map reference 408628) to the north west and (c) a line from Keith Marischal (449644) to Humbie Mains (471626) to the north east. No south western limit was found in this area.

2. Orientation and dip analysis of the till macrofabric produced several important results. The variability of preferred alignment of the constituent pebbles in the tills could be considerable in a depth of 2 ft.; on the other hand, over similar lateral distances closely comparable alignments were found. Differences of preferred orientation of the pebbles within the same till unit were as great as the differences between the three till units and there was no simple rate of change in the preferred orientation over any given depth.

Strength values of the preferred orientations were calculated and, whilst good measures of the concentration or dispersion of the stones, they varied very greatly even when similar orientation values were obtained at the same level in the till.

Peaks transverse to the main calculated alignment of stones were found in all cases. Further studies of the fragmentation within the main and minor peaks showed that caution should be exercised when interpreting the shapes of rose diagram plots.

A preferred orientation calculated on the basis of the first 50 stones measured produced a very similar value to an orientation calculated from the measurement of 100 stones: in some instances a measurement of 25 stones could be adequate. /

As a contrast, calculation based on the measurement of up to 400 stones produced no greatly different orientation value.

The full usefulness of measuring the dip of the long axis of the stones was left unanswered. For comparative purposes, the mean dip of 100 stones appeared to offer best results. Preferred direction of the dip of the stones was very inconsistent, even at the same level of study and was discredited as a reliable index in the determination of ice movement. Mean dip values for all the analyses were comparatively homogeneous with 66% of all stones measured dipping $< 10^{\circ}$: this seemed to favour deposition of the tills in a lodgement process rather than as ablation material.

In 27 of the 29 orientation analyses, statistically significant results of the calculated preferred alignment of the stones were obtained. This arrangement of the stones in response to a specific force is interpreted as evidence of a former flowage pattern of the depositing ice. Considerable variations in the direction of ice flow must have taken place during the time that the till units investigated were built up.

23 of the 29 analyses suggested movement of the depositing ice with a trend approximately north west to south east. However, since there was no way of assessing whether the flow had been north west to south east or vice versa on the basis of orientation and dip results alone, no definite conclusion could be reached solely from this form of analysis.

There may be several different pebble alignments in a till of any thickness and any one orientation analysis may not be representative of the till.

3. The tills examined are remarkably homogeneous on a particle size basis; the most striking difference, in the analyses was between tills and sands. There is thus no difference in the degree of grinding between the three different till units. It is suggested that the upper tills in the section are not derived from the lower tills./

4. On the basis of the mineralogy it is apparent that the source of the depositing ice has been the Southern Uplands with movement later across a restricted part of the Midlothian Basin. The erratic content of the three till units is not greatly different excepting the discovery of limestone in the lower parts of the middle till unit and in the lower till unit.

5. There is a general relationship between pH and soluble carbonate content. The lower till unit and bottom of the middle till unit both contain appreciable amounts of soluble carbonates and have higher pH values in comparison with the upper till unit and top of the middle till unit.

From the principal findings of the research, certain general conclusions can be made. The inclusion of erratics from the Midlothian Basin in the tills confirms that the depositing ice moved across this area at some stage and did not simply slip off the Lammermuir plateau. Adding this fact to the findings of the preferred orientation of the stones in the tills, it can be concluded that the depositing ice moved from a general north west to south east direction.

Other evidence outwith this study shows that c. 16 miles from this area ice flowing south to north from the Eddelston Valley turned north east as it entered the Midlothian Basin. If the tills examined in this study belong to the same advance of ice, some other force must have diverted the ice further round on its original path of entry into the area and towards the Fala area. Sissons (1961) believes that Highland ice was pushing against the Lammermuirs only a mile further north east from Fala at this point of the final glaciation. It may thus be that the same Highland ice mass was the cause of the Eddelston Valley ice being turned north east on entering the Midlothian Basin and eventually being pushed back south east into the area around Fala.

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APPENDIX II.I

Orientation, strength and dispersion of stones about calculated orientation.

			No. of stones within given arc across calculated orient^{n}				
No.	Orientation	Str.%	±5°	±10°	±15°	±20°	±45°
T1	N37W/S37E	51	15	23	34	42	84
T1(N)	W14E/E14S	35	7	14	28	37	78
T1(S)	N35W/S35E	39	8	29	35	43	71
T1(W)	N41W/S41E	60	21	38	50	60	85
T2	W20N/E20S	40	9	20	40	44	73
T2(N)	W25N/E25S	55	17	35	48	58	83
T2(S)	W21N/E21S	49	17	22	34	44	82
T2(W)	W35N/E35S	31	10	24	37	48	69
T3	E30N/W30S	40	8	18	31	35	74
T3(N)	E33N/W33S	24	9	15	22	32	68
T3(S)	E35N/W35S	35	14	22	33	45	71
T3(W)	E40N/W40S	66	20	35	51	61	92
T4	N/S	30	11	15	27	34	69
T5	W39N/E39S	29	5	16	31	40	67
T6	W27N/E27S	34	9	19	26	43	71
T7	W38N/E38S	67	21	38	52	59	90
T8	W30N/E30S	39	9	20	32	43	75
T9	N41E/S41W	8	3	12	16	21	54
T10	N23W/S23E	40	10	15	38	48	72
T11	N26W/S26E	12	9	18	24	31	57
T12	W35N/E35S	25	8	14	19	31	68
T13	N25W/S25E	38	9	22	35	43	73
T14	N17W/S17E	56	13	27	36	49	85
T14(A)	N23W/S23E	24	11	22	27	33	67
T14(B)	N27W/S27E	26	7	18	26	35	68
T14(C)	N/S	40	6	23	29	38	78
T15	N20W/S20E	49	10	25	36	49	80
T16	N4W/S4E	51	13	25	36	46	83
T17	N23E/S23W	50	16	32	36	44	79

APPENDIX II.II

Comparative Groupings of Orientation.

	5° grouping		"5-4" 10° grouping		"4-5" 10° grouping		"10-9" 20° grouping		"9-10" 20° grouping	
No.	Ortn.	Str.	Ortn.	Str.	Ortn.	Str.	Ortn.	Str.	Ortn.	Str.
T14	N20W/S20E	57	N17W/S17E	56	N22W/S22E	56	N22W/S22E	54	N28W/S28E	53
T14(A)	N27W/S27E	22	N23W/S23E	24	N29W/S29E	21	N28W/S28E	24	N32W/S32E	22
T14(B)	N31W/S31E	25	N27W/S27E	26	N33W/S33E	25	N32W/S32E	27	N38W/S38E	26
T14(C)	N2W/S2E	40	N/S	40	N5W/S5E	40	N4W/S4E	39	N1W/S1E	38
T1(W)	N43W/S43E	60	N41W/S41E	60	-	-	E43S/W43N	66	-	-
T7	W37N/E37S	68	W38N/E38S	67	-	-	W36N/E36S	65	-	-

APPENDIX II.III

Comparative stone numbers

	100 stones		50 stones		25 stones		10 stones		5 stones	
No.	Ortn.	Str.	Ortn.	Str.	Ortn.	Str.	Ortn.	Str.	Ortn.	Str.
T1(W)	N41W/S41E	60	N43W/S43E	54	N44W/S44E	48	N34W/S34E	47	N40W/S40E	51
T7	E38S/W38N	67	E37S/W37N	70	E38S/W38N	72	E40S/W40N	62	E35S/W35N	60
T2	E20S/W20N	40	E16S/W16N	44	E33S/W33N	42	E37S/W37N	43	E8N/W8S	27
T15	N20W/S20E	49	N24W/S24E	50	N25W/S25E	60	N27W/S27E	69	N17W/S17E	77
T3(N)	E33N/W33S	24	E43N/W43S	17	N10E/S10W	12	N16W/S16E	23	N32W/S32E	74
T5	E39S/W39N	29	E39S/W39N	30	E28S/W28N	17	S37E/N37W	10	E42N/W42S	48

APPENDIX II.IV.

Composite Recalculations of Orientation

Numbers	Orientation	Str.	Orientation *	Strs.
T1 + T1(S) + T1(W)	N38W/S38E	50	N37W/S37E	51
T1 + T1(S) + T1(N) + T1(W)	N44W/S44E	40	N37W/S37E	51
T2 + T2(N) + T2(S)	W23N/E23S	48	W20N/E20S	40
T2 + T2(N) + T2(S) + T2(W)	W25N/E25S	43	W20N/E20S	40
T3 + T3(N) + T3(S)	E33N/W33S	33	E30N/W30S	40
T3 + T3(N) + T3(S) + T3(W)	E35N/W35S	41	E30N/W30S	40
T5 + T6 + T7 + T8	W36N/E36S	42		
T10 + T11	N23W/S23E	25		
T14 + T14(A) + T14(B)	N21W/S21E	35	N17W/S17E	56
T14 + T14(A) + T14(B) + T14(C)	N16W/S16E	35	N17W/S17E	56
T13 + T14 + T14(A) + T14(B) + T15	N22W/S22E	38		
T14(C) + T16 + T17	N7E/S7W	43		

* "Original" values quoted where relevant.

APPENDIX II.V

Dip Frequencies

No.	DIP													Median	No. >	No. ≤
	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°		20°	10°
T1	21	31	17	12	4	4	2	5	1	2	1	-	-	5	15	69
T1(N)	21	37	17	12	9	2	1	-	1	-	-	-	-	5	4	75
T1(S)	25	30	19	16	2	4	3	1	-	-	-	-	-	5	8	74
T1(W)	21	42	24	4	4	2	1	-	2	-	-	-	-	5	5	67
T2	16	33	16	11	7	7	4	3	3	-	-	-	-	10	17	65
T2(N)	20	31	14	11	8	4	5	3	1	2	-	1	-	5	16	65
T2(S)	17	25	22	15	11	3	2	2	2	-	1	-	-	10	10	64
T2(W)	18	26	19	14	9	5	7	-	1	1	-	-	-	10	14	63
T3	20	23	28	17	4	3	1	2	1	1	-	-	-	10	8	71
T3(N)	14	30	24	15	7	7	2	-	1	-	-	-	-	10	10	68
T3(S)	17	30	27	15	2	4	2	-	2	-	1	-	-	10	9	74
T3(W)	23	41	18	4	7	2	2	-	2	-	1	-	-	5	7	82
T4	28	26	17	9	10	5	4	1	-	-	-	-	-	5	10	71
T5	13	25	12	15	10	10	4	7	1	-	1	1	1	10	25	50
T6	15	23	21	16	9	7	2	4	2	1	-	-	-	10	16	59
T7	14	38	22	15	3	2	3	1	-	1	1	-	-	5	8	74
T8	13	18	25	15	10	7	2	5	2	3	-	-	-	10	17	56
T9	11	32	19	14	10	2	3	4	3	2	-	-	-	10	14	62
T10	9	27	19	16	5	10	4	4	2	1	3	-	-	10	24	55
T11	12	13	18	15	10	10	5	8	4	3	1	1	-	10	32	43
T12	16	14	19	8	9	11	6	8	3	2	2	1	1	15	34	49
T13	20	21	16	19	9	4	8	1	2	-	-	-	-	10	15	57
T14	16	24	21	19	11	6	2	-	-	1	-	-	-	10	9	61
T14(A)	22	26	15	11	11	5	5	1	3	1	-	-	-	10	15	63
T14(B)	24	39	19	9	4	3	-	1	1	-	-	-	-	5	5	82
T14(C)	21	33	17	16	7	2	2	1	1	-	-	-	-	5	6	71
T15	20	33	14	20	5	3	3	1	1	-	-	-	-	5	8	67
T16	22	33	18	12	3	5	2	2	-	1	1	1	-	5	12	73
T17	19	34	18	16	7	2	3	-	-	1	-	-	-	5	6	71

APPENDIX II.VI

	MEAN DIP		
No.	All Stones	Main peak	Cross peak
T1	11.00	9.81	17.4
T1(N)	8.35	7.83	10.2
T1(S)	8.45	8.18	9.15
T1(W)	7.50	7.36	8.34
T2	11.50	9.87	15.9
T2(N)	11.60	10.12	18.8
T2(S)	11.25	10.27	15.8
T2(W)	11.30	11.09	11.8
T3	9.90	9.80	10.2
T3(N)	10.30	7.73	15.8
T3(S)	9.75	9.79	9.76
T3(W)	8.75	7.67	15.0
T4	9.15	8.78	10.0
T5	14.90	15.48	13.9
T6	12.45	10.29	17.8
T7	9.15	8.73	13.0
T8	13.90	12.99	16.6
T9	12.50	12.41	12.6
T10	14.50	12.78	18.9
T11	17.50	13.93	22.2
T12	17.20	17.50	16.6
T13	11.85	11.57	12.6
T14	10.90	10.29	14.3
T14(A)	11.75	10.60	13.9
T14(B)	7.50	6.55	9.54
T14(C)	9.00	9.04	8.86
T15	9.45	9.50	9.25
T16	9.90	9.39	12.4
T17	9.15	8.62	11.2

APPENDIX II.VII

Dip Analysis in Cross Peak.

Analysis No.	No. of stones	DIP IN DEGREES (°).												
		0	5	10	15	20	25	30	35	40	45	50	55	60
T1	16	5	1	2	-	1	2	1	3	-	1	-	-	-
T1(N)	22	5	6	2	5	3	-	-	-	1	-	-	-	-
T1(S)	29	7	6	8	5	1	-	2	-	-	-	-	-	-
T1(W)	15	2	6	5	-	1	1	-	-	-	-	-	-	-
T2	27	1	7	4	5	3	2	2	2	1	-	-	-	-
T2(N)	17	1	3	2	2	3	1	3	1	-	1	-	-	-
T2(S)	18	3	1	2	3	5	2	1	1	-	-	-	-	-
T2(W)	31	4	7	8	6	2	-	4	-	-	-	-	-	-
T3	26	6	6	5	5	1	1	1	1	-	-	-	-	-
T3(N)	32	2	3	8	8	3	5	2	-	1	-	-	-	-
T3(S)	29	6	9	7	3	1	2	-	-	-	-	1	-	-
T3(W)	8	1	1	3	-	1	1	-	-	1	-	-	-	-
T4	31	6	9	8	1	2	4	1	-	-	-	-	-	-
T5	33	4	10	4	5	3	3	1	1	1	-	-	1	-
T6	29	3	1	6	6	4	5	-	2	1	1	-	-	-
T7	10	1	2	4	2	-	-	-	-	-	-	1	-	-
T8	25	2	4	6	4	2	3	-	1	2	1	-	-	-
T9	46	7	10	10	6	8	-	2	1	1	1	-	-	-
T10	28	1	5	7	2	3	2	-	3	2	1	2	-	-
T11	43	2	3	8	4	6	6	3	6	2	1	1	1	-
T12	32	4	5	7	4	3	2	1	4	1	-	-	1	-
T13	27	6	3	5	6	2	3	1	-	1	-	-	-	-
T14	15	2	6	-	2	1	1	1	1	-	1	-	-	-
T14(A)	33	6	8	4	2	4	4	2	2	1	-	-	-	-
T14(B)	32	7	8	9	5	-	1	-	1	1	-	-	-	-
T14(C)	22	4	8	2	6	1	1	-	-	-	-	-	-	-
T15	20	3	10	2	1	1	2	1	-	-	-	-	-	-
T16	17	3	5	1	4	3	-	-	-	-	-	-	1	-
T17	21	5	4	6	1	2	1	1	-	1	-	-	-	-

APPENDIX III.I

Particle Size Analysis

(All figures expressed as percentages)

No.	<2mm.	<0.002 mm.	0.002 -0.006 mm.	0.006 -0.02 mm.	0.02 -0.06 mm.	0.06 -0.2 mm.	0.2 -0.6 mm.	0.6 -2.0 mm.	2-4 mm.	4-8 mm.	8-16 mm.	16-32 mm.	32-64 mm.	64-128 mm.	128-256 mm.
T1	81.99	18.12	6.72	6.40	8.85	24.11	13.61	4.18	0.78	1.04	1.69	3.90	2.60	7.99	-
T2	93.13	22.72	7.08	8.01	9.69	25.61	14.62	5.40	0.55	0.82	1.10	2.75	1.65	--	-
T3	84.18	19.45	5.97	6.99	8.00	23.74	15.32	4.71	2.28	2.95	4.02	5.23	1.34	--	-
T4	86.28	15.53	6.04	8.71	11.22	23.38	14.50	6.90	2.10	1.98	2.47	3.83	0.99	2.35	-
T5	78.97	12.32	4.90	7.42	9.87	23.53	15.09	5.84	5.50	4.66	3.94	3.35	3.58	-	-
T6	86.37	16.58	6.83	10.45	11.74	24.45	12.35	3.97	1.22	1.34	1.95	4.14	4.26	0.73	-
T7	85.72	14.83	6.60	9.43	12.69	25.03	12.85	4.29	0.46	0.68	1.53	4.10	4.78	2.73	-
T8	88.18	18.08	6.87	9.62	12.34	23.28	13.40	4.59	0.50	0.87	1.87	4.73	3.36	0.50	-
T9	81.35	15.54	7.16	9.60	13.26	22.20	10.01	3.58	2.58	3.03	3.29	5.49	4.26	-	-
T10	72.26	13.87	6.80	8.88	11.06	19.29	8.39	3.97	1.49	1.70	2.28	3.40	1.43	17.44	-
T11	82.40	15.74	6.59	8.57	12.36	25.05	10.71	3.38	2.95	2.83	3.33	4.08	3.51	0.91	-
T12	80.60	17.80	6.41	8.07	12.23	24.04	10.73	3.91	3.33	2.47	2.47	2.38	5.81	0.37	-
T13	83.13	17.87	8.48	9.25	12.62	21.28	10.22	3.41	1.96	1.16	2.08	3.00	2.89	5.78	-
T14	62.43	11.86	5.00	6.61	12.05	16.55	7.80	2.56	1.71	1.52	2.24	2.64	2.40	1.04	26.0
T15	80.56	14.82	6.05	8.05	10.47	19.10	13.37	8.70	1.16	1.04	4.34	6.97	5.34	0.58	-
T16	85.27	21.66	8.27	9.98	9.72	18.67	12.02	4.95	0.91	1.04	2.61	3.39	3.39	3.39	-
T17	85.93	21.40	7.90	9.63	10.91	20.11	11.77	4.21	2.08	1.56	2.78	3.82	3.82	-	-
SO	100.0	13.2	4.1	5.5	21.1	32.3	20.9	2.9	-	-	-	-	-	-	-
SI	"	12.4	4.9	10.3	22.7	43.0	6.3	0.4	-	-	-	-	-	-	-
SII	"	10.0	4.2	13.1	23.5	37.6	9.3	2.3	-	-	-	-	-	-	-
SIII	60.19	4.33	1.69	2.71	5.05	13.61	29.25	3.55	8.66	8.66	3.46	10.39	8.66	-	-
SIV	100.0	6.9	2.5	7.4	15.9	44.5	18.6	4.2	-	-	-	-	-	-	-
SV	"	7.5	2.1	5.1	17.6	60.4	6.9	0.4	-	-	-	-	-	-	-
SVI	"	5.8	1.9	5.7	18.1	54.9	13.4	0.2	-	-	-	-	-	-	-
SVII	"	11.8	6.2	17.7	23.7	30.8	8.5	1.3	-	-	-	-	-	-	-
SVIII	"	5.3	2.0	4.2	15.7	66.2	6.4	0.2	-	-	-	-	-	-	-
SIX	97.21	7.68	3.89	6.51	13.80	47.82	14.28	3.21	0.79	2.03	-	-	-	-	-

APPENDIX III.II.

Particle Size Analysis

(All figures expressed as percentages)

	Clay	Silt	Sand	Granule	Pebble	Cobble	Total
No.	< 0.002 mm.	0.002-0.06mm.	0.06-2.0mm.	2-4 mm.	4-64 mm.	64-256 mm.	> 2mm.
T1	18.12	21.97	41.90	0.78	9.23	7.99	18.00
T2	22.72	24.78	45.63	0.55	6.32	-	6.87
T3	19.45	20.96	43.77	2.28	13.54	-	15.82
T4	15.53	25.97	44.78	2.10	9.27	2.35	13.72
T5	12.32	22.19	44.46	5.50	15.53	-	21.03
T6	16.58	29.02	40.77	1.22	11.69	0.73	13.64
T7	14.83	28.72	42.17	0.46	11.09	2.73	14.28
T8	18.08	28.83	41.27	0.50	10.83	0.50	11.83
T9	15.54	30.02	35.79	2.58	16.07	-	18.65
T10	13.87	26.74	31.65	1.49	8.81	17.44	27.74
T11	15.74	27.52	39.14	2.95	13.75	0.91	17.61
T12	17.80	26.71	38.68	3.33	13.10	0.37	16.80
T13	17.87	30.35	34.91	1.96	9.13	5.78	16.87
T14	11.86	23.66	26.91	1.71	8.80	27.05	37.56
T15	14.82	24.57	41.17	1.16	17.69	0.58	19.43
T16	21.66	27.97	35.64	0.91	10.43	3.39	14.73
T17	21.40	28.44	36.09	2.08	11.98	-	14.06
SO	13.20	30.70	56.10	-	-	-	-
SI	12.40	37.90	49.70	-	-	-	-
SII	10.00	40.80	49.20	-	-	-	-
SIII	4.33	9.45	46.41	8.66	31.17	-	39.83
SIV	6.90	25.80	67.30	-	-	-	-
SV	7.50	24.80	67.70	-	-	-	-
SVI	5.80	25.70	68.50	-	-	-	-
SVII	11.80	47.60	40.60	-	-	-	-
SVIII	5.30	21.90	72.80	-	-	-	-
SIX	7.68	24.20	65.31	0.79	2.03	-	2.82

APPENDIX III.III

Distribution of Material <2 mm.

(All figures expressed as percentages)

	Clay	Silt	Sand
No.	< 0.002 mm.	0.002-0.06mm.	0.06-2.0 mm.
T1	22.1	26.8	51.1
T2	24.4	26.6	49.0
T3	23.1	24.9	52.0
T4	18.0	30.1	51.9
T5	15.6	28.1	56.3
T6	19.2	33.6	47.2
T7	17.3	33.5	49.2
T8	20.5	32.7	46.8
T9	19.1	36.9	44.0
T10	19.2	37.0	43.8
T11	19.1	33.4	47.5
T12	21.4	32.1	46.5
T13	21.5	36.5	42.0
T14	19.0	37.9	43.1
T15	18.4	30.5	51.1
T16	25.4	32.8	41.8
T17	24.9	33.1	42.0
S0	13.2	30.7	56.1
SI	12.4	37.9	49.7
SII	10.0	40.8	49.2
SIII	7.2	15.7	77.1
SIV	6.9	25.8	67.3
SV	7.5	24.8	67.7
SVI	5.8	25.7	68.5
SVII	11.8	47.6	40.6
SVIII	5.3	21.9	72.8
SIX	7.9	24.9	67.2

APPENDIX IV.I

Pebble Counts.

Sample Number	Sieve Limits	Calc. S'stn.	Sieve Limits	Ord. Silurian	Carb. L'stn.	Calc. S'stn.	Tuffs etc.	Quartz	Sieve Limits	Ord. Silurian	Carb. L'stn.	Calc. S'stn.	Tuffs etc.	Quartz	Sieve Limits	Ord. Silurian	Carb. L'stn.	Calc. S'stn.	Tuffs etc.	Quartz	Sieve Limits	Ord. Silurian	Carb. L'stn.	Calc. S'stn.	Tuffs etc.	Quartz
T1	(mm)	-	(mm)	1+	-	2+	-	-	(mm)	2+	-	13+	2+	-	(mm)	32	-	53	12	3	(mm)	32	-	41	17	10
T2	128 256	-	64 128	-	-	-	-	-	32 64	2+	-	5+	1+	-	16– 32	23	-	57	15	5	8– 16	42	-	37	8	13
T3		-	-	-	-	-	-	-		3+	-	6+	-	1+		39	-	41	17	3		42	-	39	12	7
T4		-	-	-	-	-	-	-		3+	-	7+	1+	-		34	-	42	21	3		48	-	22	25	5
T5		-	-	-	-	-	-	-		8+	-	4+	5+	-		41	-	43	15	1		38	-	36	20	6
T6		-	-	-	-	-	1+	-		4+	-	6+	4+	-		41	-	40	17	2		44	-	41	13	2
T7		-	-	-	-	2+	1+	-		6+	-	16+	3+	-		43	-	42	13	5		43	-	30	25	2
T8		-	-	1+	-	-	-	-		8+	-	7+	1+	-		33	-	45	19	3		50	-	26	22	2
T9		-	-	-	-	-	-	-		9+	-	9+	2+	-		35	4	34	24	3		44	-	35	20	1
T10		-	-	-	1+	-	3+	-		3+	1+	4+	2+	-		28	9	43	20	-		30	12	33	23	2
T11		-	-	-	-	-	1+	-		6+	2+	4+	3+	1+		23	22	36	19	-		36	22	20	20	2
T12		-	-	-	-	-	1+	-		6+	4+	2+	4+	1+		37	9	28	26	-		33	13	39	10	5
T13		-	-	-	1+	1+	-	-		7+	-	-	6+	-		39	1	40	20	-		44	-	45	10	1
T14		1+	-	1+	-	-	-	-		4+	3+	3+	5+	1+		31	8	28	32	1		42	15	29	12	2
T15		-	-	-	-	-	1+	-		5+	8+	8+	4+	-		42	18	23	16	1		35	17	32	12	4
T16		-	-	-	-	-	2+	-		3+	3+	2+	6+	-		32	26	22	20	-		38	11	36	13	2
T17		-	-	-	-	-	-	-		3+	2+	-	11+	-		33	20	22	25	-		35	24	39	10	1
SIII		-	-	-	-	-	-	-		1+	-	1+	2+	-		12+	-	11+	7+	-		36	-	50	10	4

\+ Absolute value, not percentage

APPENDIX IV.II

Heavy Mineral Analysis (a)

(All figures expressed as percentages)

No.	Iron Oxides	Augite	Garnet	Zircon	Epidote	Hornblende	Tourmaline	Muscovite	Chlorite	Biotite	Rutile	Enstatite	Apatite	Hypersthene	Weathered grains	% Heavy Mins.
T1	82.9	6.3	2.3	0.8	0.5	0.6	0.4	0.5	0.2	-	0.2	0.2	-	-	5.1	2.49
T2	81.5	7.6	1.3	1.8	0.4	1.0	0.3	0.4	0.3	-	0.3	0.1	0.1	-	4.9	1.98
T3	79.3	9.4	2.7	1.7	0.4	0.7	0.3	0.2	0.2	-	0.1	0.6	0.2	-	4.2	2.26
T4	85.7	9.2	0.9	0.7	0.4	0.4	0.1	0.2	-	-	0.1	0.3	0.2	-	2.0	2.11
T5	86.2	7.4	1.6	1.0	-	0.8	0.3	0.6	-	-	0.2	0.6	0.1	-	1.2	2.16
T6	89.2	3.9	1.2	1.0	0.1	0.9	0.2	0.1	0.1	-	0.2	0.6	0.3	-	2.2	1.55
T7	90.2	3.3	1.0	1.1	-	0.7	0.6	0.2	-	0.1	0.4	0.3	0.2	-	1.9	1.39
T8	89.3	3.6	1.3	2.4	0.1	0.8	0.4	0.1	-	-	0.2	0.3	0.3	-	1.2	1.26
T9	89.6	3.8	1.2	0.6	1.8	0.7	0.4	0.1	0.3	0.4	0.1	0.3	0.6	-	1.1	1.39
T10	87.4	4.9	1.8	1.4	0.3	0.6	0.3	0.3	0.2	0.3	0.3	0.7	0.6	0.1	0.8	1.36
T11	89.7	3.2	2.0	1.3	0.3	0.7	0.5	0.3	0.3	0.1	0.2	0.3	0.7	-	0.4	1.26
T12	89.0	3.8	1.9	0.9	0.2	0.7	0.2	0.4	0.7	0.1	0.3	0.1	0.5	0.2	1.0	1.31
T13	87.5	2.6	2.0	1.6	0.2	0.5	0.4	0.7	0.5	0.4	-	0.3	0.8	-	2.5	1.65
T14	88.0	3.7	1.0	1.2	0.3	0.7	-	0.2	0.4	0.2	0.4	0.4	0.5	-	3.0	1.79
T15	83.3	4.1	1.5	0.8	0.1	0.2	0.2	0.6	0.4	-	0.1	0.5	0.1	-	8.1	2.43
T16	79.2	5.4	1.2	1.4	0.1	0.3	0.1	0.6	0.5	-	-	1.3	-	-	9.9	2.54
T17	83.0	4.2	1.2	0.5	0.1	0.5	0.3	0.6	0.7	-	-	0.9	-	-	8.0	2.19
S0	87.9	5.3	0.7	1.8	0.6	1.6	0.5	0.8	0.2	0.1	0.1	-	-	-	0.4	1.89
SI	93.5	0.1	2.5	1.4	-	0.5	0.8	0.7	0.1	0.1	0.2	-	0.1	-	-	0.67
SII	93.2	1.1	1.4	1.2	-	0.5	-	0.4	0.3	-	0.3	-	1.2	-	0.4	1.12
SIII	81.5	11.4	2.5	0.3	0.2	1.5	0.5	0.5	-	0.4	0.2	-	0.4	-	0.5	2.40
SIV	92.3	1.7	1.8	1.1	0.1	0.4	0.9	0.4	0.2	0.1	0.1	-	0.8	-	0.1	1.20
SV	93.3	1.1	0.1	0.6	0.2	0.6	0.4	0.2	0.6	0.3	0.1	-	1.4	-	0.1	1.08
SVI	95.5	0.4	1.6	0.3	0.2	0.3	0.3	0.2	0.5	0.3	-	-	0.3	-	0.1	0.90
SVII	89.5	1.7	2.1	0.7	0.1	1.0	0.5	0.5	0.8	0.2	0.3	0.1	1.6	0.1	0.8	0.81
SVIII	96.8	0.2	1.0	-	0.1	0.5	0.2	0.4	0.2	-	-	-	0.4	-	0.2	0.75
SIX	88.5	2.7	1.5	0.5	0.2	0.2	0.4	0.9	0.6	-	0.2	0.2	0.4	-	3.7	1.49

APPENDIX IV.III

Heavy Mineral Analysis (b).

(All figures expressed as percentages)

No.	Augite	Garnet	Zircon	Epidote	Hornblende	Tourmaline	Muscovite	Chlorite	Biotite	Rutile	Enstatite	Apatite	Hypersthene
T1	62.5	12.75	8.25	2.0	4.75	2.5	2.0	1.5	-	1.75	1.25	0.75	-
T2	52.5	17.5	11.75	1.75	4.25	3.5	2.0	1.0	-	1.25	3.0	1.5	-
T3	59.5	15.75	7.0	3.0	4.0	2.0	1.25	1.25	-	2.0	2.25	1.75	-
T4	65.5	14.0	5.5	0.75	3.75	1.0	1.25	1.75	-	1.5	3.5	1.5	-
T5	60.75	9.0	8.75	1.25	5.5	2.5	4.25	1.5	-	0.5	3.5	2.5	-
T6	41.75	16.75	13.75	1.0	6.0	2.75	4.0	1.5	-	1.5	6.25	4.75	-
T7	42.0	15.0	13.5	1.5	10.75	3.25	1.75	1.75	0.25	2.75	4.5	3.0	-
T8	34.5	17.25	18.5	0.75	6.75	6.5	1.25	3.0	-	2.25	5.25	4.0	-
T9	32.25	17.25	13.75	3.75	7.75	3.75	2.25	4.75	2.5	1.5	6.5	4.0	-
T10	31.75	13.75	16.0	3.0	4.75	4.75	3.5	6.0	3.5	1.5	5.25	5.0	1.25
T11	29.75	18.25	16.25	1.5	5.75	5.0	2.25	1.5	3.25	2.5	7.75	6.25	-
T12	29.0	19.25	13.0	1.75	5.5	5.75	5.75	3.25	3.0	3.25	3.0	6.5	1.0
T13	37.25	13.75	14.75	2.5	5.75	4.25	3.25	3.5	3.25	1.5	3.0	6.0	0.25
T14	42.0	16.5	10.75	0.75	6.0	2.5	2.75	3.5	3.25	0.75	6.0	5.25	-
T15	37.0	19.25	14.25	1.0	4.5	4.5	3.25	3.75	-	2.0	8.25	2.25	-
T16	43.0	13.5	14.25	1.75	3.75	2.0	4.75	4.75	-	0.25	10.0	1.5	0.5
T17	39.5	13.5	19.0	0.5	3.5	6.25	3.5	6.25	-	0.5	5.5	1.5	0.5
SO	41.25	12.25	18.5	0.75	10.25	5.0	8.25	1.75	0.5	1.0	-	-	-
SI	1.0	32.75	21.5	2.5	10.5	8.5	4.5	3.25	2.25	4.25	3.0	6.0	-
SII	15.25	18.25	15.5	1.25	7.0	9.5	4.5	5.0	1.5	2.0	-	20.25	-
SIII	71.25	8.5	4.25	0.25	5.25	2.5	3.0	0.25	1.25	1.0	-	2.5	-
SIV	16.5	18.5	15.75	1.75	11.25	6.5	5.0	5.0	1.75	2.25	-	15.75	-
SV	8.5	28.25	8.75	1.75	8.0	5.0	3.25	9.5	6.0	1.0	0.75	18.75	0.5
SVI	18.0	26.0	4.5	1.5	8.0	7.75	2.5	10.5	7.0	0.5	-	23.75	-
SVII	13.25	22.0	9.75	1.25	9.75	7.75	4.5	8.5	2.0	2.75	0.5	17.5	0.5
SVIII	4.25	19.75	7.0	1.5	10.25	7.0	8.0	18.75	1.75	0.25	0.5	21.0	-
SIX	31.5	19.75	13.25	1.75	6.0	4.75	7.25	3.75	0.5	1.5	1.75	8.25	-

APPENDIX IV.IV

Light Mineral Analysis.

(All figures expressed as percentages).

No.	Quartz	Orthoclase	Plagioclase	Muscovite	Biotite	Coal	Weathered grains	% Light Minerals
T1	85.7	5.1	-	0.4	0.2	3.4	5.2	97.51
T2	86.1	4.6	0.1	-	0.1	5.0	4.1	98.02
T3	90.8	2.6	0.2	0.1	0.1	2.5	3.7	97.74
T4	87.4	3.6	-	0.3	0.5	3.1	5.1	97.89
T5	87.9	5.3	0.1	0.2	0.2	2.7	3.6	97.84
T6	86.4	3.9	-	0.5	-	5.4	3.8	98.45
T7	85.8	5.1	0.1	0.5	0.4	3.2	4.9	98.61
T8	83.2	4.3	0.1	0.8	0.1	6.2	5.3	98.74
T9	82.5	4.8	0.1	0.3	0.3	4.5	7.5	98.61
T10	85.4	3.9	-	0.4	0.3	3.1	6.9	98.64
T11	82.9	4.5	0.2	-	0.3	4.8	7.3	98.74
T12	79.6	3.5	-	0.6	0.1	7.8	8.4	98.69
T13	81.0	5.8	-	0.5	0.6	5.7	6.4	98.35
T14	79.8	3.6	-	1.4	0.6	7.9	6.7	98.21
T15	86.7	3.5	-	0.8	0.4	2.7	5.9	97.57
T16	85.3	4.2	0.1	0.4	0.5	5.7	3.8	97.46
T17	89.3	2.7	-	0.4	0.2	4.1	3.3	97.81
SO	85.6	4.4	-	0.8	0.1	2.3	6.8	98.11
SI	88.8	5.0	0.1	1.0	0.1	2.4	2.6	99.33
SII	82.1	4.5	0.2	1.5	0.8	3.3	7.6	98.88
SIII	83.8	3.5	0.3	0.3	0.4	2.9	8.8	97.60
SIV	82.7	5.0	0.2	0.4	1.0	5.5	5.2	98.80
SV	81.2	5.0	0.4	1.1	0.6	5.2	6.5	98.97
SVI	71.7	4.0	0.2	0.8	0.6	16.8	5.9	99.10
SVII	74.3	4.2	0.2	0.3	0.9	15.3	4.8	99.19
SVIII	82.6	5.2	0.2	0.1	0.5	3.9	7.5	99.25
SIX	89.4	2.2	0.3	-	0.4	4.1	3.6	98.51

APPENDIX V.I.

pH and Soluble Carbonate Analysis

SAMPLE NUMBER	pH 2mm. fraction	pH 200mm. fraction	Soluble Carbonates %
T1	6.20	6.00	0.67
T2	6.30	6.45	0.67
T3	6.25	6.275	0.50
T4	6.275	6.20	0.34
T5	6.40	6.45	0.34
T6	6.55	6.40	0.59
T7	6.50	6.40	0.50
T8	6.90	6.85	0.71
T9	7.85	7.825	10.05
T10	8.25	8.15	13.90
T11	8.375	8.20	14.62
T12	8.275	8.20	5.49
T13	7.05	6.40	1.17
T14	8.10	7.90	14.07
T15	8.15	7.90	20.20
T16	8.15	7.85	24.94
T17	8.20	7.95	24.85
S0	5.35	5.20	0.46
SI	5.875	5.825	0.17
SII	6.375	6.425	-
SIII	6.60	6.50	0.63
SIV	6.15	6.30	0.46
SV	7.25	7.15	0.59
SVI	7.00	7.25	0.21
SVII	6.50	6.70	0.25
SVIII	6.15	6.05	0.46
SIX	7.40	7.65	5.49