THE MINERALOGY AND WEATHERING OF ~~DEVENSIAN~~ WEICHSELIAN TILLS IN EASTERN ENGLAND

By

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ABSTRACT

The mineralogy and particle size distribution of a large number of till samples from eastern England were studied. Only two members of the Devensian till succession of the Holderness area of Yorkshire are recognised, not three as earlier supposed. These two tills, the Purple and Drab, can be distinguished texturally, mineralogically, and by their colour. However, both weather by oxidation to a reddish brown till, and are then virtually indistinguishable in the field; this weathered material was previously thought to represent a distinct unit, the Hessle Till. The lower Devensian till (the Drab) extends on to the eastern footslopes of the Yorkshire Wolds, and is correlated with the Marsh Tills of Lincolnshire and the Hunstanton Till of north-west Norfolk. The upper Purple Till occupies only an arcuate area of south-eastern Holderness. A grey older till at Welton-le-Wold (Lincolnshire) is tentatively correlated with the pre-Devensian Basement Till of Holderness.

Soil development on these tills was investigated, mainly in a profile on the Purple Till at Tunstall in eastern Holderness. Particle size, mineralogical and chemical analyses were used to establish the uniformity of the original parent material in this profile, and to quantify weathering and other changes that occurred during its development in post-Devensian times. The calculations were based on the method outlined by Barshad (1964), using the quartz and felspar content as an index of weathering. The profile is oxidised to a depth of about 5m and leached of calcium carbonate to 0.7m. Gleying is prominent at depths of 0.2 - 2m. Rock fragments have been disaggregated and fine clay formed from coarser fractions in the upper part of the profile. Much of this fine clay has been translocated to lower horizons (0.3-1.4m depth), but there is little remaining evidence for translocated clay in the micromorphology of these horizons. The main mineralogical change in fine soil fractions was the weathering of mica to fine clay sized vermiculite.

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CHAPTER 1 INTRODUCTION

The main purpose of the present study is to assess as carefully as possible the effects of weathering in some fairly widespread and agriculturally important English soils. Quantitative assessment of weathering changes in relation to time, physiographic situation, past and present climatic and vegetational conditions, and human influence, depends first upon selection of suitable soil profiles for study. These should preferably be developed in uniform parent materials containing a range of stable and unstable minerals, and development should have occurred over a known period of time, under known climatic and vegetational regimes, with neither loss of material by erosion nor deposition of new material at the surface.

The most easily detected and important weathering changes occur in soils whose parent materials contain a high proportion of unstable minerals (i.e. minerals out of equilibrium with their present environment). For example, basic igneous rocks contain minerals formed in a very different physico-chemical environment from that of the present-day land surface, and therefore may undergo considerable alteration on weathering. However, many of the weathering studies made on such materials have suffered from disadvantages, such as lack of uniformity in the soil parent material, loss of upper soil horizons by erosion, or incomplete knowledge of the duration of soil formation. In Great Britain, and indeed over much of the mid-latitude land areas of the northern hemisphere, extensive Quaternary glacial or periglacial erosion has disturbed or removed earlier weathering mantles. Also, most of the land surface is now covered by variable thicknesses of unconsolidated Quaternary sediments. Consequently, sedentary soil profiles on pre-Quaternary parent materials are rare.

As no Quaternary igneous rocks are exposed in Britain, the areas most likely to provide profiles suitable for the present study are those covered by Quaternary sediments. Many pre-Quaternary sediments are derived largely from earlier sediments, so that their constituent minerals are mainly the most stable types that have resisted two or more weathering cycles, and are not greatly altered by further weathering, at least in temperate conditions. However, many of the Quaternary sediments in Britain contain material derived by glacial erosion and transportation from rocks composed largely of unstable minerals, and are therefore more likely to show interesting changes on weathering. Soils on glacial deposits, such as tills, should therefore offer advantages for weathering studies over other English soils.

Quaternary till sheets are widespread in Britain (see Fig. 1) and are the parent materials of many soils in some of the most agriculturally productive areas, such as East Anglia. They often contain a conspicuous number of igneous and metamorphic erratic boulders, which suggests that a proportion of the finer material is also derived from these sources. Thus, the weathering of such deposits probably causes large changes in their composition. The tills occur typically in relatively flat sheets, giving a land surface on which erosion has played a relatively minor role. Therefore, sites should be available where post-glacial erosion and/or deposition do not complicate the history of soil formation.

Much research effort has been employed in determining the geographical boundaries of the various tills and their relative ages, and there is still much controversy over the absolute ages of most of them; Fig. 2 shows the glacial boundaries proposed by various authors in East Anglia. However, the tills of East Anglia and much of the Midlands are regarded by most authorities as either Anglian (Bristow and Cox, 1973) or

Wolstonian (West and Donner, 1956; Shotton, 1953) in age (see Table 1 for Quaternary stratigraphic terminology). Whichever age is correct, these deposits have been exposed to weathering and erosion during at least one interglacial period (Ipswichian) and one glacial period (Devensian). Sedentary soils are likely to occur only on interfluves, but Hodge and Perrin (1967) and Perrin et al. (1974) have shown that on such sites in East Anglia the soils are almost universally affected by the addition of sand and/or silt to the upper horizons, probably as a result of aeolian deposition. Catt et al. (1971) showed that the soils of N.E. Norfolk are affected by addition of loessial material. The sandy drift of Breckland was formerly considered by Perrin (1955) to represent the Gipping Till, but Watts et al. (1966) thought the sand is more likely to be aeolian in origin. Fig. 3 illustrates the distribution of these sandy and silty surface deposits in East Anglia. Thus, soils developed on these older tills are likely to have complex histories; the effects of weathering would be difficult to evaluate, and their relationship to other factors, such as time and past climates, would be difficult to determine.

The Hessle/Purple/Drab till sequence exposed on the Holderness coast (Catt and Penny, 1966) is now known to be of Late Devensian age, since radiocarbon dates of 18,500 ± 400 years B.P. (I - 3372) and 18,240 ± 250 years B.P. (Birm. - 108) were obtained from samples of moss from the underlying Dimlington Silts (Penny, Coope and Catt, 1969). Radiocarbon dates have also been obtained from overlying deposits, the most significant for the present study being those from the peat bed at Grimston Hall (TA 289354): leaves from 6 - 7 cm above the base of the bed had a radiocarbon age of 12,230 ± 120 years B.P. (Birm. - 298). Thus, the age of these tills in Yorkshire is known within fairly close limits.

The Hessle Till of the Holderness coast has been correlated by Catt and Penny (1966) with the upper till in East Lincolnshire, and with the Hunstanton Till of North Norfolk. In their words (p. 400 - 401):- "This is merely the local name for the uppermost till along much of the east coast of England, from County Durham where it is called the Upper Boulder Clay . . . to Norfolk where it is called the Hunstanton Till. It exhibits 'newer drift' topography, it carries on its surface no organic deposits older than Zone I of the Late - Glacial; it is, in Norfolk, younger than the March Gravels (Eemian), and in Yorkshire younger than the interglacial deposits at Sewerby.".

The Hessle Till was therefore chosen as the main subject for the weathering study, because it forms large areas of agriculturally important soils, is accurately dated yet young enough not to have suffered extensive erosion or veneering with other deposits, and because the climatic changes and vegetational regimes since its deposition are well known from pollen and other studies of English postglacial history (e.g. Godwin, 1956).

TABLE 1a QUATERNARY STRATIGRAPHIC TERMS

	British	British	N.W. Europe	Alps	N. America	Other Equivalents
	Geological Society (1973)	West (1968)	Woldstedt (1958)	Woldstedt (1958)	Flint (1957)	
Holocene	Flandrian	Flandrian				Recent Post-Glacial
Upper Pleistocene	Devensian*	Weichselian	Weichselian	Wurm	Wisconsin	Last Glaciation
	Ipswichian	Ipswichian	Eemian	Riss/Wurm	Sangamon	Last Interglacial
			Warthe			
	Wolstonian*	Gippingian	Saale	Riss	Illinoian	
Middle Pleistocene	Hoxnian	Hoxnian	Holstein	Mindel/Riss	Yarmouth	Great Interglacial
	Anglian*	Lowestoftian	Elster	Mindel	Kansan	
	Cromerian	Cromerian	Cromerian	Gunz/Mindel	Aftonian	
	Beestonian	Beestonian		Gunz	Nebraskan	
	Pastonian	Pastonian				
Lower Pleistocene						

* Glaciation in the British Isles

TABLE 1b SUBDIVISION OF THE LAST GLACIATION

				POLLEN ZONES		RADIOCARBON YEARS B.P.
FLANDRIAN	HOLOCENE	HOLOCENE		VIII VII VI V IV POST-GLACIAL		10300
LATE DEVENSIAN	LATE WEICHSELIAN	LATE-GLACIAL		III YOUNGER DRYAS		10800
				II ALLERØD OSCILLATION		12000
				Ic OLDER DRYAS		
				Ib BØLLING OSCILLATION		
				Ia OLDEST DRYAS		13000
	MIDDLE WEICHSELIAN	UPPER PLENIGLACIAL				26000
MIDDLE DEVENSIAN						29000
		MIDDLE PLENIGLACIAL				40000
		LOWER PLENIGLACIAL				50000
EARLY DEVENSIAN						55000
	EARLY WEICHSELIAN	EARLY GLACIAL				>70000
IPSWICHIAN	EEMIAN	EEMIAN				

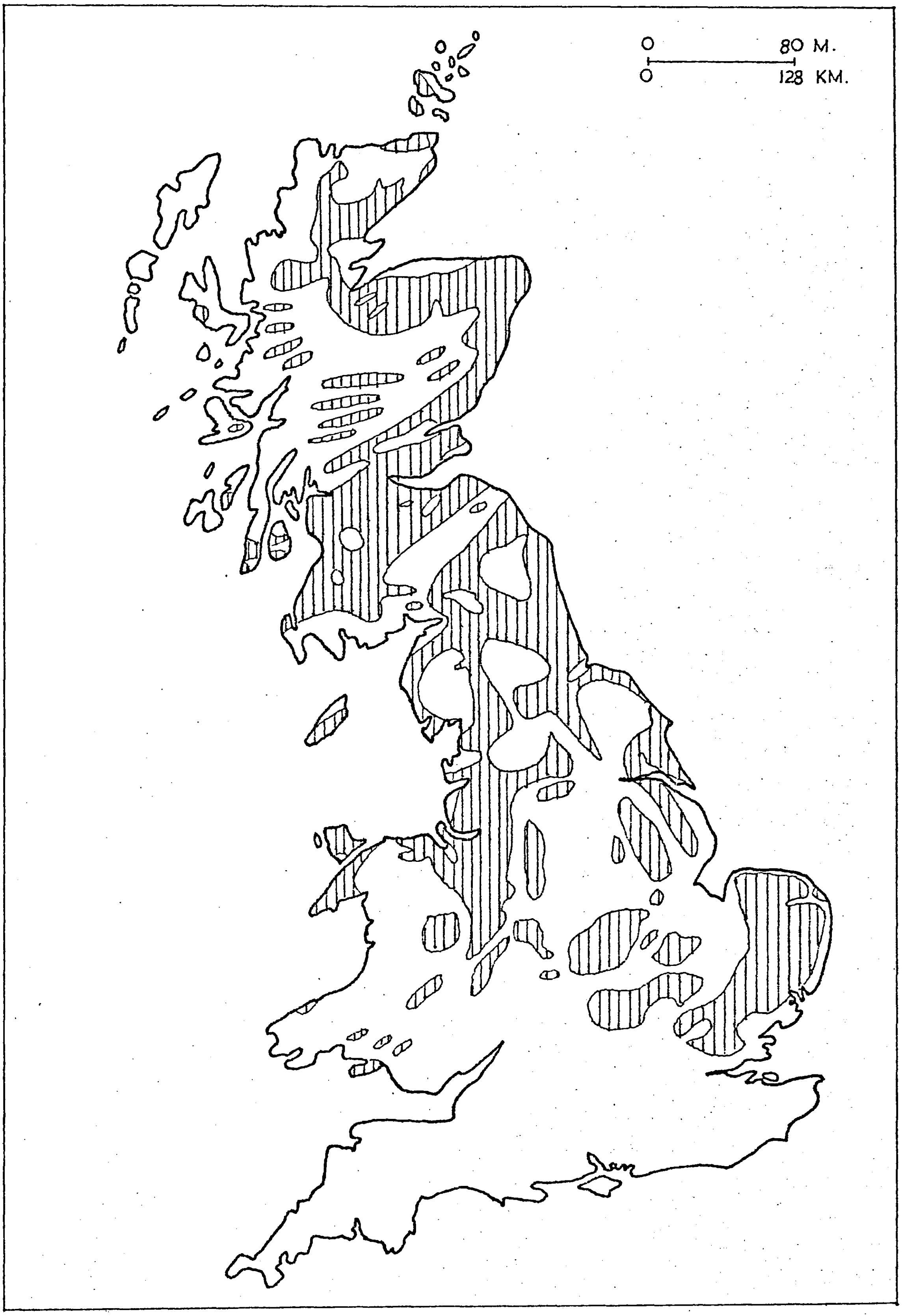


FIGURE 1 DISTRIBUTION OF TILL IN GREAT BRITAIN (After West, 1968)

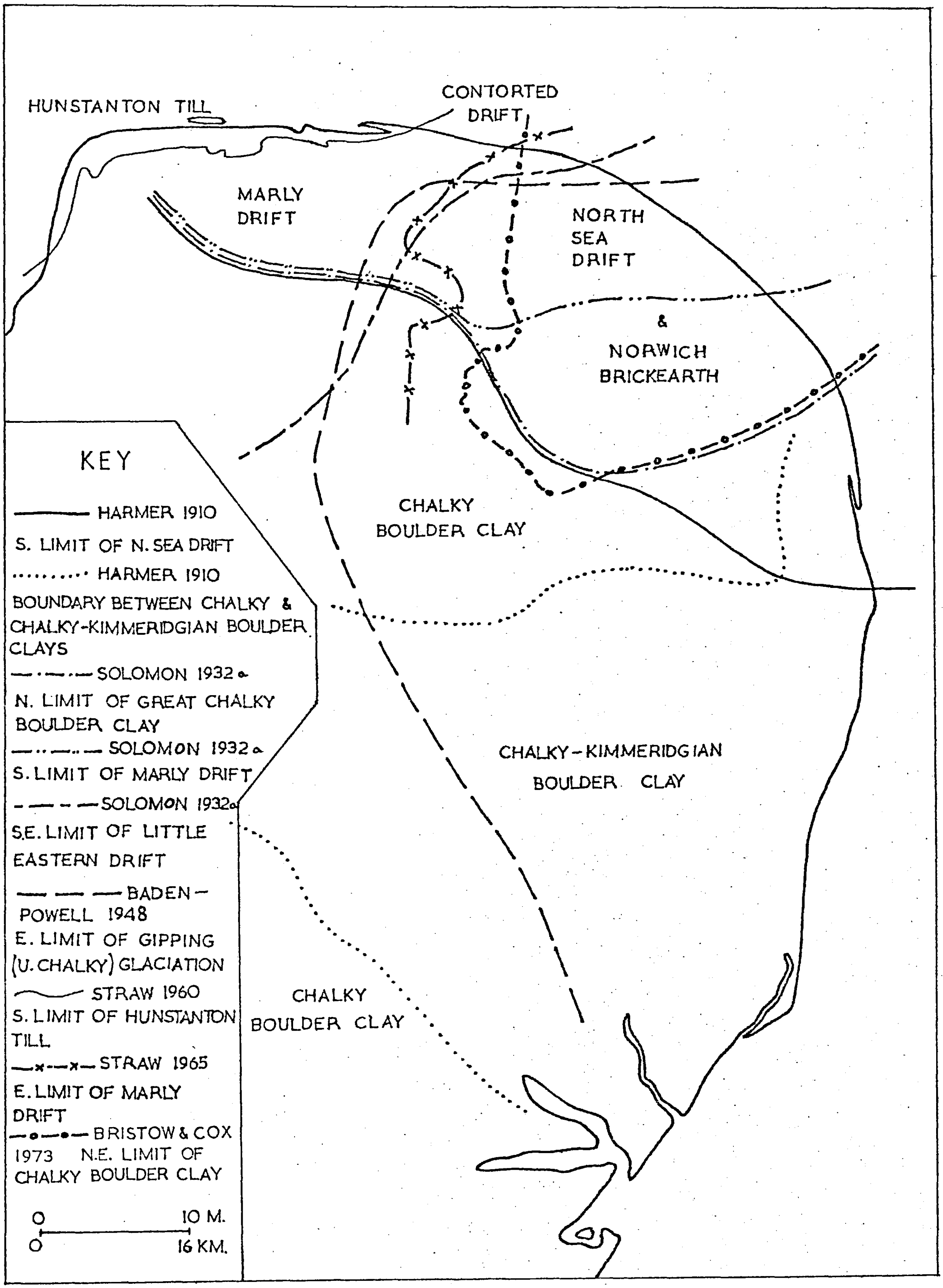


FIGURE 2 EAST ANGLIAN TILLS

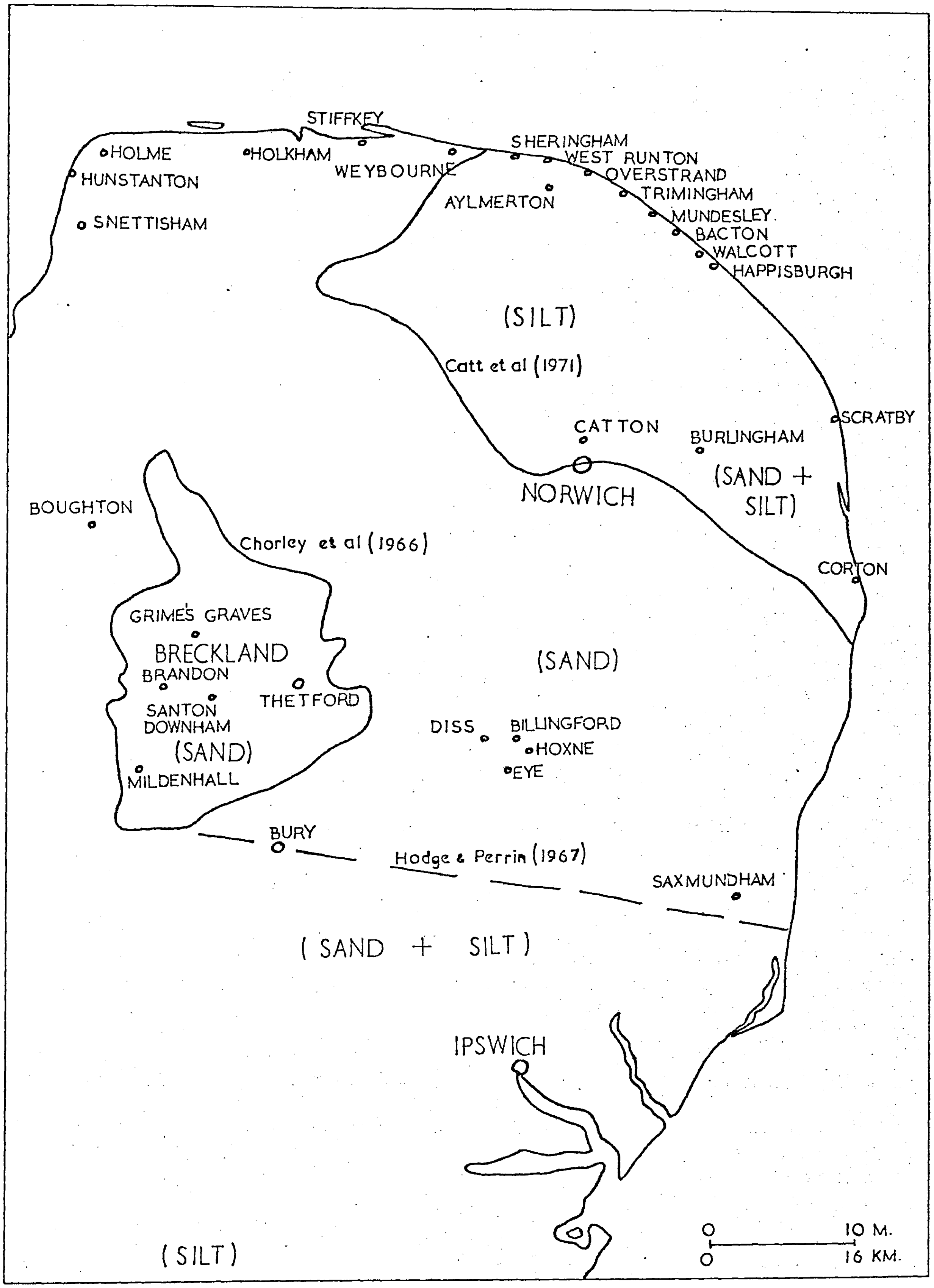


FIGURE 3 EAST ANGLIA : LOCATION MAP & DISTRIBUTION OF 'COVERSAND' & 'COVERLOAM'

CHAPTER 2 OUTLINE HISTORY OF RESEARCH

2.1 Glacial Deposits of Eastern England

The glacial deposits of Holderness, Lincolnshire and East Anglia have been studied by geologists for over a century. Wood and Rome (1868) were the first to subdivide the Holderness and Lincolnshire deposits into three parts, which they called the Basement, Purple and Hessle Clays. Subsequent workers in Yorkshire have used the same names, but not always for the same deposits, thereby generating considerable confusion; Catt and Penny (1966) summarised the changes in nomenclature that the Holderness deposits have undergone since 1868. Bisat (1932a, 1939a) introduced the term "Drab" for the upper part of Wood and Rome's Basement, and recognised within it five separate layers. However, Catt and Penny (1966) subsequently adopted a simple four-part succession (in ascending order: Basement, Drab, Purple and Hessle). Unlike all other workers in Holderness, Bisat distinguished the Hessle of inland sections (e.g. at Hessle itself) from that exposed in the coastal cliffs of Holderness, and equated the former with his Middle Drab (1939a); others have merely followed Wood and Rome, who described the Hessle as lying "like a cloth" over the whole area.

Jukes Browne (1885b) recognised that in Lincolnshire there was a period of erosion and cliff formation between deposition of the Basement and Purple Boulder Clays, but a similar break in the glacial deposition was not recognised in Yorkshire until Bisat and Dell (1941) reported a bed containing moss remains between the Basement and Drab Clays at Dimlington, and Catt and Penny showed that the Ipswichian Interglacial cliff and beach at Sewerby also separate the Basement and Drab. The radiocarbon dating of the Dimlington moss (Penny et al., 1969) later showed that the Drab, Purple and Hessle were all deposited in the Late Devensian after approximately 18,500 years B.P.

Charlesworth (1931), Suggate and West (1959), Straw (1960) and others extended the limit of the "Last" (i.e. Devensian) Glaciation beneath The Wash or north-east Fenland into north-west Norfolk, to include the Hunstanton Brown Boulder Clay, which is lithologically similar to the Hessle of East Yorkshire and Lincolnshire. However, on geomorphological evidence Farrington and Mitchell (1951) and Valentin (1953, 1957) proposed limits further north (Figure 4), and Clayton (1957b) suggested that the margin extended beyond the western edge of The Fens. The derived Upper Palaeolithic implements found in the Hunstanton Clay (Reid Moir and Burchell, 1930; Reid Moir, 1931) indicate its Late Devensian age, and therefore support in general terms the correlation with the Hessle-Purple-Drab sequence of Holderness.

The glacial deposits in other parts of East Anglia comprise the Chalky Boulder Clay of Wood (1870), Harmer (1902) and others, and the North Sea Drift (Reid, 1882), which includes the Cromer Tills and Norwich Brickearth. Baden Powell (1948) divided the Chalky Boulder Clay into a lower Lowestoft Till and an upper Gipping Till, separated by the Hoxnian Interglacial. This distinction was supported by stone orientation measurements (West and Donner, 1956), but Bristow and Cox (1973) assembled stratigraphical evidence to show that there is only one Chalky Boulder Clay in East Anglia, and Perrin et al. (1973) suggested that the lithological uniformity of the deposit over a large area also indicates deposition from only one ice sheet. The North Sea Drift exposed on the Norfolk coast between Sheringham and Mundesley is in part extensively contorted, and contains three separate tills (Banham, 1968, 1970) with intercalated waterlain deposits. A large part of north Norfolk, west of Sheringham, Hempstead and Edgefield is covered by an extremely chalky boulder clay, the Marly Drift of Boswell (1935), which has been correlated with the Lowestoft Till (Solomon, 1932a; Baden Powell, 1948; West, 1958), with the North Sea Drift (Woodward, 1884), and with the Gipping (i.e. Wolstonian) Glaciation (Straw, 1965).

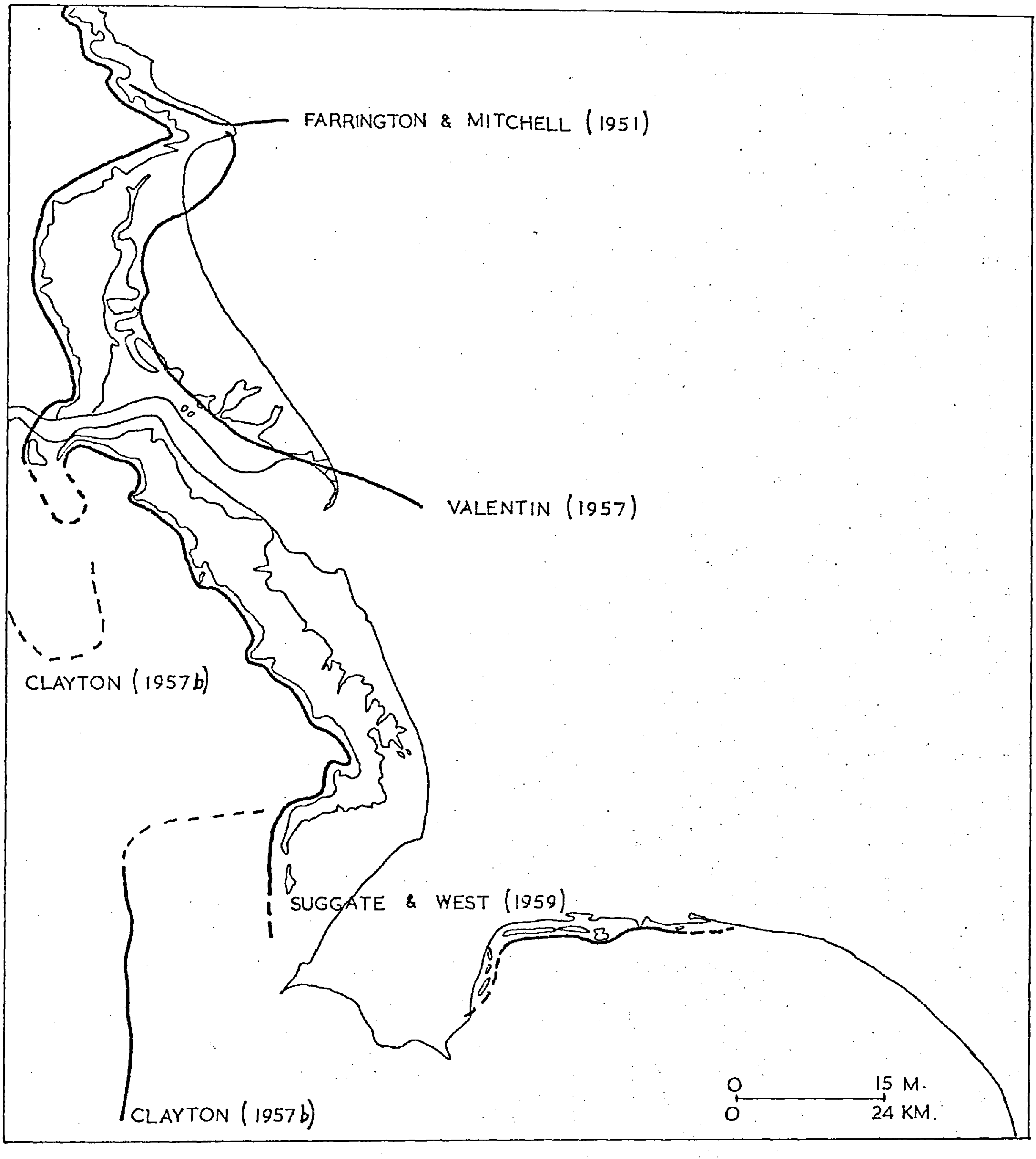


FIGURE 4 DEVENSIAN ICE LIMITS IN EASTERN ENGLAND AFTER VARIOUS AUTHORS, WITH OUTCROP OF BROWN BOULDER CLAY.

2.2 Pedological Studies

2.2.1 British Soil Studies

Bunting (1964) produced a bibliography of memoirs and papers on the soils of the British Isles, and Burnham (1970) discussed the regional pattern of soil formation in Great Britain. The Soil Survey of England and Wales have produced memoirs on the soils of specific areas, at scales of 1:63,360 and 1:25,000, but so far none deal with soils developed on Devensian tills in East Yorkshire, Lincolnshire or North Norfolk, though 1:25,000 sheets and records of several areas of Norfolk and the Vale of York are available (Corbett and Tatler, 1970; Matthews, 1971; Corbett, 1973; Jarvis, 1973; Bullock, 1974). Perrin (1961), Straw (1969a) and Crompton (1961) gave general accounts of the soils of Norfolk, Lincolnshire and Yorkshire respectively, and Johnson (1969) described the soils and land-use on the Chalky Boulder Clay.

Mineralogical studies of rock weathering and soil formation in Great Britain include the following : Crompton (1939) and Wager (1944) studied Shap Granite; Stephen (1952a, 1952b) studied soils on the Malvern Hills; Butler (1953) investigated the soils of the Lizard area, Cornwall; Smith (1962) studied some Scottish basic igneous rock; Wilson investigated sedentary profiles on ultrabasic rocks of Rhum (1969), biotite-hornblende rock in Inverness-shire (1970), and boulder conglomerate in north-east Scotland (1971).

2.2.2 Soils Developed on Tills

Much of the early work on weathering of tills concerned palaeosols developed on the older till sheets. Before 1900, geologists in the American mid-west were intrigued by peculiar grey tenaceous clays ("gumbos") lying on the older drifts (McGee, 1891). Kay (1916) studied these clays, which he termed gumbotils, and concluded that they are ancient <u>in situ</u> weathering profiles; he recognised three, of different ages, on the three older till sheets of Iowa (the Nebraskan, Kansan and Illinoian). The material was not recognised on the youngest till sheets, the Iowan and Wisconsinan (Kay and Pearce, 1920). Leighton and MacClintock (1962) considered that the gumbotil represents a more advanced stage of weathering than that of the Wisconsinan-Recent profiles. During later years Kay greatly extended his studies on gumbotil (e.g. Kay and Apfel, 1929; Kay, 1930; Kay and Graham, 1943), and was joined by other workers (e.g. Alden and Leighton, 1917; Leighton and MacClintock, 1930; Allen, 1930, 1959). However, Krusekopf (1947) thought that gumbotil was waterlaid, weathered and leached when deposited, and did not develope its characteristics by prolonged weathering of till. This view became popular because of the loose way in which the term was applied to materials which obviously had not developed in situ (e.g. Ruhe, 1956). This led Frye, Shaffer, Willman and Ekblaw (1960) to abandon the term, which was promptly defended by Trowbridge (1961), Allen (1962) and Leighton and MacClintock (1962). Whether the term has outlived its usefulness or not, the study of gumbotils has greatly aided the elucidation of till stratigraphy in the mid-west (e.g. Thornbury, 1940). The term seems not to have been used in England.

Studying weathered zones of the various drift sheets of Illinois, Leighton and MacClintock (1930) proposed a five-fold division of the profiles. Horizon 1 was the surficial soil, horizon 2 the chemically decomposed till, 3 the leached and oxidised till, 4 the oxidised but unleached, and horizon 5 the unaltered till. This nomenclature has been followed by many later workers (e.g. Gravenor, 1954) in preference to the pedological nomenclature of A, B and C horizons.

Recent studies of soils developed on tills in America have been concerned with specific aspects of weathering. Merritt and Muller (1959) studied the depth of leaching in relation to carbonate content of tills in

New York State. Flint (1949) had earlier concluded that the depth of leaching of carbonate in till soils was unlikely to help determine their relative ages, because of the large number of variables involved. Brophy (1959) and Bhattacharya (1963) studied the weathering of heavy minerals, and many others have studied the alteration of clay minerals in till soils (e.g. Beavers et al., 1955; Droste, 1956; Droste et al., 1958; 1962; Bhattacharya, 1962; Fanning et al., 1965; Borchardt et al., 1968; Birkeland and Janda, 1971). Variation of clay content with depth was studied by Wenner et al. (1961), Allen and Hole (1968) and Smeck et al. (1968). More broadly based mineralogical studies were made by Brydon and Marshall (1957), Pawluk (1961), Willman, Glass and Frye (1963, 1966) and De Kimpe (1970). General accounts of weathering of glacial till include those of Mick (1949), Ehrlich and Rice (1955), Thorp et al. (1959) and Wascher et al. (1960). Few have attempted to estimate quantitatively the mineralogical changes during profile development, exceptions being the work of Mick (1949), Westin (1953), Franzmeier et al. (1963), and Redmond and Whiteside (1967).

In Britain there have been few studies of till soils, and none has attempted detailed quantitative calculations of profile development. Early mineralogical studies include those of Hendrick and Ogg (1916), Hendrick and Newlands (1923, 1925), Hart (1929, 1938, 1941, 1942) and Stewart (1933), all on Scottish drift soils. Hendrick and Newlands (1925) considered that, under the conditions prevailing in Scotland, the Post-glacial period has been too short for chemical weathering to have affected the mineralogical composition of the soil, except in readily decomposable materials.

Perrin (1955) studied soil formation on the supposed Gipping Till of the Brecklands, but Watt et al. (1966) suggested that the parent materials were periglacially reworked mixtures of aeolian sand and chalky drift. The micromineralogy of drift soils in North Wales was studied by Smithson (1953), and Seale (1956) and Crampton (1959, 1961) studied the heavy minerals of drift soils in Cambridgeshire, Yorkshire and Glamorgan respectively, in order to ascertain their origin. Mitchell (1963) studied the mineralogy of a soil on granitic till in Scotland, and concluded that biotite was altered to trioctahedral illite and then to vermiculite, and that dioctahedral illite and kaolinite formed by alteration of plagioclase felspars; however, he thought that the mineralogy of the soil clay reflected mainly that of the parent till, which was composed largely of previously weathered granite. Wilson (1973) studied the clay mineralogy of soils on till derived from Old Red Sandstone in Scotland, and found that the main effects of pedogenesis were rapid degradation of expansible trioctahedral minerals, and vermiculitization of dioctahedral mica in the A horizon.

2.2.3 Quantitative Aspects of Soil Genesis

Soil development studies fall into two main categories. One involves the study of particular soils as they are developed in the field, identifying features that characterise the various horizons, and analysing the material of which they are composed. The other adopts a synthetic approach, studying the reactions of particular soil constituents (e.g. minerals, humic materials) in simulated soil conditions, to build up a model of the likely changes during soil development. Both methods are necessary for a full appreciation of pedogenesis, but in the present study the analytical approach was adopted, the aim being the quantitative estimation of changes in soils developed on boulder clays.

Many analytical studies of soils have presented mineralogical and/or chemical data with qualitative discussions of pedogenesis, on the assumption that the C horizons represents the parent material of the whole profile. However, Arnold (1968) showed that the presence of a lithological discontinuity in a profile can greatly affect the evaluation of soil forming factors. Without recognition of discontinuities, explanations of pedogenesis are likely to be misleading. In many studies the absence of an obvious unconformity within the deposit from which the soil has developed is regarded as sufficient evidence for uniformity of the parent material (Sudom and St. Arnaud, 1971).

The uniformity of the parent material of a soil profile can be determined by studying the more resistant, and therefore relatively unchanging, fractions of the soil; Barshad (1964) summarised the main techniques that have been employed. Early workers took account mainly of the resistant minerals of coarser soil fractions, often the heavy mineral suite of the fine sand, and particle size distribution of the non-clay fraction (Haseman and Marshall, 1945; Humbert and Marshall, 1943; Marshall, 1940; Marshall and Haseman, 1942; Mickelson, 1943). More recent studies of this type include those of Wicklund and Whiteside (1959), Wascher et al. (1960), Redmond and Whiteside (1967), Bourne and Whiteside (1962), Franzmeier, Whiteside and Mortland (1963), and Jones and Beavers (1964). Since the advent of rapid chemical analyses using for example X-ray fluorescence spectrometry, the determination of elements such as zirconium and titanium has been used to establish uniformity of parent materials (e.g. Beavers, 1960; Chapman and Horn, 1968; Sudom and St. Arnaud, 1971).

In order to quantify the weathering and other changes during profile development (gains, losses, translocations and transformations), some form of "weathering index" is required. This should be a readily analysable material, which remains constant in composition and amount during profile development. A common assumption in early soil development studies was that the oxides of certain elements, in particular Al_2O_3, Fe_2O_3, and SiO_2, remained constant during weathering (e.g. van Hise, 1904; Merrill, 1906; Harrison, 1934; Goldich, 1938; Brewer, 1964; Ruxton, 1968). However, it is now known that during soil formation colloidal particles containing these elements are translocated from one position to another in the profile, thus destroying the uniform distribution of the constituents chosen for the calculations of gains and losses.

Marshall (1940) introduced the concept of the "index mineral" for minerals such as zircon, tourmaline, garnet, anatase and rutile, which are resistant to weathering and immobile (i.e. contained in the non-clay fraction of the soil); Barshad (1964) added quartz, albite and microcline to this list. Mickelson (1943) and Haseman and Marshall (1945) investigated the quantitative estimation of such index minerals and their use in the measurement of the changes occurring during soil formation. Major difficulties are the presence of coated grains, which are difficult to identify, and the errors inherent in converting numerical grain counts into weight percentages of the soil. For these reasons, Haseman and Marshall adopted a chemical technique for the determination of zircon before making their calculations of soil formation and development in a Grundy silt loam profile. Barshad (1964) proposed a method based on the degree of change in the chemical composition of the non-clay fraction to calculate the amount of clay formed, use being made of the many readily available chemical analyses of soils for assessing their relative profile development. This method was applied to a large number of soils to determine the effect of pedological factors on clay formation and migration (Barshad, 1959). He concluded that clay formation is at a maximum in all soil profiles in a layer 5-50 cm below the surface, and progressively decreases below this, that clay migration is the most important process involved in the formation of horizons of clay enrichment and in producing large changes in the chemical composition of the soil, and also that clay formation is responsible for most of the changes in the mineralogical composition of the soil.

Redmond and Whiteside (1967) studied chernozems derived from till in North Dakota, and were able to make quantitative calculations of the changes in two profiles by the methods outlined by Marshall and Haseman (1942) and Barshad (1964), using total quartz as their index mineral. Calculations of net changes in sand, silt, clay, $CaCO_3$ equivalent, organic matter and volume were presented, but the rather erratic results were attributed to heterogeneity of the till. Franzmeier, Whiteside and Mortland (1963) used non-clay quartz, determined by X-ray diffractometry, to calculate changes in podzols developed on glacial drifts in northern Michigan; they found net losses of clay from the A2 horizon and net gains in the horizons below, suggesting eluviation from upper horizons and accumulation beneath. Westin (1953) used zircon as an index mineral to evaluate volume changes during the development of a solonetz soil on glacial till in South Dakota, and Mick (1949) used resistant heavy minerals to study the genesis of a grey brown podzolic soil on Wisconsinan till in Michigan, concluding that the A2 horizon had lost approximately 85 % of its clay content, and that silt and sand particles in the A2 and B2 horizons had diminished in size.

British workers seem to have made little use of the index mineral method of pedogenic calculation. Khan (1957, 1959) studied soils on limestones, including the Chalk of The Chilterns, which he considered had developed in uniform parent materials, and used zirconium as a weathering index. However, his conclusions are probably invalid, as almost all Chiltern soils contain two or more different parent materials (Avery, 1964). Weir <u>et al.</u> (1971) established the essential uniformity of a buried soil developed in loess at Pegwell Bay (Kent), using detailed particle size and heavy mineral analyses, and attempted to calculate changes in clay content and mineralogy; however, they were restricted by the unknown extent of erosion losses from the upper part of the profile. Stewart, Adams and Abdulla (1970a, 1970b) made some quantitative studies on soils derived from Silurian mudstones, using silt percentage as an internal standard.

CHAPTER 3 SOILS STUDIED

Reasons for the eventual choice of the Devensian tills of Holderness, East Lincolnshire and North Norfolk for this soil development study have already been given in Chapter 1. However, this choice was not finally made until after a search had been made for suitable soil profiles in East Anglia. The greater portion of the cliffed coastline of Norfolk and Suffolk was investigated, several miles of open gas pipeline trench examined, and numerous quarries visited (Fig. 3).

3.1 East Anglia

The cliffs of Hunstanton (TF 675420) are in Cretaceous rocks. From Hunstanton to Weybourne (TG 117437) the coast is uncliffed, but from Weybourne to Happisburgh (TG 397300) cliffs are almost continuous. The stretch between Weybourne and Trimingham (TG 282390) is largely occupied by the Contorted Drift (Reid, 1882) which is a mixture of tills, sands, laminated clays and chalk rafts, too heterogeneous for the proposed weathering study. Eastwards from Trimingham three laterally persistent till units with associated water-deposited clays, sands and gravels can be distinguished (First, Second and Third Tills of Banham, 1968, p. 508). Only the Third Till reaches the cliff-top to the west of Bacton (TG 337347). This till, however, "is an inhomogeneous, obviously deformed till . . . which contains a high proportion of sand . . . both as discrete lenses and laminae and dispersed throughout the brown, silty clay of the matrix." (Banham & Ranson, 1970). Between Walcott (TG 363328) and Happisburgh both the First and Second Tills are exposed at the cliff top. Profiles developed in the ~~former~~ latter are non-uniform, however, sandy lenses becoming abundant in the upper part. Profiles on the First Till seem more uniform, but as this is the lowest member of the local glacial succession, considerable erosion must have taken place for it to be exposed at the surface.

At Scratby (TG 516152), Chalky Jurassic Boulder Clay (Lowestoft Till of Baden-Powell & West, 1960) occupies the upper part of a short stretch of cliff to the north of California Gap. Soil profiles developed on it show extensive pipes of well-sorted sand descending as much as 1.6 m into the till from the surface, which itself is sandier than usual; also shallow depressions in the till surface are filled with a silty deposit. The cliffs at Corton (TM 545975), type locality of the Lowestoft Till (Baden-Powell, 1948, p. 283), have recently been redescribed by Banham (1971), who found the Pleasure Gardens Till over the Lowestoft Till. However, this in turn is overlain by plateau gravels and blown sand and silt. Further south in Suffolk coastal till exposures are rare, and the cliffs were not investigated. Thus, nowhere along the coastal sections are suitable soil profiles found; they all suffered from one or more of the disadvantages of lack of uniformity, erosion of upper layers, or addition of material to the surface.

Pipeline trenches radiating from the North Sea Gas terminal at Bacton provided excellent opportunities for examining long continuous sections of soil profiles. One such trench investigated was the portion between Billingford (TM 168798) and Eye (TM 149748). The sections were similar to those seen in the Lowestoft Till at Scratby, with lenses and pipes of well-sorted brown sand extending down into the till, though here the overlying silty deposit was lacking. More permanent sections in gravel workings and chalk quarries in various parts of Norfolk and Suffolk all confirmed the impression that undisturbed sedentary profiles on these East Anglian tills are probably non-existent.

3.2 East Yorkshire and Lincolnshire

Attention was therefore directed to the younger tills of Holderness, East Lincolnshire and North Norfolk, the outcrop of which is shown in Fig. 4 . Apart from the artificial warpland soils on the northern side of the Humber (Heathcote, 1951), the soils of this area have never been mapped or studied in detail, though general accounts of soil distribution in East Yorkshire and East Lincolnshire (including a map of the latter area) have been given by Crompton (1951) and Straw (1969a).

To the west of the Devensian glacial limit on the Yorkshire Wolds and much of the Lincolnshire Wolds the Chalk is nearly always close to the surface. The steeper slopes, such as the sides of dry valleys, are cut in solid Chalk and have very thin, brown calcareous soils or rendzinas. Dry valleys are floored with flinty colluvial deposits of variable texture, and on the more gently sloping surfaces of the Wolds, brown earths are developed in thin loamy and flinty drifts derived largely from a thin cover of loess, which exceeds 1 m in thickness only in some of the higher parts of the Yorkshire Wolds (Catt _et al._, 1974). Erratic stones and coarse sand are occasionally present in Yorkshire (Versey, 1938; Bisat, 1939a), suggesting the local presence of a remanié of Wolstonian or older glacial drift. Deposits resembling the Clay-with-Flints of southern England occur only at Staxton (TA 016763) and a few other isolated localities near the northern edge of the Yorkshire Wolds.

On the central part of the Lincolnshire Wolds a very chalky boulder clay, the Calcethorpe Till of Straw (1969b, p. 89) gives brown earths, together with some calcareous gley soils in the shallow valley floors. East of Caistor (TA 118013) the flatter parts of the Lincolnshire Wolds are covered by blown sand (Straw, 1963), often thick enough to give rise to sandy brown earths over Chalk.

Soils developed on the Hessle Till and its correlatives occupy most of eastern Holderness, and form a wide strip along the eastern margin of the Wolds. Small areas also occur in the northern part of the Ancholme valley, and protrude southwards into the Fens as the Stickney moraine. In Norfolk the outcrop extends as a discontinuous strip about 1 km wide along the coast from near Snettisham (TF 653332) to Holkham (TF 870430) (Suggate and West, 1959; Straw, 1960). Most of these soils are imperfectly drained clay loams, though where the till is thin and overlies Chalk (as on the eastern parts of the Wolds) or gravel, they may be freely drained. Although originally calcareous throughout, the soils are now leached to a depth of between 0.6 and 2 m, and often have a subsoil layer apparently enriched in clay.

Fluvioglacial sands and gravels associated with the Devensian ice-sheet occur in the northern and central parts of Holderness, particularly around Driffield (TA 025575) and Brandesburton (TA 117475) and in the Irby-Brocklesby-Killingholme area of north Lincolnshire. They generally contain chalk and give rise to well-drained sandy brown earth soils, neutral to slightly acid in reaction.

Along the Humber estuary and the coasts of Lincolnshire and Norfolk the tills are overlain by marine alluvium, up to five miles wide in Lincolnshire, but usually less than a mile in Norfolk. These materials are compact and fine-grained, and because most of the area is below 3 m O.D. the persistently high water-table gives rise to mostly grey, slightly to moderately acid non-calcareous gley soils.

Bordering the Humber estuary are areas of warpland soils, low-lying riverside land on which a highly calcareous and micaceous fine sandy or silty alluvial deposit has been built up either naturally or artificially by successive tidal floodings of the sediment-laden river. The local drainage conditions largely determine the occurrence of brown earths or gleys on this material.

To the south of the Lincolnshire Wolds, Fen alluvium and peat overlie the boulder clay. The soils of these areas, originally mainly calcareous gleys, have been modified by deep artificial drainage and arable cultivation to more of a brown earth character. Oxidation and blowing are reducing the area of the peaty soils. In Holderness, an extensive area of the Hull valley north of Thearne (TA 075368) is occupied by similar peat and freshwater alluvium.

As no surveying had been done by the Soil Survey of England and Wales in east Yorkshire and Lincolnshire, profile descriptions and samples of the till soils were unavailable. To avoid the possibility of wasting much time in digging profile pits that might prove unsuitable, it was decided to investigate first the known exposures of till in the area. Inland sections are unfortunately rare in lowland Holderness and East Lincolnshire, although pits in chalk overlain by till are common on the Wolds. However, these pits are often cut into steep slopes, and the till is thin and weathered throughout. Cliff sections are almost absent in Lincolnshire, and that at Hunstanton in Norfolk is in Cretaceous rocks, the Devensian ice-sheet apparently having failed to over-ride this rib of chalk (Straw, 1960). However, the Holderness coast is almost continuously cliffed, and cut entirely in Quaternary deposits. The north-south cliff line intersects the fresh, low-relief topography of eastern Holderness, where drainage is predominantly from east to west into the Hull valley. Thus, extensive flat interfluve areas are seen in section at several places along this coast. Marine erosion of the cliffs is rapid, having averaged about 1.2 metres/year for the period 1852 - 1952 (Valentin, 1954), so fresh sections are constantly being exposed. Therefore, the initial search for a suitable profile was conducted along this promising coast line.

Four distinct tills have been described from the cliffs of Holderness (Fig. 5). The lowest, the Basement Till, is Wolstonian or older (Catt and Penny, 1966, p. 402), and does not occur at the surface. The Drab Till, the lowest member of the Devensian sequence, is exposed throughout the length of the Holderness coast, except between Holmpton (TA 376237) and Withernsea (TA 345278), where it sinks below beach level. North of Ulrome (TA 176572), as far as Bridlington, it is the only till exposed, but is here mostly overlain by gravels. The Purple Till is of more restricted occurrence, being seen in the Holderness cliffs only between Easington (TA 403200) and Mappleton (TA 242419). The Hessle Till, the topmost member of the till succession recognised by Catt and Penny (1966), is widespread, though often locally removed by erosion, for example at Grimston Hall (TA 289352) where Late-glacial beds lie directly on Purple Till. Nevertheless, it seems to occupy the cliff-top along the majority of the Holderness coast.

The cliff-section between Dimlington (TA 399206) and Out Newton (TA 385225) was investigated first, but near Dimlington Farm (TA 399206) there is considerable human disturbance in the form of farm-tracks, roads, ditches and rubbish-heaps, and the relatively steep slopes inland from the cliff near Dimlington High Land (TA 390218) may have encouraged removal of some soil by surface erosion. For these reasons the soil profile was not sampled here. The Tunstall cliffs (TA 314318) were then investigated, and a site was chosen in the middle of an extensive flat interfluve area. Nowhere was a plough layer absent, but there had been no recent cultivation, and a fresh profile had recently been exposed by a landslip. For a comparison with soils developed on the most southerly outcrop of the Devensian tills, a profile was collected from the Hunstanton Till exposed in the Holkham brick-pits (TF 863428).

After selection of these two sites, faces of suitable depth were cleared, ensuring that the profiles sampled extended well into the calcareous parent material. Field descriptions of the profiles were made using the methods detailed in the Soil Survey Handbook (1960), horizon boundaries being established on differences in colour, structure, texture, stoniness and carbonate content. A clean stainless steel trowel was used for sampling to avoid rust and other contamination. 2 kg samples were taken from each horizon, placed in 500 gauge polythene bags, then double-wrapped to avoid contamination during transport.

In order to ascertain the textural and mineralogical variability of the Devensian tills, both vertically and laterally, samples (as unweathered as possible) of each till were also collected from a broad spread of localities (Fig. 6). Existing exposures were utilised wherever possible, to minimise sampling time, but a few samples were obtained with a Dutch auger. Samples of pre-Devensian tills exposed in eastern England were also collected for comparative purposes. Sampling localities are detailed in the Appendix (Table 3), and are also shown in Figs. 3,7 & 8.

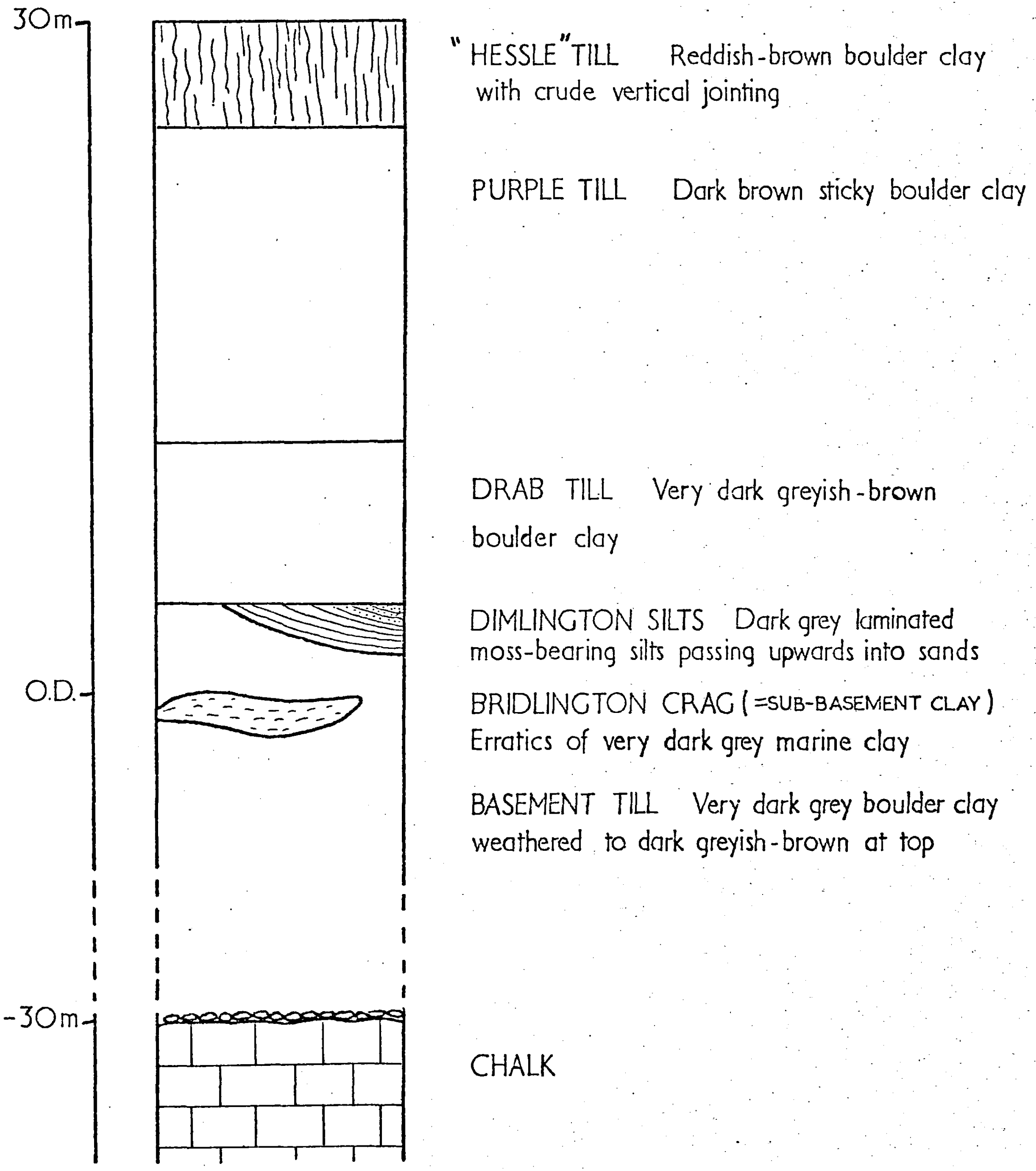


FIGURE 5 GLACIAL SUCCESSION OF THE HOLDERNESS COAST: DIMLINGTON

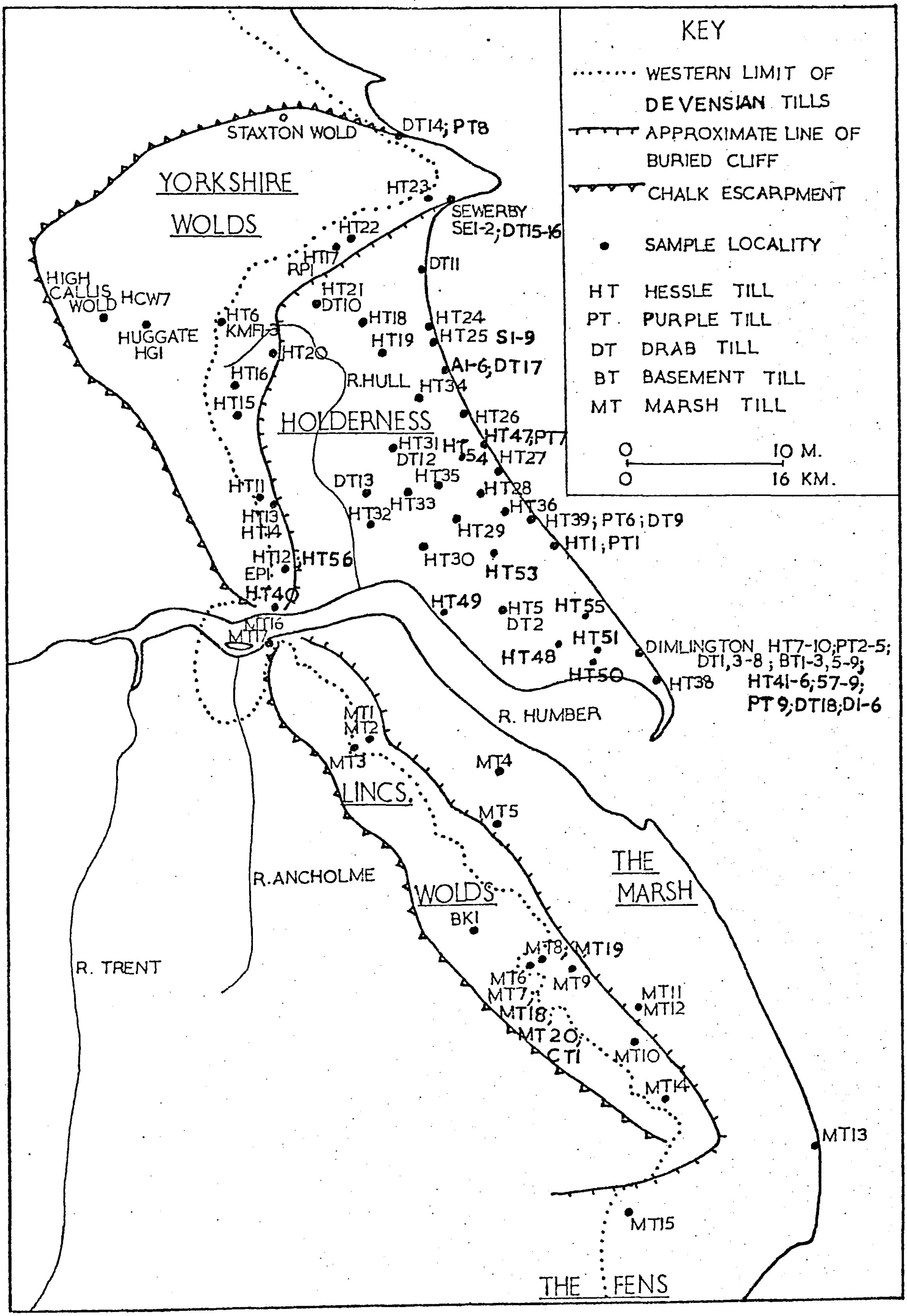


FIGURE 6 SAMPLE LOCALITIES : YORKSHIRE & LINCOLNSHIRE

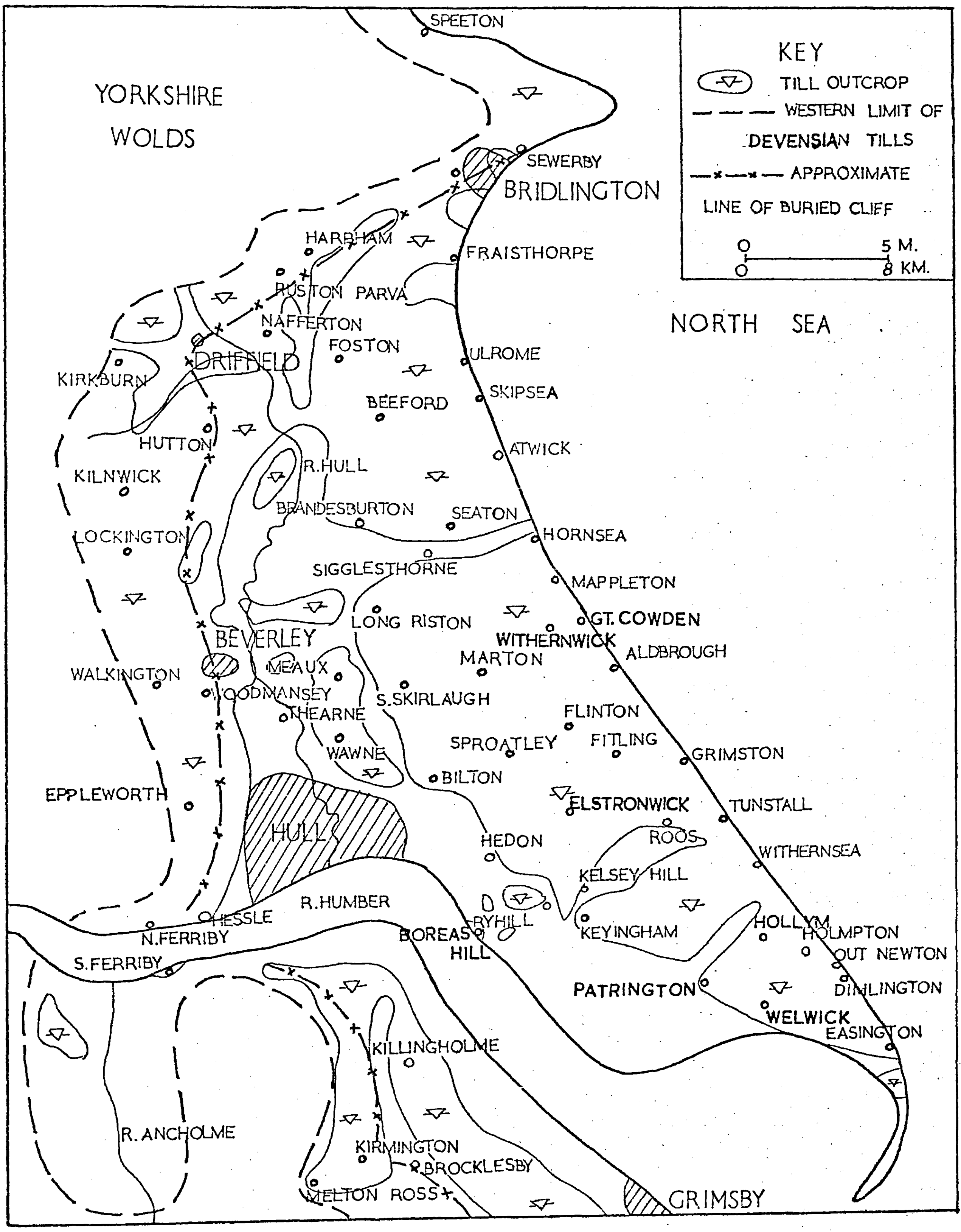


FIGURE 7 LOCATION MAP : HOLDERNESS

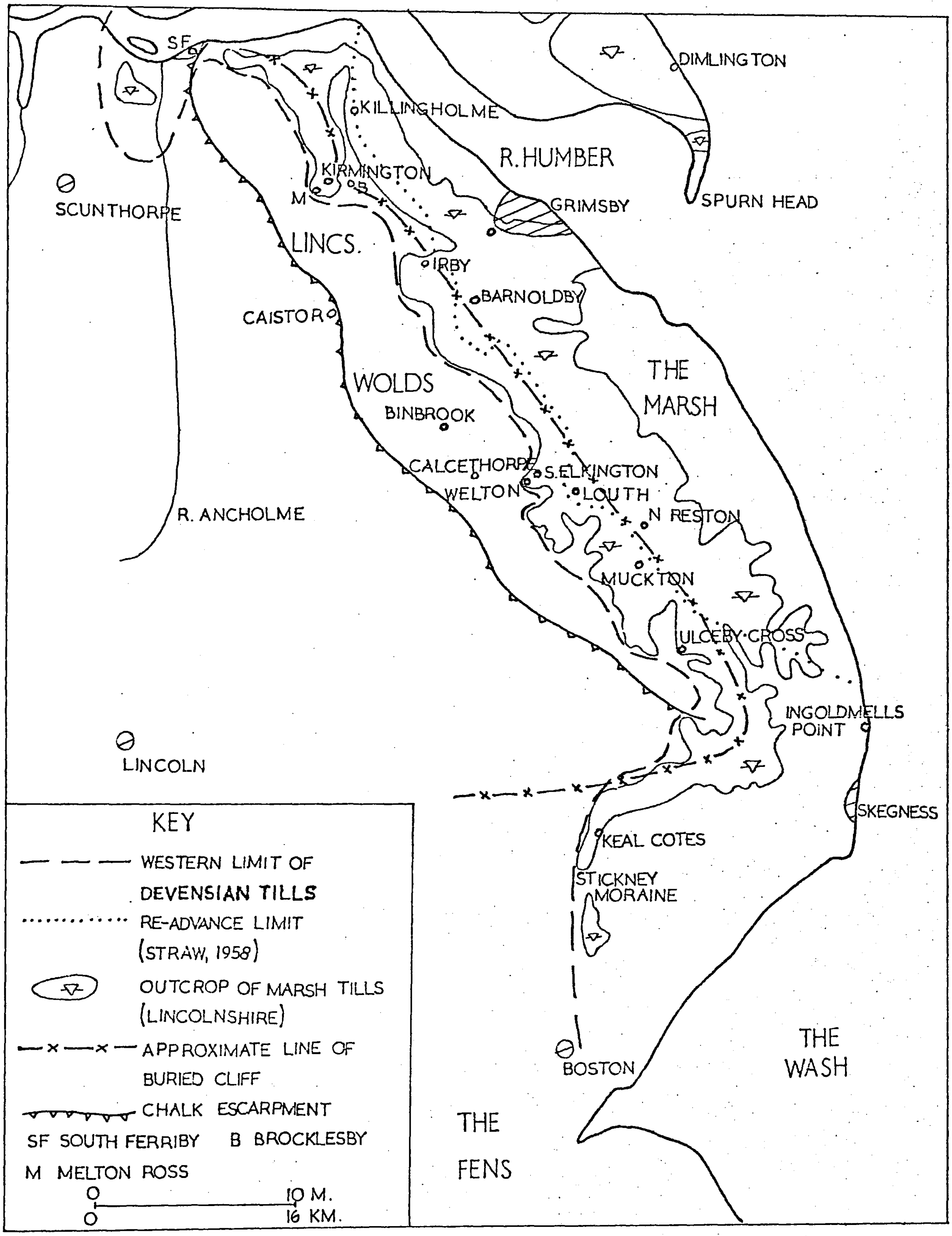


FIGURE 8 LOCATION MAP : LINCOLNSHIRE

CHAPTER 4 ANALYTICAL METHODS

4.1 Preliminary Treatment

Each sample was air-dried on a cardboard tray for several days. Before bagging and boxing the dry samples, the colour in the air-dried state was determined by reference to Munsell soil colour charts (1954 edition). Moist colours were determined at the time of collection of the samples. Samples were broken up by hand or, if necessary, by light pressure in a mortar and pestle. After a quartering procedure to ensure homogeneity of the sample, one weighed portion was divided into "fine earth" (< 2000 μm) and "stones" (> 2000 μm) by dry sieving through a No. 8 mesh (2000 μm) brass sieve. The stones were then washed, subdivided into lithological types, and weighed separately.

4.2 Bulk Density Measurement

Natural soil clods of about 10 - 20 g were collected from each horizon, dried slowly in air, and then thoroughly in an oven at 110°. The dry clods were weighed, then dipped in molten paraffin wax. This served to coat the clod thoroughly with an air and water tight surface layer. Reweighing the coated clod gave the weight of adhering wax, the volume of which could then be calculated. The clod was then reweighed in water and Archimedes' Principle used to calculate its volume after allowing for the volume of the wax coating. The bulk density of the soil was then calculated from the volume and dry weight of the clod.

4.3 pH Determination

The pH of each soil horizon was determined by the method of Jackson (1958, p. 46). 10 g samples of the air-dried soil were placed in 50 ml beakers, and 25 ml of boiled distilled water added. The slurry was stirred regularly for 20 - 30 minutes, when the pH was measured on a Vibret pH-meter, the electrode being inserted immediately after a final stirring.

4.4 Carbonate Determination

Carbonate contents were determined by the calcimeter method of Bascomb (1961).

4.5 Organic Carbon Determination

Samples of dried soil were ground in a tungsten-steel Tema mill for ten minutes. Their organic carbon contents were determined by ignition in a current of CO_2-free oxygen, the carbon dioxide formed being dried, collected by adsorption in soda-lime packed tubes, and weighed.

4.6 Particle Size Distribution

Particle size distribution was determined by the pipette sampling method, using 10 g sub-samples. These were first decalcified, where necessary, with 2 N acetic acid. Excess acid was removed by centrifugation and decantation. After transferring to 600 ml pyrex glass beakers, 100 ml of 40 vol. hydrogen peroxide were added to destroy organic matter. This was left overnight, then the excess peroxide destroyed by boiling. The suspension was cooled and transferred to one litre polythene shaking bottles, 25 ml of 5% "Calgon" (sodium hexametaphosphate) solution added, and the bottles rotated overnight in an end-over-end shaker. Each sample was then washed into a thick glass beaker and subjected to one minute of mild ultrasonic agitation in a five litre tank agitator rated at 200 W at 25 kHz. The suspensions were transferred to one litre cylinders, made up to volume with distilled water, the temperature of the liquid noted and fall times calculated for the fractions to be sampled (Tanner and Jackson, 1948, p. 61). A rubber plunger was used to thoroughly stir the suspensions. 20 ml aliquots were removed with a sampling pipette at the appropriate times and depths for the various fractions, then transferred to previously weighed crucibles, dried overnight at 105°, and weighed.

The sand fraction (> 53 µm) was removed by wet-sieving from the remaining suspension, dried and weighed. The oven-dry weight (105°) of the soil was determined on a separate sub-sample. A "Calgon" blank value was obtained by evaporating to constant dry weight 20 ml portions of "Calgon" solution similar in strength to that used for dispersion of the 10 g soil samples in 1000 ml water. Allowance was made for carbonate and organic matter contents in the calculation of results.

Detailed particle size distributions of the sand fractions were determined on separate 150 - 200 g sub-samples by dry-sieving at $\frac{1}{4}$ Ø intervals. The samples were prepared by mild ultrasonic dispersion in dilute (0.02%) "Calgon" solution, and the sand separated from silt and clay by wet sieving through a 300 mesh (53 µm) sieve.

4.7 Size Fractionation

Size separates from the sand sieving were combined to give two fractions, 53 - 250 µm (4.25 to 2.00 Ø) and 250 - 2000 µm (2.00 to 1.00 Ø). With most of the till samples, from which only small amounts of clay and silt fractions were required for subsequent mineralogical analysis, these were separated from the < 53 µm suspensions remaining after the pipette sampling. However, larger fractionated samples were required from profiles HT1 and HT2. To prepare these, 50 g sub-samples were treated to remove calcium carbonate and organic matter, and then dispersed in 0.05% "Calgon" solution with mild ultrasonic agitation. Roberson et al. (1968, p. 242) have shown that this method produces no perceptible disruption of clay particles. The sand > 53 μm was first removed by wet-sieving the suspension through a 300 mesh sieve; it was then dried and re-sieved, the portion passing through the dry sieve being recombined with the silt and clay suspension. Clay (< 2 μm), fine silt (2 - 5 μm), medium silt (5 - 20 μm) and coarse silt (20 - 53 μm) fractions were separated by repeated sedimentation in a column of water. The clay was further divided into coarse and fine fractions (0.25 - 2 μm and < 0.25 μm respectively) by repeated centrifugation in an M.S.E. Major centrifuge. The coarse silt was dried from acetone after filtering through a Whatman No. 50 paper. The remaining fractions were Mg-saturated by two washings with 1N magnesium chloride solution in 250 ml polypropylene centrifuge bottles, then washed twice with distilled water to remove excess magnesium chloride, once with methanol and twice with acetone to remove water, and finally once with petroleum ether to remove traces of acetone. After the final centrifugation and decantation the bottles were left by a warm radiator overnight to dry.

4.8 Mineralogy

The mineralogy of the fine sand (53 - 250 μm) and coarse silt (20 - 53 μm) fractions was determined with a Leitz Dialux-Pol petrographic microscope, while X-ray diffractometry of oriented aggregates and selected chemical methods were employed for mineralogical analyses of finer fractions.

4.9 Heavy Mineral Separations

Heavy (specific gravity > 2.9) and light (S.G. < 2.9) separates of the fine sand and coarse silt fractions were prepared, using bromoform as the heavy liquid. The sands were separated by the usual shaking and settling procedure using 10 g samples with 150 ml of bromoform in 250 ml conical separating funnels. The silts were too fine-grained for this procedure to give a satisfactory separation, so a centrifugation method was adopted. 0.5 g samples were added to 50 ml pointed glass centrifuge tubes containing about 40 ml of bromoform. Before placing the tubes in the centrifuge the silt was gently stirred throughout the liquid. Rubber caps were used to avoid the convection currents in the liquid that can result from air currents in the centrifuge. Ten minutes' centrifugation at 1500 r.p.m. in an M.S.E. Multex centrifuge sufficed for separation of heavy and light fractions, which were then recovered by inserting the point of the tube in a freezing mixture of ice and sodium chloride until the bottom inch or so of bromoform was frozen. The unfrozen liquid containing the light minerals was decanted off through Whatman No. 50 filter papers and the tubes rinsed with further bromoform from a wash-bottle. After thawing the remaining bromoform the heavy fraction was similarly filtered off, the bromoform recovered, and both fractions washed thoroughly with acetone before air-drying. This is essentially the same as the method adopted by Fessenden (1959).

4.10 Optical Mineralogy of Fine Sands and Coarse Silts

Temporary mounts were made up of a few hundred grains spread out in drops of Clove Oil (refractive index 1.54) on glass slides. This procedure was time-saving compared with the preparation of permanent mounts in Canada Balsam, and allowed manipulation and removal of individual grains to aid identification. Approximately 1000 grains were counted for each heavy fraction, of which generally about 400 - 500 were non-opaque, but if a sample was very rich in a particular mineral or group of minerals proportionately more grains were counted. As the light fractions contained fewer minerals than the heavy fractions, only 300 - 400 grains were counted for each sample. Confirmation of the identity of a few individual grains was obtained by X-ray powder diffractometry in a Philips PW1026 Debije-Scherrer camera.

4.11 X-Ray Diffractometry

Approximately 100 mg samples of the dry magnesium-saturated clay or silt were dispersed in 2 ml distilled water in plexiglass tubes by agitation on a Wig-L-Bug shaker. The resultant suspension was spread on four labelled glass slips, cut from microscope slides (Madgett and Edwards, 1972). X-ray diffractometry was done with a Philips PW1050 diffractometer using the following settings:- Ni-filtered Cu radiation from a tube run at 44 kV and 30 mA; goniometer scan setting; divergence slit $\frac{1}{4}^{o}$, receiving slit 0.3 mm, antiscatter slit 1°, Ni foil 0.013 mm, scan speed 1°/minute; detection by xenon-filled proportional detector tube, operated with an attenuation of 2, window 1.20, lower level 1.60; ratemeter with 1 sec. time constant; chart display with full scale deflection 2×10^3 or 4×10^3 counts/sec., chart speed 600 mm/hr.

Each set of four slips received the following treatments before diffractometry:-

1. Drying in air at 20°C.
2. Solvation with ethylene glycol vapour at 80° for 4 hours (modification of Brunton, 1955).
3. Heating for 4 hours in a muffle furnace at 335°, cooled and stored in a dessicater.
4. Heating for 4 hours in a muffle furnace at 525°, cooled in the furnace to 335° as a precaution against warping of the glass slide, then further cooled and stored in a dessicator.

The previously heated specimens were heated to 150° on a heating stage (Brown _et al._, 1972) during diffractometry to prevent rehydration of collapsed smectites and vermiculites. The spacings of diffractogram peaks were converted from degrees 2 θ to d spacings in Å units by means of a ruled perspex overlay calibrated for Copper K α radiation and the chart speed used.

4.12 Interpretation of Diffractograms

"Since the diffraction pattern of each crystal species is a unique sequence of diffraction maxima, like a fingerprint, the pattern serves the purpose of identification of each separate species present. Ordinarily, dependence is placed on the most intense one to three diffraction peaks for qualitative identification." Jackson (1964, p. 253).

A first approximation to understanding the clay mineralogy of the specimens, ignoring complex interstratification and mixed layering, was obtained using the d spacings of clay minerals (from Brown, 1961) given in Table 2.

Thus, a 14 Å d spacing from an air-dried magnesium-saturated sample may indicate the presence of vermiculite, smectite or chlorite, or a mixture of these minerals. Glycol solvation causes expansion of the smectite lattice to 17 Å, whereas the d spacings of chlorites and vermiculites remain at about 14 Å. On heating to 335° both smectites and vermiculites collapse to about 10 Å, while chlorite maintains its 14 Å spacing. Swelling chlorites are known, though rare (e.g. Stephen and MacEwan, 1950, 1951; Honeyborne, 1951; Lippmann, 1954; Martin-Vivaldi and MacEwan, 1957). The persistence of a 14 Å peak on heating distinguishes them from smectites, however. Vermiculites with a small interlayer charge may expand beyond 14 Å on glycol solvation (Walker, 1958), so glycerol treatment is necessary to distinguish effectively between these and smectites. Mg-saturated vermiculites give a diffraction spacing of 14.3 Å on glycerol solvation, whereas smectites give a peak at 17.7 to 18 Å. Ethylene glycol was used as the standard organic solvating agent instead of glycerol because of its considerably lower boiling point.

Table 2. Diffraction Spacings (Å) of Mg-Saturated Specimens

Mineral	Air-Dried	Ethylene Glycol Solvated	335° Heated	525° Heated
Smectite	14	17	10	10
Vermiculite	14	14	10	10
Chlorite	14	14	14	14
Mica	10	10	10	10
Kaolinite	7	7	7	--
Quartz	4.26	4.26	4.26	4.26
Feldspar	3.18 - 3.24	3.18 - 3.24	3.18 - 3.24	3.18 - 3.24
Lepidocrocite	6.27	6.27	--	--
Goethite	4.18	4.18	--	--

Heating the fourth slip to 525° is designed to distinguish between chlorite and kaolinite. Both give diffraction peaks at about 7 Å, and sub-multiples of this, but at 525° the crystal structure of kaolinite is destroyed, whereas that of most chlorites is but little altered. The second (7 Å) and fourth (3.5 Å) order reflections of the chlorite are normally weakened, while the first order peak at 14 Å is usually strengthened. However, since an iron-rich chlorite before heat treatment may give second order and weak first order reflections, the presence of weak 14 Å and strong 7 Å peaks does not prove the co-existence of chlorite and kaolinite (Brindley, 1961, p. 85). The reflection at about 3.5 Å can be employed to decide on the presence of both species, as there is usually some separation of the fourth order chlorite peak (at about 3.52 Å) from the second order kaolinite peak (at about 3.57 Å). By using the 335° heated trace for this distinction, confusion with the fourth order vermiculite peak can be avoided.

4.13 Chemical Methods of Clay Mineral Analysis

Amounts of quartz, feldspars and mica in each size fraction were calculated from figures for total K, Na and Ca in the Mg-saturated samples and in the residues from fusion with sodium bisulphate (Kiely and Jackson, 1965). Amounts of amorphous silica and alumina in the finer fractions were determined by the alkali dissolution technique of Hashimoto and Jackson (1960). Free iron oxide determinations were made on samples of the whole soil and of the finer fractions using the dithionite-citrate method of Mehra and Jackson (1960). The methods of Pruden and King (1969) were used for all elemental analyses.

4.14 Quantitative Estimates of Clay Mineralogy

Quantitative estimates of quartz, feldspars, mica, iron oxides and amorphous material were made from the chemical determinations. The difference between the totals for these determinations and 100% was sub-divided between kaolinite, expanding layer silicates and chlorite on the basis of their relative peak intensities, according to the following scheme. Total expanding layer silicates were estimated on the basis of the difference in intensity of the 10 Å peak of the glycol solvated sample and that of the 335° heated sample. If no independent chemical determination of mica was available, the 10 Å peak intensity of the glycol solvated sample was used as an estimate of its relative abundance. Estimates of the abundance of vermiculite relative to smectite were based on the intensities of the 14 Å and 17 Å peaks of glycol solvated samples. The intensity of the former peak was reduced by an amount equal to that of the 14 Å peak of the 335° heated sample to allow for the chlorite contribution. The intensity of the 17 Å peak was reduced by half to allow for the increase in intensity due to the lower reflection angle. The 7 Å kaolinite peak of the 335° heated sample was similarly reduced by one third to allow for the difference in intensity of diffraction from equal weights of kaolinite and micaceous minerals. No similar factor for chlorite is in general use, but as amounts, where present, appeared to be small, the intensity of the 14 Å peak of the 335° heated sample was also reduced by half for comparison with the 10 Å peaks.

4.15 Micromorphology

Thin sections were prepared of ped samples from the Tunstall Hessle Till profile by the resin impregnation method used by the Soil Survey of England and Wales (Avery, 1974). These were examined with a polarising microscope.

CHAPTER 5 DISCUSSION OF RESULTS: PARENT MATERIALS

5.1 East Anglian Tills

Chapter 3 describes the field investigations in East Anglia, and Appendix Table 3 gives descriptions of exposures of the tills and soil profiles developed in them. Field study of these profiles was sufficient to show that the main East Anglian till-sheets are unsuitable materials for meaningful studies on soil formation and mineral weathering, at least until a full study has been made on more uniform and less disturbed and eroded materials. The limited laboratory work on these tills and their soil profiles confirmed this impression.

Appendix Table 6 gives the particle size distributions, on a carbonate-free basis, of the East Anglian samples. Cumulative particle size distributions of Chalky Boulder Clay samples from East Anglia are shown in Fig. 9 . The non-uniformity of a typical profile, LT5, at Eye (TM147757) developed on this material is shown in Fig. 10 . Perrin (in Hodge, 1972, p. 145) observed similar inhomogeneity in soils on Chalky Boulder Clay from three widely separated sites in East Suffolk, and Hodge (p. 143) states that the surface layers of soils on Chalky Boulder Clay over much of east Suffolk and south Norfolk contain more sand than the underlying till. Pockets of sand or loamy sand are common in this upper layer, and sometimes extend deep into the calcareous till. Fig. 11 shows the textural similarity of samples from these sandy pockets (samples LT1/6 and LT5/4) to the sands of Breckland (samples WO1/1, WO2/1, WO3/1 and BR1), which are regarded by Watt _et al_. (1966) and Perrin _et al_. (1974) as aeolian in origin.

Catt _et al_. (1971) showed that many soils in north-east Norfolk contain loess; cumulative particle size curves of some of these soils are given in Fig. 11 . At Scratby (TG516152) soil profiles over Chalky

Boulder Clay (Lowestoft Till) contain this silty loam; also lenses and pipes of brown loamy sand extend nearly 2 metres into the till (see Figs. 12-14). The stratigraphy at this site gives some indication of relative ages of sand and silt deposition on the surface of the Lowestoft Till. The proposed order of events is as follows:

1. Deposition of the Lowestoft Till.
2. Erosional interval of unknown length.
3. Deposition of aeolian (?) sand (possibly contemporary with deposition of the Breckland sands).
4. Incorporation of this sand into the upper 2 m of the till by periglacial processes (e.g. frost-cracking, cryoturbation).
5. Deposition of aeolian silt (loess) (= coverloam of Catt et al., 1971)
6. Partial erosion of the silt cover, with solifluction causing some admixture with subjacent deposits.
7. Further addition of sand (modern blown sand?) to surface horizon.

The deposit of stony loam described by Baden-Powell (1944) as "Hessle Boulder Clay" capping the cliffs between Happisburgh and Mundesley may well consist, at least in part, of coverloam. Fig. 15 compares the particle size distributions of sample HT4, from the top of the cliffs near Bacton (TG333350), undoubted Hunstanton Till (HT2) from Holkham (TF863428), and other coverloam samples; no textural similarity between samples HT4 and HT2 is apparent, but HT4 is very like the coverloams.

The coastal section of north-east Norfolk has cliffs largely developed in tills of the North Sea Drift, mechanical analyses of a few samples of which are presented in Fig 9 . They contrast markedly in texture with the Chalky Boulder Clay, being much sandier.

Samples of Norwich Brickearth from north-east Norfolk are similar in texture to the North Sea Drift tills. Since the area occupied by the North Sea Drift/Norwich Brickearth sequence in north-east Norfolk approximates to the distribution of coverloam (Fig. 3), it is unlikely that uniform, undisturbed and untruncated soil profiles exist on these tills.

The Pleasure Gardens Till (Banham, 1971) at Corton (TM547967) is a more silty deposit than either the underlying Lowestoft Till or the North Sea Drift tills (Fig. 3). However, it is of restricted occurrence, and is covered by later deposits (including coverloam) in the cliff-section, so was not considered as a soil parent material.

The mineralogy of the heavy fractions from fine sands of some samples was also investigated (Appendix, Table 18), but the number of samples analysed is too small for any generalisations to be made concerning significant differences between tills. However, all four samples of North Sea Drift tills are essentially alike in their mineralogy, even though all three of the till units recognised by Banham (1968, p. 508) are represented. They contain less zircon but more hornblende than the Lowestoft Till at Eye (sample LT5/3). The sandy upper horizons and sand inclusions of the Eye profile (LT5/2 and LT5/4) are mineralogically alike, and differ only slightly from the calcareous till (LT5/3). The underlying shelly sands, LT5/7 (equivalent to the Corton Beds?), are also mineralogically similar to the till. The sandy inclusion (LT1/6) in the Lowestoft Till at Scratby is mineralogically similar to that sampled from the Eye profile (LT5/4). The Lowestoft Till at Corton is remarkable for its very high content of siderite, this mineral also being abundant in the overlying Pleasure Gardens Till. The two Breckland sand samples analysed (WO1/1 and WO2/1) resemble one another mineralogically, but contain more zircon and less hornblende and epidote than the sandy pockets (LT1/6 and LT5/4) in the Lowestoft Till further east. No conclusions as to the possible relationships of these sands can be drawn from this limited data.

5.2 Yorkshire, Lincolnshire and North Norfolk

Experience in East Anglia showed it was necessary to establish definitely whether the surface of the Devensian tills in Yorkshire, Lincolnshire and Norfolk is contaminated by later aeolian deposits or not. Coversands of Late Devensian or early Holocene age overlie lacustrine deposits and Devensian tills in the Vale of York (Matthews, 1970; Gaunt et al., 1971), and also occur extensively in north Lincolnshire to the west of the Jurassic and Cretaceous scarps, and to a small extent on the crest of the Cretaceous scarp near Caistor (Straw, 1963). However, the only blown sand known in Holderness and Lincolnshire east of the Wolds occurs as dunes along certain low-lying parts of the coast. A sandy loam deposit (HT14) overlies till at Woodmansey (TA023383), but no sharp junction is discernible between the two deposits, and as the sandy deposit is not much better sorted than the till itself and far less well sorted than known blown sand deposits (e.g. DMS2, Fig. 15), it is either a sandier phase of the till or a poorly sorted outwash deposit.

The loess that forms thin flinty silt loam soils, characteristic of large areas of the western Chalk Wolds in Yorkshire and Lincolnshire, is probably older than the Devensian tills and is therefore unlikely to contaminate soils on the surface of the tills. In several quarries on the Wolds silty chalk head deposits occur between the till and solid chalk, and removal of the carbonate from samples of these (EP1 and RP1) gave silty residues with particle size distributions similar to those of the loessial deposits beyond the Devensian till margin in Yorkshire, Lincolnshire and Norfolk (Fig. 16). The head deposits incorporating loess seem to have formed before the ice-sheet which deposited the overlying till reached its maximum extent. However, the loessial deposits are probably not much older than the tills, because they show some mineralogical similarities to the tills, and at Sewerby silty material (samples SE1 and SE2), texturally and mineralogically similar to the loess of the Wolds, occurs in a solifluction deposit under the Drab Till, but overlying the Ipswichian raised beach deposit (Catt, Weir and Madgett, 1974).

Laboratory analyses also showed that the surface of the Devensian tills is generally free of aeolian or other contaminating deposits. Fig. 17 shows cumulative particle size distribution curves of the top-soils and calcareous sub-soils of the profiles at Tunstall, HT1 (TA314318) and Holkham, HT2 (TF863428), compared with loess (EP1, Eppleworth, TA021324) and cover-sand (LT5/4, Eye, TM147757) samples. In contrast to curves for profiles on the Lowestoft Till at Eye and Scratby (Figs. 10 & 12), no contamination of the upper horizons by sand or silt is evident. Although both top-soils (HT1/1 and HT2/1) are slightly more sandy than their respective sub-soils (HT1/7 and HT2/5), no bimodal distribution of grain-size is apparent, suggesting that the top-soils have developed directly from material similar to that of the sub-soils.

Deposition of new material seems not to have occurred extensively on the surface of the Devensian tills. It does not present a problem in soil profile studies, providing sampling sites are chosen on flat plateau areas, avoiding alluvial deposits, irregular depressions in the till surface containing Late-Glacial and Holocene deposits (e.g. The Bog, Roos, TA274288; the Old Mere, Hornsea, TA210475; and Grimston Hall, TA289352), and steep slopes where erosion and truncation of soil profiles could have occurred.

To determine whether the conclusions drawn from the profile studies (Chapter 6) could be applied to all the soils developed on Devensian tills in eastern England, samples were collected from many localities (Figs. 6 - 8) to estimate the extent of lithological and mineralogical uniformity in the tills. It was also anticipated that such analytical data could have a stratigraphic significance, perhaps supporting the three-fold division of the Devensian succession (Drab, Purple, Hessle), and assisting lateral correlation in eastern England. Details of the sampling sites and analytical results are given in the Appendix (Tables 3 - 21).

5.2.1 Colour

On the east coast of south Holderness, where the Basement (Wolstonian) and all three Devensian tills are represented, their matrix colour can usually be used as a distinguishing feature (Catt and Penny, 1966). The typical moist colours of the till matrices in southern Holderness are 5YR3/4 to 4/4 (dark reddish brown to reddish brown) for the Hessle; 7.5YR3/2 (dark brown) for the Purple; 10YR3/2 (very dark greyish brown) for the Drab; and 2.5Y3/2 to 5Y3/1 (very dark greyish brown to very dark grey) for the Basement Till. It is unlikely that colour alone is reliable for long distance correlation, but the moist colours of all the samples studied (Appendix, Table 4) correspond closely with these four.

Catt and Penny (1966, p. 393) maintained that the surface till over most of Holderness and the Yorkshire Wolds is the Hessle, and that this is underlain by Purple Till near the coast in south-east Holderness, by Drab Till elsewhere in Holderness, and by Chalk on the Wolds. At a few inland exposures 10YR3/2 colours at depth indicated the presence of Drab Till, but otherwise the surface till samples from inland Holderness and the

Yorkshire Wolds were nearly all reddish brown. They are referred to as Hessle Till in this thesis, being given the prefix "HT". Sample HT18 was predominantly dark yellowish brown (10YR4/4), but was referred to the Hessle Till because its pale colour was probably due to gleying and secondary carbonate deposition along fractions, and traces of redder colours were discernible in the interiors of peds. Hunstanton Till samples from north Norfolk also have 5YR4/4 colours, and are numbered in the "HT" series. The prefix "PT" was used to denote Purple Till samples (all from the coast), "DT" for Drab Till, and "BT" for Basement Till. Although the pre-Devensian Basement Till is seen only in cliff and beach exposures, it was included for comparative purposes.

Straw (1969b, p. 97) correlated the tills of east Lincolnshire with the Drab/Purple/Hessle sequence of Holderness, but described them as Upper and Lower Marsh Tills, relating to separate ice advances within the Devensian. The extent of each advance is indicated on Fig. 8. This usage is followed here, samples from Lincolnshire being given an "MT" prefix. Moist colours of the Marsh Tills range from 10YR3/2 and 4/2, through 7.5YR4/2 and 4/4, to 5YR4/4 the last being the most common. The 10YR colours may indicate a Lincolnshire development of the Drab Till; this is certainly so for sample MT17, from south Ferriby (SE996223) which is on the south side of the Humber estuary, only a few miles from an exposure of Drab Till at north Ferriby (SE983251). A sample of till (MT18) from Welton-le-Wold (TF282883) has a moist colour of 2.5Y4/2, comparable with that of the Basement Till at Dimlington.

5.2.2 Carbonate Content

Table 5 gives the results of carbonate analyses on the till samples. The maximum calcium carbonate equivalent was found in sample HT16, from the Yorkshire Wolds, directly overlying chalk. Calcareous till samples from the Wolds, both in Yorkshire and Lincolnshire, contain about 15 - 20% carbonate. Small chalk fragments are common, but do not necessarily come from the chalk beneath; many Hessle Till samples far removed from outcropping Chalk contain similar amounts of carbonate (e.g. HT29 has 17.9% carbonate), and the average for samples of the Drab Till, which contains abundant chalk fragments, is about 15%. The Hessle Till on the south-east coast of Holderness contains about 8% carbonate, and the underlying Purple Till about 9%.

5.2.3 Texture

Particle size determinations and textural classes (U.S.D.A., 1951) of the samples are given in Appendix Table 6 ; the textural range for each till unit is indicated in Figs. 18-26 . The Basement, Drab and Purple Tills are texturally distinct, the main difference between them being in coarse silt (20 - 53 μm) content. All Basement Till samples analysed contain less than 28% silt, the Drab Till contains 28 - 40%, and the Purple Till 40 - 45%. Samples of Hessle Till contain from 29 - 44% silt, their textural range almost completely overlapping those of the Purple and Drab Tills. Hessle Till samples from south-eastern Holderness form a tightly clustered group on the textural diagram (Fig. 19) at the sandy end of the Purple Till range. The textural range of Hessle Till samples from central and northern Holderness (including the coastal section north of Hornsea) overlaps that of the samples overlying chalk or chalk head on the Yorkshire Wolds, and both lie within the range of the Drab Till samples. Samples of Hessle Till from south-east Holderness are more silty and, in general, less sandy than those from other parts of east Yorkshire. Fig. 27 , based on samples from an east-west transect across southern Holderness shows this change of texture in the Hessle Till.

Since the clay content is less variable than the silt and sand in the Hessle Till samples, the sand to silt ratio is used for mapping their textural variability. Unlike Raad and Protz (1971) who used a straightforward sand/silt ratio, with its attendant problems of an infinite range of values (x% sand/0% silt gives a ratio of infinity), the more meaningful ratio % sand/% sand + % silt, which has a range of values from 0 to 1, is used here. For convenience this ratio is converted to a percentage. Fig. 28 shows that apart from three samples near the edge of the till sheet on the Wolds, one of which is almost certainly contaminated with loessial silt (see below), a line drawn from Hedon (TA190280) to Atwick (TA190510) separates samples to the west having ratios greater than 45 from those to the east having ratios less than 45. Maximum values, of 58 - 60, representing the sandiest tills, occur in central Holderness. The Purple Till, which is restricted to the south-eastern coastal area of Holderness, has a sand/sand + silt ratio consistently less than 45, and the Drab Till, which probably underlies most of Holderness, has a ratio generally greater than 45, often as high as 58 - 60 (see Appendix, Table 7).

Two samples, HT5 and HT6, are somewhat abnormal in texture. Both are enriched in clay and depleted in sand compared with other Hessle Till samples. In HT6, from Kirkburn (SE975566), this may result from its position on the Yorkshire Wolds at the extreme feather edge of the till. The sample may represent the clay-enriched horizon of a truncated soil profile developed in thin till over chalk; such horizons often develop immediately above the contact of drift deposits and calcareous substrata (Bartelli and Odell, 1960, p. 388). The higher silt content compared with other Hessle Till samples from the Wolds may reflect the incorporation of loess from beneath, since a thin silty chalky head occurs immediately below the till. However, incorporation of loess does not occur where the till on the Wolds is thicker. Figs. 16 + 29 compare the particle size distribution of samples from Kirkburn with typical loess from Binbrook, Lincolnshire (TF178957), Huggate (SE875548) and High Callis Wold (SE828560), and with samples from Ruston Parva (TA070618) and Eppleworth (TA021324) where silty chalky deposits also occur between the till and the chalk. Modification of the shape of the curve by loess incorporation is evident only in till sample HT6 (Kirkburn). The topsoil above the till at Kirkburn has less silt than the loess-contaminated till; its sand/sand + silt ratio is 45, compared with 31 for the till, 27 for the silty chalk rubble, and 20 for the Huggate loessial drift. This reinforces the stratigraphical evidence that the loess was deposited prior to the maximum advance of the Devensian ice in this area.

The other clay-enriched and sand-depleted sample, HT5, was collected from above the Kelsey Hill sands and gravels at Keyingham (TA235255). The Hessle Till seen by Catt and Penny (1966) in this position was interpreted by them as partly reworked by solifluction. However, incorporation of subjacent material would lead to a sandier texture. Since the silt content of HT5 is no greater than that of nearby Hessle Till samples, a loessial admixture cannot explain its silty clay texture. However, HT5 resembles texturally two samples of Purple Till from Dimlington (TA392217), and may be an inland representative of this till rather than of the Hessle Till.

Samples of Marsh Till from Lincolnshire are texturally more variable than the Yorkshire Devensian tills, although the range is again centred on the clay loam class. No textural distinction can be discerned between the Lower and Upper Marsh Tills of Straw (1969b) - see Fig. 20 . Two samples, MT6 and MT7, both of the lower till at Welton-le-Wold (TF282883), have about 25% silt, which is within the range shown by Basement Till samples from Dimlington. At Welton this greyish-brown till is overlain by an intensely chalky deposit, which resembles the pre-Devensian Calcethorpe Till but was originally regarded by Straw (1969b) as reworked by solifluction during the Devensian. However, recent exposures in this pit have led to a re-interpretation of this chalky deposit as till in situ, and the discovery of Acheulian implements and typical Hoxnian mammal remains in flint gravels beneath the lower grey till indicate that this lower till must be Wolstonian (Straw, personal communication). Sample MT17 from south Ferriby (SE996223) is probably equivalent to the Drab Till, although it is slightly sandier than any Drab Till sample from Yorkshire. Most of the remaining samples are texturally within the range of the Yorkshire Hessle Till samples. As this range overlaps those of the Drab and Purple Tills, no correlation between the till sequences of the two areas can be made on texture alone.

The only calcareous Hunstanton Till sample analysed is texturally similar to the most clay-rich of the Drab Till and "Wolds Hessle" samples.

The stratigraphic significance of the particle size data may be summarised as follows. Small textural differences can be discerned between different groups of the Yorkshire tills; in particular, distinctions can be drawn between the Basement, Drab and Purple Tills, and between geographical groupings of the Hessle Till. The textural range of the Basement Till is distinct from the ranges of the Devensian tills. However, the textural range of all the Hessle Till samples overlaps those of the Drab and Purple Tills almost completely (Fig. 19), so that a particular Devensian till in the succession described by Catt and Penny (1966) cannot be recognised on the basis of texture alone. The lower silt and higher sand contents of the Drab Till compared with the Purple, and of the inland Hessle Till compared with Hessle Till samples from south-east Holderness, are shown by a noticeable concavity of the curves in the size-ranges less than 250 μm (2 ϕ). Fig. 30 illustrates a westerly increase in this concavity for samples of Hessle Till in a transect across southern Holderness. Most Marsh Till samples show a similar concavity in their cumulative curves.

Recent work on the particle size distribution of tills has shown that the shape of the cumulative curve may reflect some features of the provenance of the glacial debris. One noticeable feature of the cumulative curves for all the samples analysed in this work is the pronounced break of slope occurring in the range 500 - 250 μm (1 - 2 ϕ). Beaumont (1971) noted a similar feature in tills from eastern Durham. He discovered that it coincided with a change in the constitution of individual grains from predominantly rock fragments to predominantly mineral grains, and thought that the position of the break of slope reflects the dominant particle size distribution of the rocks eroded by the ice. Dreimanis and Vagners (1971) showed that the frequency distribution of rock fragments (clasts) and the constituent mineral grains in basal tills is often distinctly bimodal. The proportions of each vary with distance from the source area, the clast-size mode being larger near the source, and the mode of individual grains increasing with increasing distance from the source. Most of the till samples from eastern England contain < 5% stones > 2 mm, and none contains > 10%. Following Dreimanis and Vagners (1971) this could be interpreted as implying a great transport distance for the till material, assuming that originally there was a high stone content. However, without a series of samples from the same till at progressive distances from the source area (i.e. samples much further north than the present ones, all collected from within about 30 km of the local ice-limit) the original stone content and likely distance of transport of the till material cannot be inferred. It is more likely that the tills contain much material derived from relatively local pre-existing unconsolidated sandy, silty and clayey deposits, the position of the break in slope reflecting the dominant grain-size of these materials.

5.2.4 Clay Mineralogy

The < 2 μm clay fractions of a selection of till samples were analysed by X-ray diffractometry in order to establish whether the clay mineralogy of the parent materials of the Tunstall and Holkham soil profiles was representative of the whole Devensian sequence. All the samples contained the same main clay components (Table 8 and Fig. 31). However, the Hessle Till of south-east Holderness contains roughly equal amounts of mica and expanding minerals, whereas the Hunstanton Till contains 60% expanding minerals and 20% mica; other samples were between these two extremes. Nearly all samples contain 20 - 30% kaolinite but the Basement Till contains less than the other tills. HT14, the sandy upper part of the Hessle Till at Woodmansey, contains more kaolinite than other samples, but this may be due to its coarse texture, since kaolinite is nearly always more strongly represented in coarse than fine clays, and sandy sediments are often relatively depleted in fine clay. Chlorite was detected in small amounts in the coastal Hessle, the Purple, Drab and Basement Tills, but not in the Marsh, inland Hessle or Hunstanton Tills. No differences could be detected between the clay fractions of the Purple and Drab Tills.

5.2.5 Heavy Mineral Analyses, 20 - 53 μm

Tables 9-14 (Appendix) and Figs. 32-37 give the mineralogical composition of the 20 - 53 μm fractions of till samples. Vertical variations are apparent in the sequence of samples from the Dimlington cliffs. The absence of siderite and pyrite distinguishes the Hessle from the lower tills. The Purple, Drab and Basement Tills differ in their relative contents of pyrite, chlorite, chamosite, biotite, epidote and hornblende, as illustrated in Fig. 32. Samples of Hessle Till from other parts of east Yorkshire, of Marsh Till from east Lincolnshire, and of Hunstanton Till from north Norfolk, all lack siderite and pyrite, except for samples MT6 and MT7 from Welton-le-Wold, Lincolnshire. The coarse silt mineralogy of these two samples resembles most closely that of the Basement Till of Dimlington (Fig. 32).

The Hessle Till samples display a lateral variation in their coarse silt mineralogy. Those from Dimlington and Tunstall, on the south-east coast of Holderness, contain abundant chlorite, chamosite and biotite, but are poor in epidote and amphiboles, whereas those from the Wolds contain lesser amounts of the micaceous minerals, but are rich in epidote and amphiboles. The Marsh Tills, both Upper and Lower, and the Hunstanton Till all resemble the "Wolds Hessle" in their mineralogy (Fig. 33). Since some samples were collected from relatively thin decalcified tills, mineralogical compositions were recalculated after the omission of those minerals most susceptible to weathering, i.e. apatite, chlorite, chamosite and biotite (Table 14). Fig. 36 shows that the distinctions and similarities mentioned above are not caused by weathering. Three possible reasons for the lateral variability in coarse silt mineralogy of the Hessle Till are considered below.

(a) <u>Incorporation of loessial material</u>

Catt et al. (1971, 1974) noted that the coarse silt mineralogy of the loess deposits in Norfolk, Lincolnshire and Yorkshire is similar to that of the Devensian tills, and suggested that outwash from the ice-sheet was the most probable source of the loess. However, the coarse silt of the loess is mineralogically similar only to that of the Hunstanton, Marsh and "Wolds Hessle" tills. Fig. 37 compares the more resistant minerals of these loessial deposits with those of the tills, and shows that the coastal Hessle Till samples are significantly different, mineralogically, from the loess. Assuming that the Hessle Till had an initially uniform composition similar to the Hessle at Dimlington and Tunstall, incorporation of loessial silt could produce the lateral changes in silt mineralogy of the Hessle Till. However, a large addition of loess to the till would be required; since the loess contains very little sand-sized material, this addition should be evidenced by a substantial increase in silt content of the "Wolds Hessle" compared with that from south-east Holderness. In fact, the "Wolds Hessle" is the less silty, and similar mineralogical changes to those mentioned above were found in the fine sand fractions of the tills (see later section). Therefore this hypothesis is not considered further. Derivation of the loess from outwash materials in front of the advancing Devensian ice-sheet is a more likely explanation of the mineralogical similarities between the loess and the till.

(b) Incorporation of material derived from underlying tills

Gross and Moran (1971) ascribed lateral variation in Wisconsin tills of Ohio and Pennsylvania to progressive incorporation of underlying bedrock of a different mechanical and mineralogical composition from that of the original till material. In the present case the underlying "bedrock" is the Purple Till along the south-east coast, the Drab Till elsewhere in Holderness, and chalk or chalky silty head on the Wolds. Incorporation of significant amounts of the last has been discounted, since carbonate and silt contents are insufficiently increased in the Wolds till compared with the coastal till. If the Hessle Till represented a separate ice advance later than the Purple and Drab Tills, then the Hessle ice-sheet must have advanced over the surfaces of these two tills to reach the Wolds, and some incorporation of these deposits in the Hessle Till might be expected. However, Catt and Penny (1966) present evidence to show that the Hessle Till should be regarded as the product of the upper layer of a multiple ice-sheet, not of a distinct advance. If this is the case, such incorporation of subjacent deposits seems less likely. The three ice-layers proposed would each contain till-material derived from their respective source areas. After superposition of the ice-sheets only the basal ice (i.e. that depositing the Drab Till) could add further to its load, modifying its texture and mineralogy. Significant modification of the load of the upper ice-layer could only be achieved by large-scale mixing within the ice-sheet, possibly by thrusting upwards of wedges of the basal ice. This process would probably produce large-scale contortions in the resultant deposits, but such structures are rare in the Holderness tills.

(c) Weathering of the Drab Till

The mineralogical similarities between the Hessle Till of the Wolds and the Drab on the one hand, and the Hessle Till at Dimlington and Tunstall and the Purple on the other, suggest that the Hessle is a weathered equivalent of either till. The main mineralogical difference between the Hessle and these lower tills, the lack of siderite and pyrite, could be due to weathering of these easily oxidised minerals, since most samples of the Hessle Till were collected within 2 - 3 m of the surface. The similarities become apparent when the non-opaque heavy minerals are expressed on a siderite-free basis (Table 13, Fig. 34). To avoid other possible weathering effects in the uppermost tills the relative proportions of the more resistant minerals were also calculated (Table 14 and Fig. 35). On this basis the coarse silt mineralogy of the Drab Till is virtually identical to that of the Hessle

Till of the Wolds. Also, the Till of south-east Holderness is similar to the Purple Till, differing only in the relative amounts of epidote and zircon, the Purple Till containing more epidote than zircon, the reverse being true of the Hessle.

The close similarity of the "resistant" coarse silt mineralogy of the Drab Till and the "Wolds Hessle" supports the suggestion that the thin reddish-brown till on the Yorkshire Wolds (together perhaps with the Marsh and Hunstanton Tills) may represent weathered Drab Till. Their textures are also similar, and the mineralogical differences between them are restricted to weatherable minerals - the lack of siderite and pyrite in the Hessle, and slightly greater amounts of chlorite and biotite in the Drab Till. Similar conclusions apply to the south-east coastal area of Holderness, where the mineralogical resemblance of Hessle Till to the Purple suggests it may be weathered Purple.

5.2.6 Heavy Mineral Analyses. 53 - 250 µm

Tables 15-21 give the mineralogical composition of fine sand (53 - 250 µm) fractions of the till samples. These show the same geographic variation in the composition of the Hessle Till (Fig. 38) as do the 20 - 53 µm fractions, which confirms that the mineralogical variation does not result from loessial contamination of the till, because loess contains very little sand. The additional samples analysed from central and northern Holderness enable a gradational pattern to be discerned (see Fig. 39). Samples HT27 - HT30 occupy an east-west transect across southern Holderness from Aldbrough (TA257396) to Bilton (TA156343), and samples HT24 - HT27 represent a north-south transect along the coast from Ulrome (TA177570) to Aldbrough. In both sequences there is a decrease in the content of micaceous minerals (chlorite, biotite), and an increase in amphibole and epidote content away from Aldbrough.

Sample HT27 is representative of the Hessle Till in the south-east coastal region of Holderness, and samples HT24 and HT30 are mineralogically similar to the samples from the Wolds.

Analyses of Marsh, Hunstanton, Purple, Drab and Basement Tills are also given in Tables 15 - 21 . Once again, no distinction can be drawn between samples of Upper and Lower Marsh Tills (Fig. 40), as both resemble closely the Hessle Till samples from central and northern Holderness and the Yorkshire Wolds. The Hunstanton Till (Fig. 40) also resembles these tills.

Unlike the Hessle Till, which rarely contains siderite, the Purple, Drab and Basement Tills all contain moderate amounts of sand-sized siderite grains, the Purple Till tending to contain most and the Basement Till least. Chlorite, chamosite and biotite are also more common in the Purple than in the Drab and Basement, but amphiboles and epidote are more abundant in the Drab and Basement Tills. Samples MT6 and MT7, already mentioned as resembling the Basement Till in texture and coarse silt mineralogy, are also similar to it in the composition of their fine sand fractions (Fig. 41).

The samples containing abundant siderite also contain much pyrite (Table 17). This mineral is especially abundant in the Purple and Drab Tills, but less so in the Basement Till, and is virtually absent from the Hessle, Marsh and Hunstanton Tills. The occasional grains noted in the Hessle Till were present as infillings of foraminiferal shells, and were thus protected to some extent from oxidative weathering. The grain shown in Fig. 42 , from sample HT28, is noteworthy for the oxidation of the pyrite infilling the last chamber of the multilocular foraminiferal shell. It seems likely that any unprotected pyrite grains which may have occurred in the Hessle Till would have been oxidised, and now be represented by limonite. Weathering to limonite could also account for the lack of siderite in the Hessle Till.

Pyrite occurs in quantity in sample MT17, from south Ferriby (SE996223), supporting the identification of this till as the Drab. It occurs only in accessory amounts in samples MT6 and MT7, the Welton-le-Wold grey till, supporting the suggestion that this resembles the Basement.

To facilitate stratigraphically meaningful comparison between the tills, the composition of the heavy sand fractions were recalculated first on an opaque minerals and siderite free basis (Table 19 and Fig. 43). As with the coarse silt fraction, the Purple Till on this basis resembles the Hessle Till of south-east Holderness, whereas the Drab is more like the remaining Hessle Till samples and the Marsh Till (Figs. 38 + 40). In order to eliminate completely all possible effects of weathering on the sand mineralogy, the relative proportions of the more resistant mineral groups were also calculated (Table 20 and Figs. 44-50). The choice of these mineral groups was made on the basis of the sand mineralogy of the Tunstall soil profile (see Chapter 6). Figure 82 illustrates that zircon, tourmaline, epidote, garnet, rutile and amphiboles are almost constant with respect to one another throughout the profile, and may thus be regarded as resistant minerals. Fig. 82 (p.200) shows that pyroxenes (mainly augite) are depleted with respect to the above minerals in the upper 30 cm of the profile, but below this are constant in amount. Since virtually all the till samples analysed were collected from depths greater than 30 cm, the inclusion of pyroxenes with the "resistant" minerals was considered valid.

On this basis further distinctions between the tills are apparent; Fig. 51 illustrates these differences for the Dimlington cliff section in southern Holderness. Amphibole, epidote and garnet all decrease in amount up the succession, the reverse being true for pyroxene, zircon, tourmaline and rutile. Although the pyroxene, amphibole and tourmaline contents appear to allow a separation to be made on mineralogical grounds between the Hessle and Purple Tills on the one hand, and the Drab and Basement Tills on the other, the ranges of variation of other minerals tend to overlap. The Hessle Till samples, on this basis, exhibit the same east-west and south-north variation already noted (Figs. 52-58). Most of the mineral groupings show a fairly sharp gradation in amount a few miles inland from the south-east coastal area of Holderness, an exception being garnet, which is at a maximum in central Holderness and the central section of the Wolds, between Beverley and Driffield. The use of mineral ratios produces a clearer picture of the variation, especially if pairs that vary antipathetically are chosen. Two ratios seem to be the most useful:- amphibole/amphibole + pyroxene (A/A + P) and epidote/epidote + zircon (E/E + Z) (Table 21). These are plotted in Figs. 59 + 60 ; the isopleths on these maps are interpolated by eye.

From Figs. 52-60 and from the particle size variation data (Fig. 28), it is possible to differentiate three zones within the Hessle Till, which are indicated on Fig. 61 . Zone A includes coastal Hessle Till samples south of Hornsea, but not samples HT38 and HT46 from Easington, which resemble, both texturally and mineralogically, the Hessle Till of Zone C. The till of Zone B is transitional in character between the coastal samples, and those of central Holderness. Only seven samples are included within it, although the transition of properties continues to some extent in samples HT29 and HT52. In the extreme south-east of Holderness any representative of this zone must occur in the short distance (< 4 km) between samples HT7 (Dimlington) and HT38 (Easington). Zone C comprises all those samples north-west and south-west of the arcuate line from Atwick (TA 190510) through Flinton, Ryhill, Patrington, Welwick and Easington, but also includes HT38 and HT46 near Easington.

No significant differences in mineralogy or particle size distribution can be detected between the Hessle Till from the Wolds and that from central Holderness, so these are included in the same zone.

A plot of the mineral ratios $\frac{A}{A + P}$ and $\frac{E}{E + Z}$ against one another (Fig. 62) highlights the differences between these three zones of the Hessle Till of Holderness, and shows the similarities between the Hessle of Zone A and the Purple, and that of Zone C and the Drab. The Hessle of Zone B is intermediate in character, but more closely resembles the Purple than the Drab. A similar plot for the Marsh and Hunstanton Tills illustrates their close resemblance to the Hessle of Zone C and to the Drab Till.

5.2.7 Variability of the Hessle Till

In summary, the main differences between the Hessle Till of Zones A, B and C are:

(i) In Zones A and B, the till contains more silt than in Zone C (see Fig. 28 and Table 7);

(ii) the content of micaceous minerals in both the fine sand and coarse silt fractions is considerably less in Zone C samples than in those of Zones A and B (see Figs. 33 + 61);

(iii) on the "resistant" minerals basis, the contents of pyroxene, zircon, rutile and tourmaline are also less in Zone C than in A and B, whereas the reverse is true of epidote, garnet and amphibole (see Figs. 35 + 63).

The same changes also occur through the vertical succession, the Drab Till resembling the Hessle of Zone C and the Purple Till the Hessle of Zone B (see Figs. 34, 35, 63, 64). The lateral variation in the composition of the Drab and Purple Tills is small compared with that of the Hessle as a whole, but within each of the Zones A, B and C, the Hessle is no more variable in composition than the Drab or Purple.

In particle size distribution and heavy sand and silt mineralogy the Marsh and Hunstanton Tills resemble the Drab Till and Hessle of Zone C, rather than the Purple and Hessle of Zones A and B (see Figs. 20,36,64). No distinction can be drawn between Upper and Lower Marsh Till samples on either a textural or a mineralogical basis.

The mineralogical and textural variability of the Hessle Till across Holderness may be related to the direction of ice movement, since the isopleths (Figs. 59+60) are approximately parallel to Devensian ice-fronts postulated by various authors (e.g. Valentin, 1957, Karte 6). Similar variations were reported for Wisconsinan tills in Ohio and Pennsylvania by Gross and Moran (1971). They noted an increase in percent sand and a decrease in feldspar content of the fine sand in the direction of ice movement for each of three superposed tills of progressively younger age. Similar changes were also noted in the vertical succession, the younger tills being finer-grained and richer in feldspar than the older ones. The thickest and oldest till, the Titusville, was found to contain these same variations within its own thickness. Gross and Moran suggested that fine-grained feldspar-rich glacial debris had been mixed with coarser, feldspar-poor, quartzose material derived from sandstone outcrops striking at right-angles to the ice-movement direction. However, in Holderness the situation is different, because the lower Devensian tills, the Drab and Purple, show little lateral variation in composition, whereas the uppermost till, the Hessle, exhibits significant lateral variation. Further, the Drab Till may incorporate some material derived from the underlying Basement Till, because the two are mineralogically similar, but no progressive changes in the properties of the Drab Till have been detected.

The main mineralogical variation in the Hessle Till seems to be related to the extent of the Purple Till. The Hessle Till of Zone A is restricted to samples known to overlie Purple Till in the cliff-section, and where the Purple Till is definitely absent, as at Easington and Skipsea, the Hessle Till mineralogy is that of Zone C, which is, in resistant minerals, similar to that of the immediately underlying Drab Till. Wherever a lower till is visible in Zone C it is always the Drab (e.g. Nafferton, Long Riston). In the Hull area, boreholes and temporary exposures often show the Drab Till and a reddish till like the Hessle beneath the post-glacial deposits (Catt and Penny, 1966, p. 401).

The mineralogy of the Zone B Hessle Till resembles that of the Purple Till rather than that of the Drab; texturally also, the resemblance is with the more silty Purple Till. At Hornsea (TA212472) the Hessle of Zone B (HT26) rests on Drab Till, and at Keyingham (HT5; TA235255) it overlies the Kelsey Hill gravels, which in turn rest on the Drab Till. However, at both these localities the Hessle differs appreciably in texture and mineralogy from the Drab Till. At the two remaining Zone B localities, Flinton (HT28; TA230362) and Fitling (HT36; TA249349), the underlying till was not seen. Across this transitional zone, approximately 10 km wide, mineralogical and textural changes are rapid, whereas in Zones A and C the Hessle Till is relatively uniform.

The main differences between the Hessle and underlying tills are:-

(a) Colour The Hessle Till is nearly always dark reddish brown or reddish brown (5 YR 3/4; 4/3; 4/4) when moist, whereas the Purple Till is invariably dark brown (7.5 YR 3/2), and the Drab Till very dark greyish brown (10 YR 3/2; 3/3). However, some Zone C Hessle Till samples are dark brown (7.5 YR 4/2; 4/4).

(b) Texture The Hessle Till of Zones A and B and the Purple Till contain more silt than the Drab, but the Hessle Till of Zone C is texturally similar to the Drab.

(c) Mineralogy

(i) The Purple and Drab Tills both contain abundant pyrite and siderite, whereas these minerals are rare or absent from the overlying Hessle. The Purple Till is richer in these minerals than the Drab.

(ii) The Drab and Purple Tills contain more coarse silt sized biotite and chlorite than the overlying Hessle of Zones C and A respectively, but this distinction does not hold for the sand fraction. The Purple Till and Hessle of Zone A contain more of these minerals than do the Drab Till or Hessle of Zone C.

(iii) The epidote/zircon ratio (in both coarse silt and fine sand fractions) is greater in the Drab and Hessle of Zone C than in the Purple or Hessle of Zone A.

(iv) The amphibole/pyroxene ratio of the fine sand fraction of the Purple Till is slightly greater on average than that of the Hessle Till of Zone A, but smaller than that of Zone B. This ratio is slightly smaller on average in the Drab Till than in the Hessle of Zone C, but both have greater amphibole/pyroxene ratios than the Purple Till or Hessle of Zones A and B.

The Purple and Drab Tills are thus mineralogically and texturally distinct from one another, and each is relatively uniform; the Hessle Till; however, has much of the character of the underlying till, either Purple or Drab. The Hessle is the relatively thin uppermost member of the Holderness glacial succession, and oxidation could have affected its total thickness. The difference in colour between it and underlying tills, and its lack of siderite and pyrite, could result from oxidative weathering. The small differences in amounts of silt-sized micaceous minerals contained in the Hessle and underlying tills could also result from weathering.

5.3 Implications for Till Stratigraphy

Catt and Penny (1966) considered that the three tills were the product of one composite ice-sheet, the "Drab" ice extending across the whole of Holderness to the vicinity of the buried cliff, and into the Humber Gap, the overlying "Purple" ice being a discrete unit impinging only on the extreme south-east coastal area of present-day Holderness, while the uppermost "Hessle" ice extended above the other two on to the Wolds. Following Carruthers (1953), they thought that a three-tiered ice-sheet arose by superposition of large valley glaciers from perhaps the Tyne, Tees and Cheviot areas, which were diverted southwards along the coast by pressure from a lobe of Scandinavian ice in the North Sea (see also Valentin, 1957, Karte 10). The upper layers were thus probably carried passively on the basal "Drab" ice. Unless extensive mixing occurred after superimposition, the three resultant tills would retain distinct lithologies determined by their source areas, though variation could arise in the lowest till by incorporation of material from beneath the glacier (e.g. the Basement Till). The Drab and Purple Tills are distinct lithologically, but the Hessle tends to resemble the till beneath, whether that is the Purple or the Drab. Where the Hessle is apparently the only till present, as on the Wolds, it resembles the Drab.

If the Drab and Purple Tills had been deposited by separate ice advances, mixing would be expected in the lower part of the Purple by incorporation of Drab Till picked up by the "Purple" ice-sheet; the lower till would be unaffected except perhaps by contortion. Detached lenses of the Drab are present within the lowest layers of the Purple Till in a few places, and contortions occur in the Drab Till, but the latter appear to be primary structures, mainly well below the top of the till; there is little evidence of contortion of the upper layers of the Drab. There is no weathering of the upper surface of the Drab Till. The evidence is thus somewhat equivocal, and the question of deposition of the Purple and Drab Tills from a multiple ice-sheet or by separate advances must be left open at present. It is, however, worth noting that all three observations (contortion of the underlying till, detached lenses of the lower in the upper till, and weathering of the upper surface of the lower till) have been made with regard to the junction of the Drab Till with the Basement Till (Lamplugh, 1881b, p. 537; Catt and Penny, 1966), which were definitely separated by a long ice-free interval.

The junction of the Hessle Till with the underlying till, whether that is the Purple or Drab, affords little evidence for an ice-free interval. The Kelsey Hill Gravels occur at this level, but despite their Eemian fauna (Baden-Powell, 1955; Penny, 1963) Catt and Penny (1966) considered that they have an essentially glacial origin. Where the Hessle Till overlies Drab Till the exact junction is often difficult to pinpoint because the colour change is gradual. At several places (Skipsea, Easington and South Ferriby), where this junction was examined, no textural difference could be discerned between the two tills, and the reddish colour occasionally extended vertically downwards along more or less open fissures in the underlying grey till, giving rise to reddish-brown partings within it. Colour alone seems an unreliable guide to this particular boundary. However, in the sections mentioned no other discontinuity could be found in the exposed till. Catt and Penny (1966, p. 392-3) noted that at Easington the crude vertical jointing and blue-grey alteration along the structural faces (previously regarded as typical of the Hessle, but now understood as the result of near-surface weathering processes such as desiccation, decalcification and oxidation/reduction) continue down into the Drab, the Purple here being absent, and that at Tunstall they extend into the Purple.

The junction of the Hessle with the Purple Till on the coast is often marked by beds of sand or gravel, the Hessle Gravels of Wood and Rome (1868). However, Catt and Penny (1966) consider that the lack of indigenous fossils in these gravels, and lack of contortion and weathering of the underlying Purple, together with the macro- and micro-fabric evidence for the same direction of ice-movement for all three tills, indicate that these gravels are probably englacial, and do not represent a retreat between deposition of the Purple and Hessle Tills. These gravels could have emphasised the differences between the two tills, as they would help drain the overlying material, which would thus show more strongly the results of desiccation, decalcification and oxidation.

The evidence presented above leads to the conclusion that the Hessle Till as currently defined, is in reality a composite unit. It seems that the reddish till of Zone C is the weathered upper part or feather edge of the Drab Till. The red till of Zone B is probably the weathered remains of the thin westward and northward extension of the Purple Till. In the remaining narrow coastal strip (Zone A) the Hessle could be a weathered upper layer of the Purple Till, or the weathered remains of a separate third till. Its mineralogical composition differs slightly from that of the Purple and of the Hessle of Zone B, but the change is probably gradational and may simply represent slight vertical variation in mineralogy of the Purple Till, which is at its thickest in this area. To test this adequately a full vertical sequence of samples throughout the Purple Till of the cliff sections is required. As yet it has not been possible to obtain this, because the central portions of the cliffs are usually either badly slumped, or have inaccessible vertical faces.

However, it has been possible to obtain a series of samples through the "Hessle Till" down into fresh Purple Till, and also across the Drab/Purple Till boundary where this occurs near the base of the cliffs. Analyses of the former (Table 18g + Figures 65 + 66) show that the Purple Till immediately below the supposed Hessle/Purple boundary is indeed identical mineralogically (except for the readily weatherable minerals, pyrite and siderite) with the overlying "Hessle" Till". Analyses of samples across the Drab/Purple Till boundary (Table 18h) indicate that the mineralogical break is not always as sharp as the colour change by which the tills are identified in the field. Nevertheless, the mineralogical break is real. The range of composition of the Purple Till samples analysed spans the gap between the Drab Till and the Hessle of Zone A (Fig. 63), giving further evidence for a mineralogical gradation within the Purple Till. The balance of evidence is therefore in favour of the "Hessle Till" of the southern coastal sections being a weathered version of the upper part of the Purple Till.

Catt and Penny (1966, p. 392) also considered the Hessle Till of the cliff sections to be a distinct entity in the till sequence on the grounds of a distinct erratic suite. Because of the characteristic 5 YR 4/4 colour of this till, which is evident in surface exposures all over Holderness and on the Wolds, they accepted Wood and Rome's idea of the Hessle Till lying "like a cloth" over the whole area. Bisat (1932 and later papers) considered that the Wolds till was older than the topmost coastal till, and equated it tentatively (1940) with his Middle Drab division, on the grounds of the presence of rhombporphyry in the "Wolds Hessle" but not in the "coastal Hessle". Catt and Penny found this type of erratic in the coastal Hessle as well, and therefore discounted Bisat's suggestion. However, the mineralogical and textural evidence leads to a conclusion similar to Bisat's, that the "Wolds Hessle Till" (and therefore that of the type-site, at Hessle) is Drab Till oxidised throughout its thickness.

Fig. 68 illustrates the new interpretation of the Devensian stratigraphy of Holderness. The Purple Till extends almost as far west as the Sproatley-Sigglesthorne ridge, but since samples HT29 and HT35, collected from the eastern slopes of this ridge, are of Drab-type mineralogy, it is unlikely that the ridge itself is capped by Purple Till. The Keyingham sample, HT5, probably representes the feather edge of the Purple Till sheet in the south. The coastal ridge near Dimlington and Tunstall probably results from thickening of the Purple Till.

These conclusions indicate that the name "Hessle Till" is misleading stratigraphically. At the "type-locality" (TA013260) the till is oxidised and decalcified throughout. The name should not be retained for the red till of the Yorkshire Wolds, which is regarded as weathered Drab Till, and the uppermost till of the coastal sequence (Hessle of Zone A) is regarded as weathered Purple Till.

5.3.1 Correlations of the Revised Holderness Sequence with Lincolnshire and Norfolk

Straw (1969b) subdivided the Marsh Tills of Lincolnshire into Upper and Lower units on the basis of position east or west of a "re-advance limit" of the last glaciation recognised geomorphologically. In the present study no differences could be detected between the two divisions, both being similar to the "Hessle Till" of Zone C in Yorkshire. Since this is weathered Drab Till, it seems reasonable to suggest that the Marsh Tills are also Drab or weathered Drab, especially as Drab Till overlain by a reddish till resembling the Marsh Tills, yet mineralogically identical to the Drab, is exposed at South Ferriby. No till resembling the Purple or "Hessle" of Zones A and B was found in Lincolnshire. The Hunstanton Till of North Norfolk is the southernmost representative of the "Hessle

Zone C" mineralogy, and is probably the oxidized southernmost extension of the Drab Till. Thus, the stratigraphic relationship of the Devensian tills of eastern England is one of offlap, not of overlap as stated by Catt and Penny (1966).

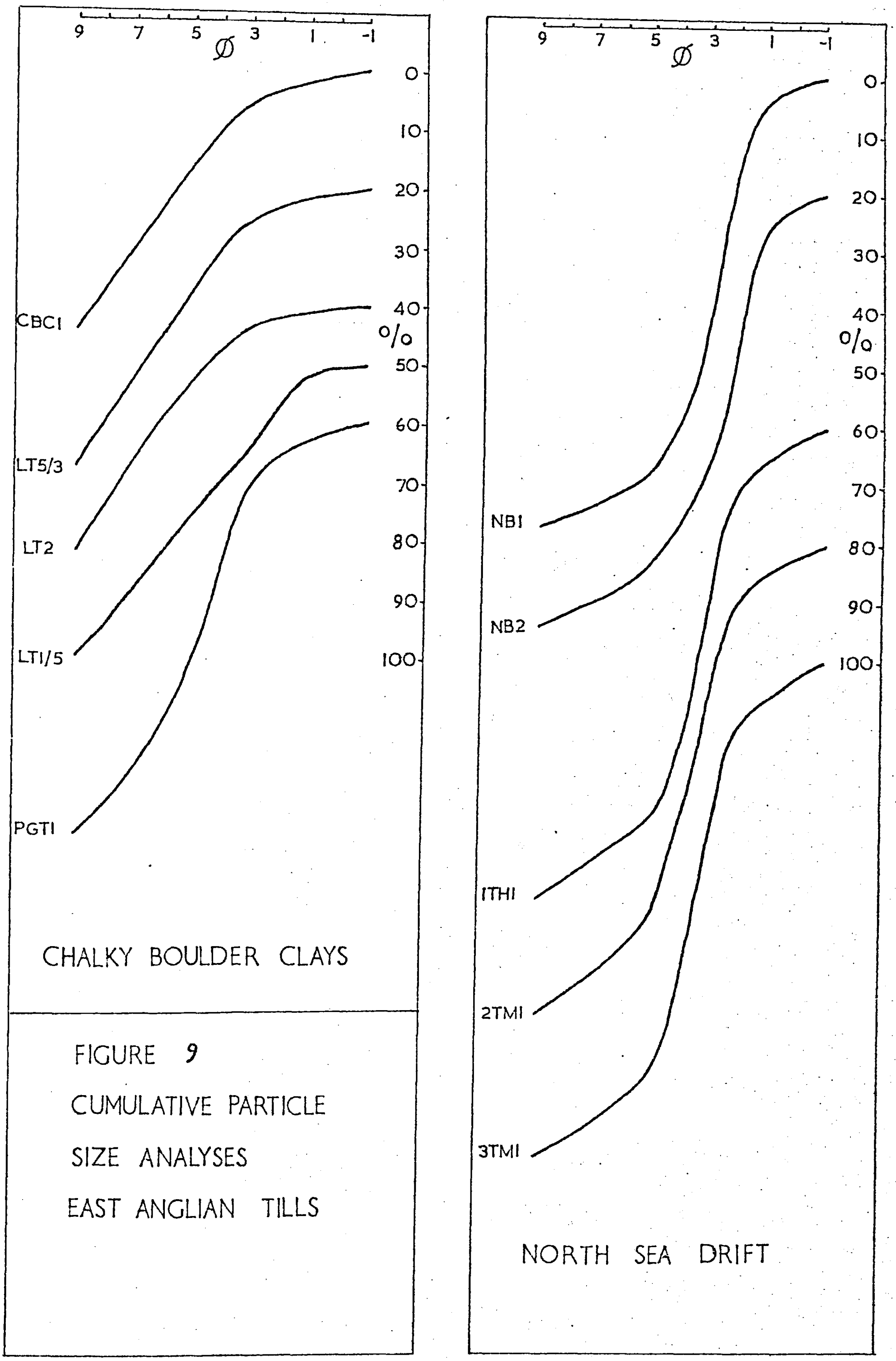
5.3.2 The Age and Extent of the Basement Till

The dark greyish brown till at Welton-le-Wold (MT6 and MT7) petrographically resembles the Basement Till of Holderness rather than the Drab, and is mineralogically similar to North Sea Drift tills of north-east Norfolk, though not so sandy. This suggests that the Basement Till should perhaps be correlated with the North Sea Drift, a conclusion that would be supported also by the common occurrence of Scandinavian boulders in both deposits and the fact that both the North Sea Drift and the till at Welton-le-Wold are overlain by chalky tills.

However, the Scandinavian erratics may imply nothing more than the existence of Scandinavian ice in eastern England during ~~more than~~ at least one glaciation, and the relationship of the tills to known interglacial deposits indicates that correlation of the North Sea Drift and Basement Till is unlikely to be correct. The Basement Till underlies the Ipswichian beach at Sewerby and contains erratics of Bridlington Crag, which was probably a Hoxnian marine deposit as it contains, according to Catt and Penny (1966, p. 402), a glacial heavy mineral assemblage and a relatively small proportion of extinct molluscs. This would imply that the Basement Till is Wolstonian. Reid and Downie (1973) found that the dinoflagellate assemblage of the Bridlington Crag resembles that of the Pastonian in the Ludham borehole (Wall and Dale, 1968), so the palaeontological evidence of the age of the Basement Till is somewhat conflicting. However, a Wolstonian age is indicated for the till resembling Basement at Welton-le-Wold, as the gravels beneath it have yielded Hoxnian mammals and Acheulian implements (Straw, personal communication and in press).

In contrast, the North Sea Drift is underlain by Cromerian deposits (West and Wilson, 1966), and although Hoxnian deposits have not yet been reported over these tills, an Anglian age is indicated by the superposition at Corton of the Lowestoft Till, which is in turn overlain by Hoxnian deposits at many localities (e.g. Hoxne itself). The North Sea Drift therefore seems to be a glaciation older than the till at Welton-le-Wold, and probably also the Basement Till of Holderness.

At Kirmington in north Lincolnshire the interglacial deposits, which are regarded as Hoxnian by Watts (1959) and Boylan (1966), underlie weathered Drab (the lower Marsh Till according to Straw, 1969b), and rest on 1 - 2 m of "tough compact lead-coloured clay, with a few small foreign pebbles" described as resembling "in colour the basement clay of Holderness" (Stather, 1905c). As this deposit must be Anglian, it complicates still further the argument concerning the age of the Basement, and there is clearly a need for reinvestigation of the lower part of the Kirmington succession.



CHALKY BOULDER CLAYS

NORTH SEA DRIFT

FIGURE 9
CUMULATIVE PARTICLE
SIZE ANALYSES
EAST ANGLIAN TILLS

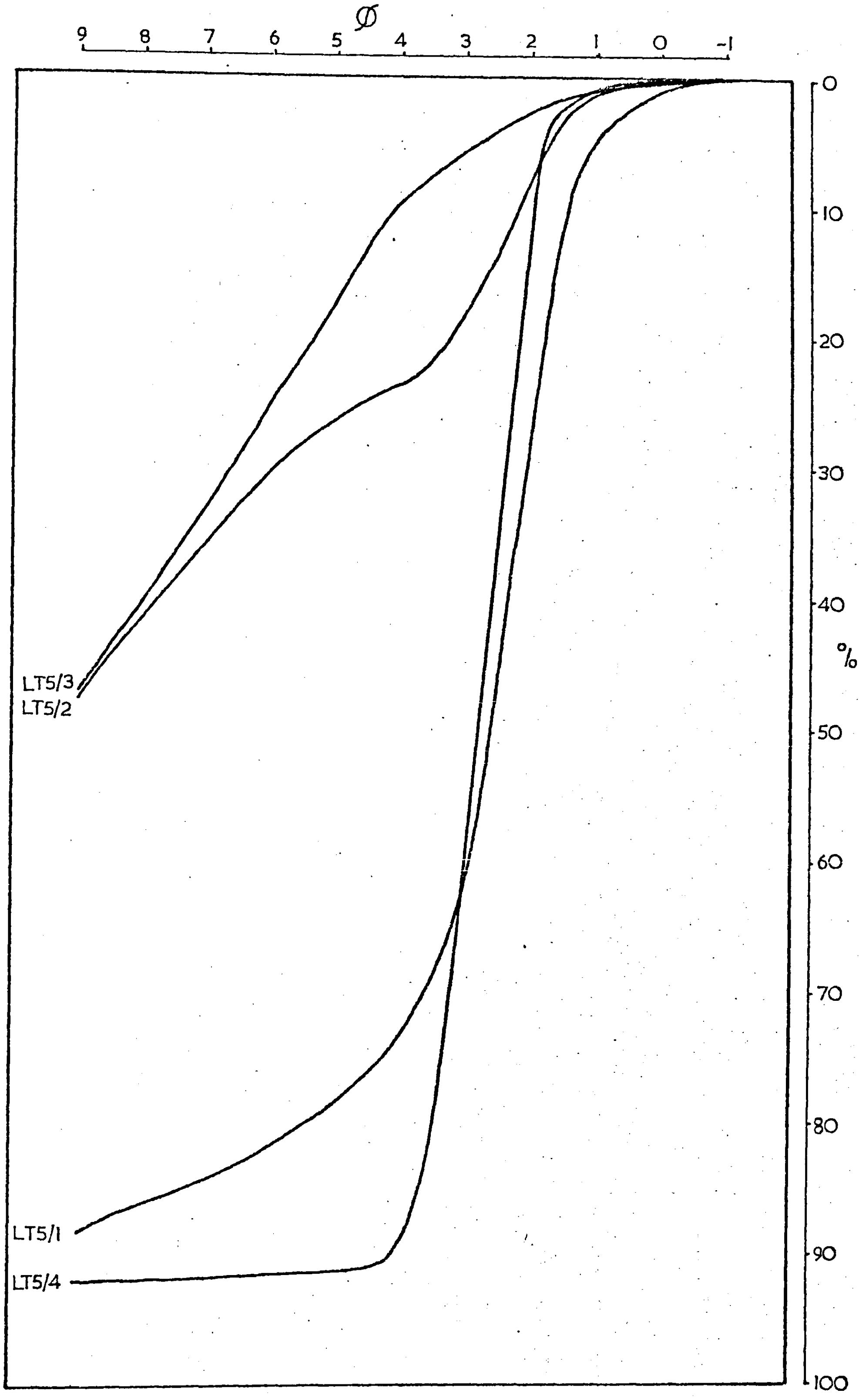


FIGURE 10 CUMULATIVE PARTICLE SIZE ANALYSES
EYE PROFILE ON LOWESTOFT TILL (LT5)
TO ILLUSTRATE CONTAMINATION OF THE DECALCIFIED TILL (LT5/2) BY COVER-SAND MATERIAL (LT5/4)

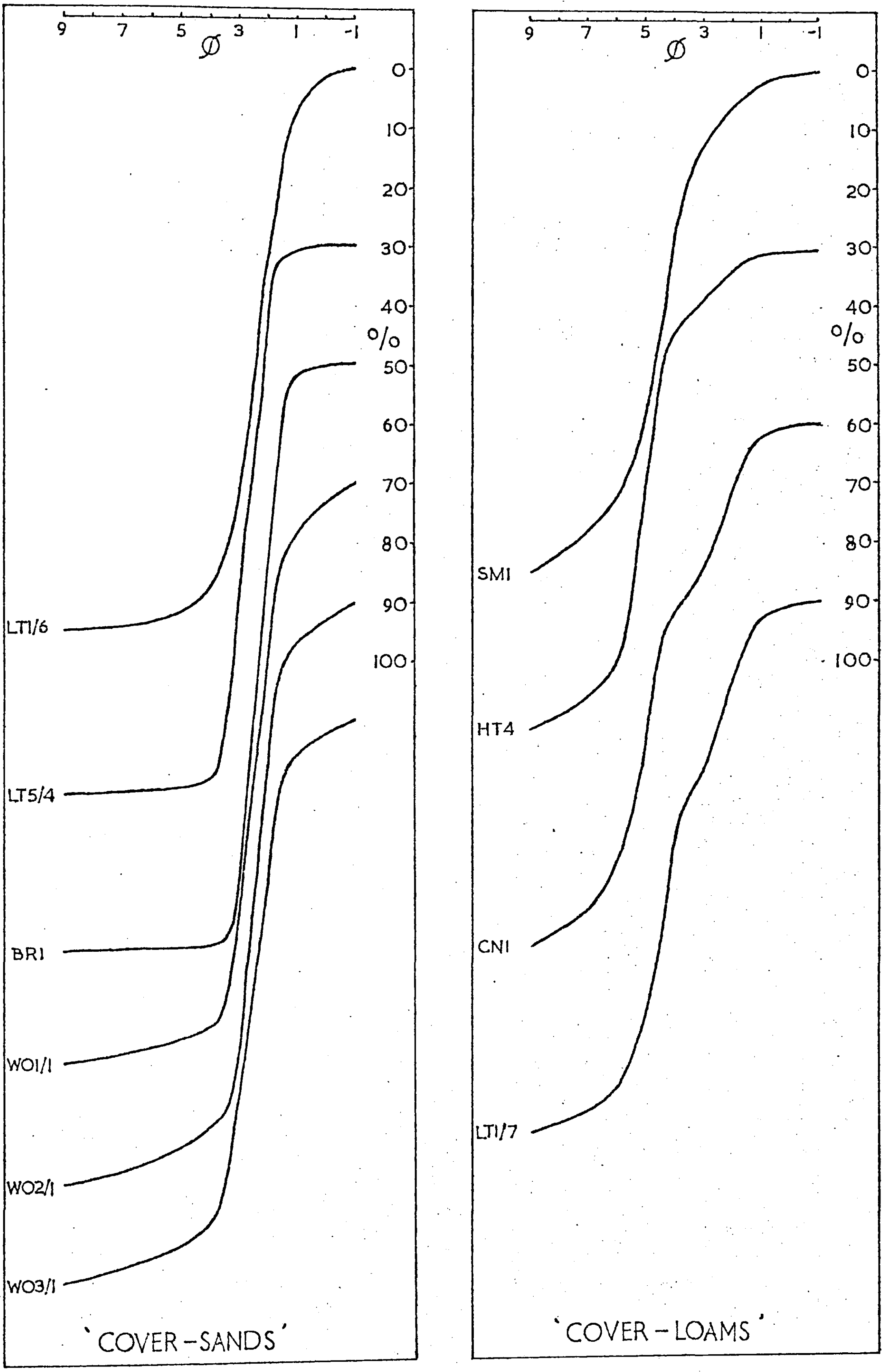


FIGURE 11 CUMULATIVE PARTICLE SIZE ANALYSES

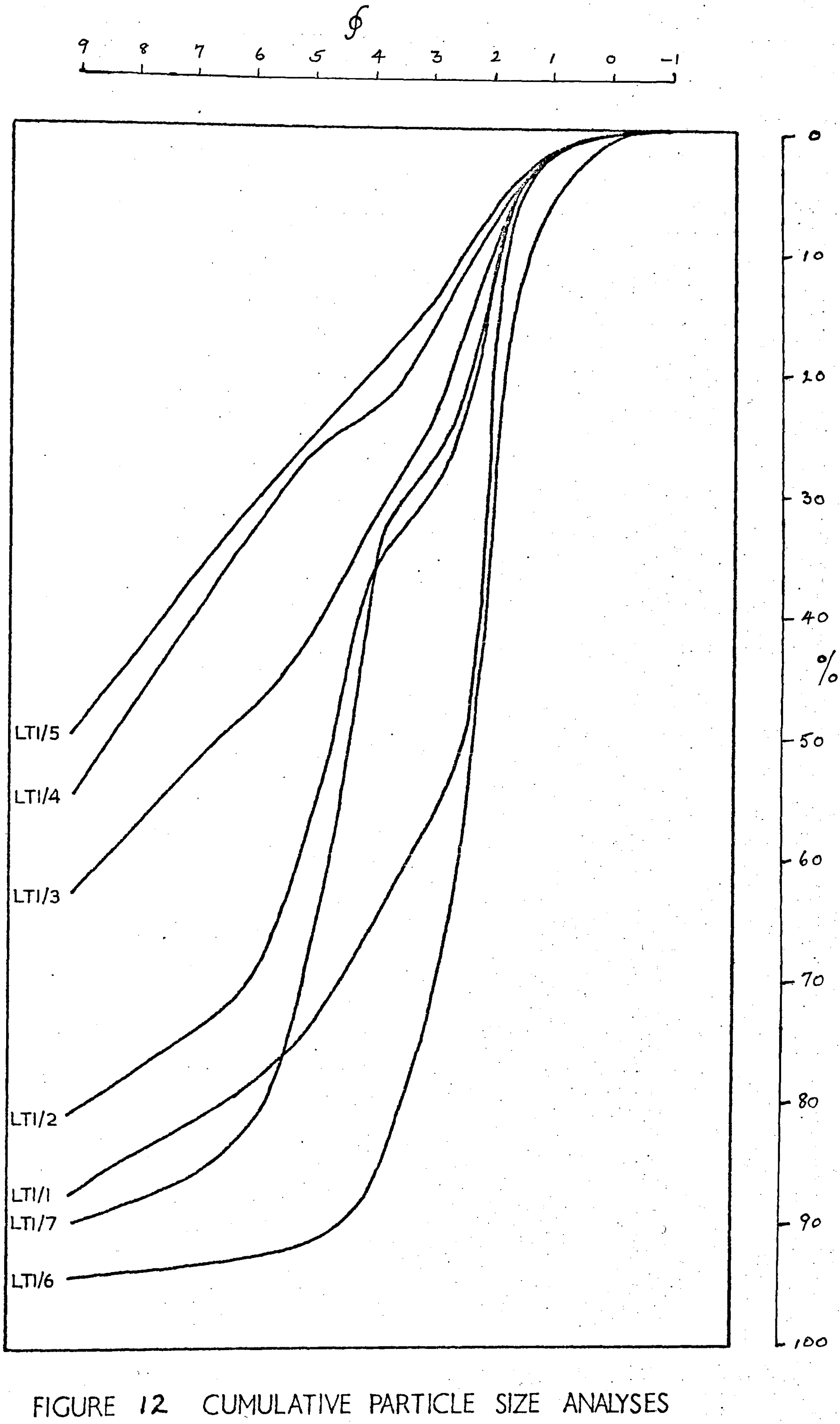


FIGURE 12 CUMULATIVE PARTICLE SIZE ANALYSES
SCRATBY PROFILE ON LOWESTOFT TILL (LT1)
TO ILLUSTRATE CONTAMINATION OF THE PROFILE (LT1/1-5)
BY COVER SAND (LT1/6) AND LOESSIAL MATERIAL (LT1/7)

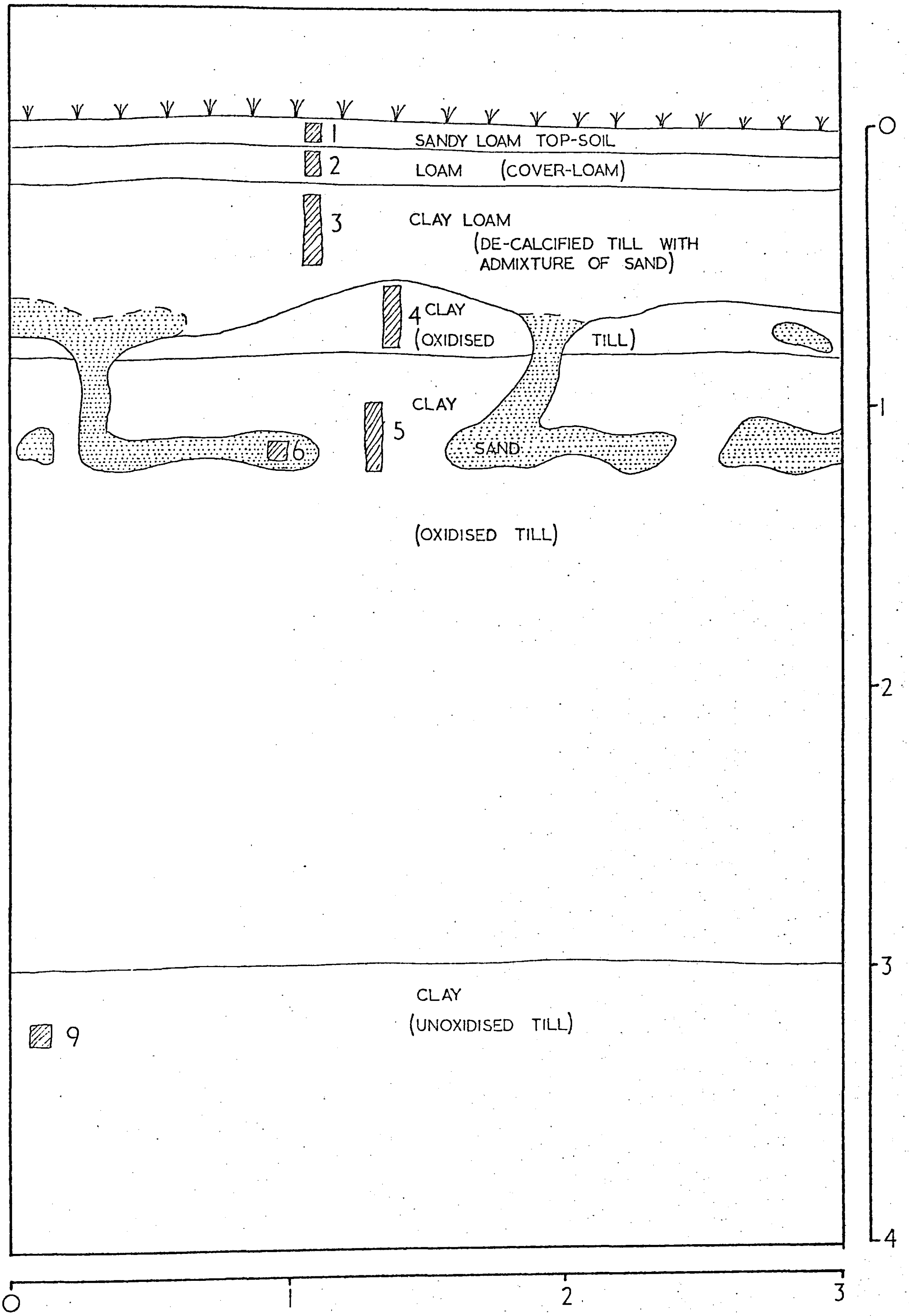


FIGURE 13 SOIL PROFILE (LT1) ON LOWESTOFT TILL, SCRATBY

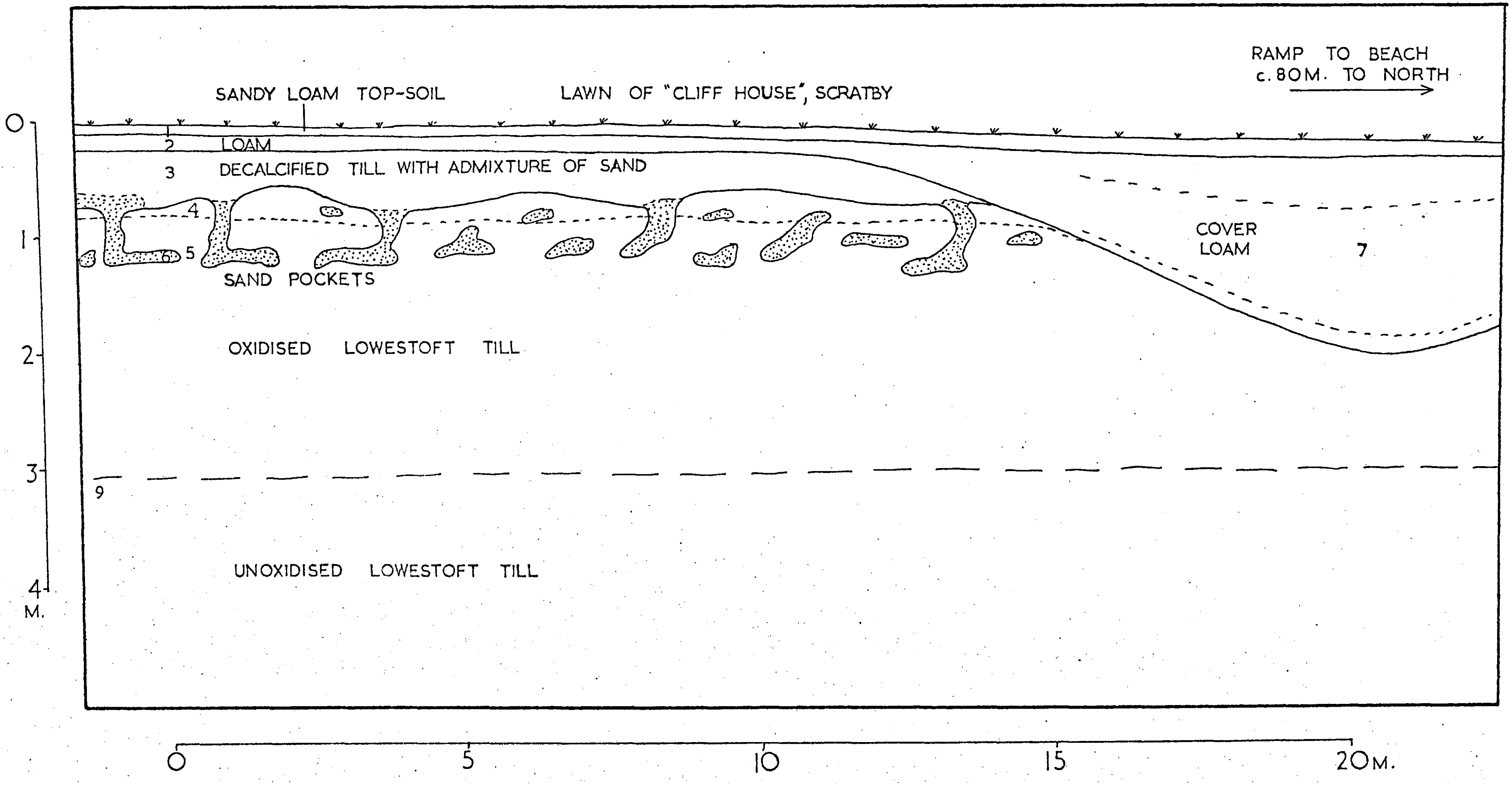


FIGURE 14 STRATIGRAPHICAL RELATIONSHIPS OF SAND & LOAM DEPOSITS, SCRATBY CLIFFS

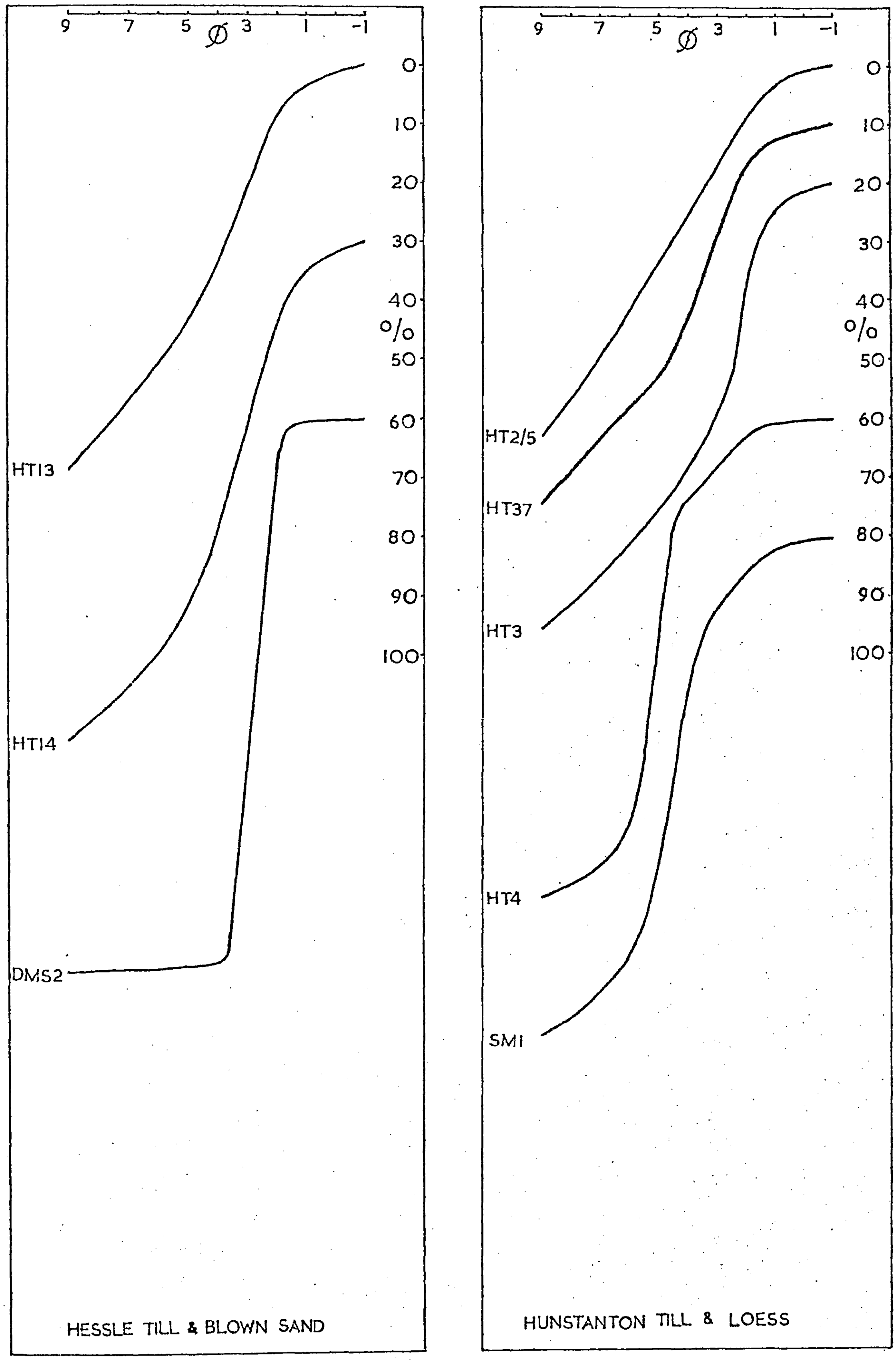


FIGURE 15 CUMULATIVE PARTICLE SIZE ANALYSES

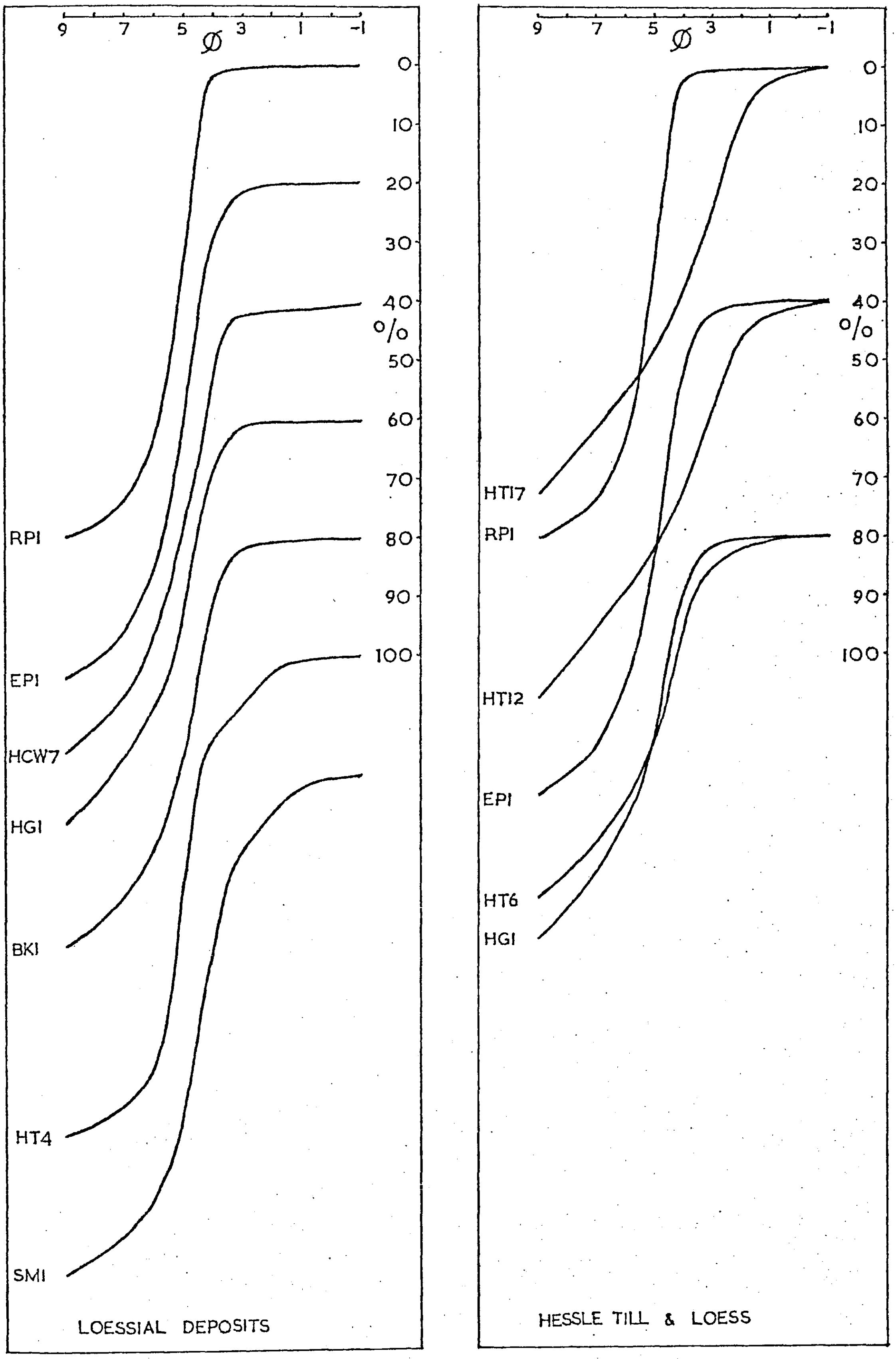


FIGURE 16 CUMULATIVE PARTICLE SIZE ANALYSES

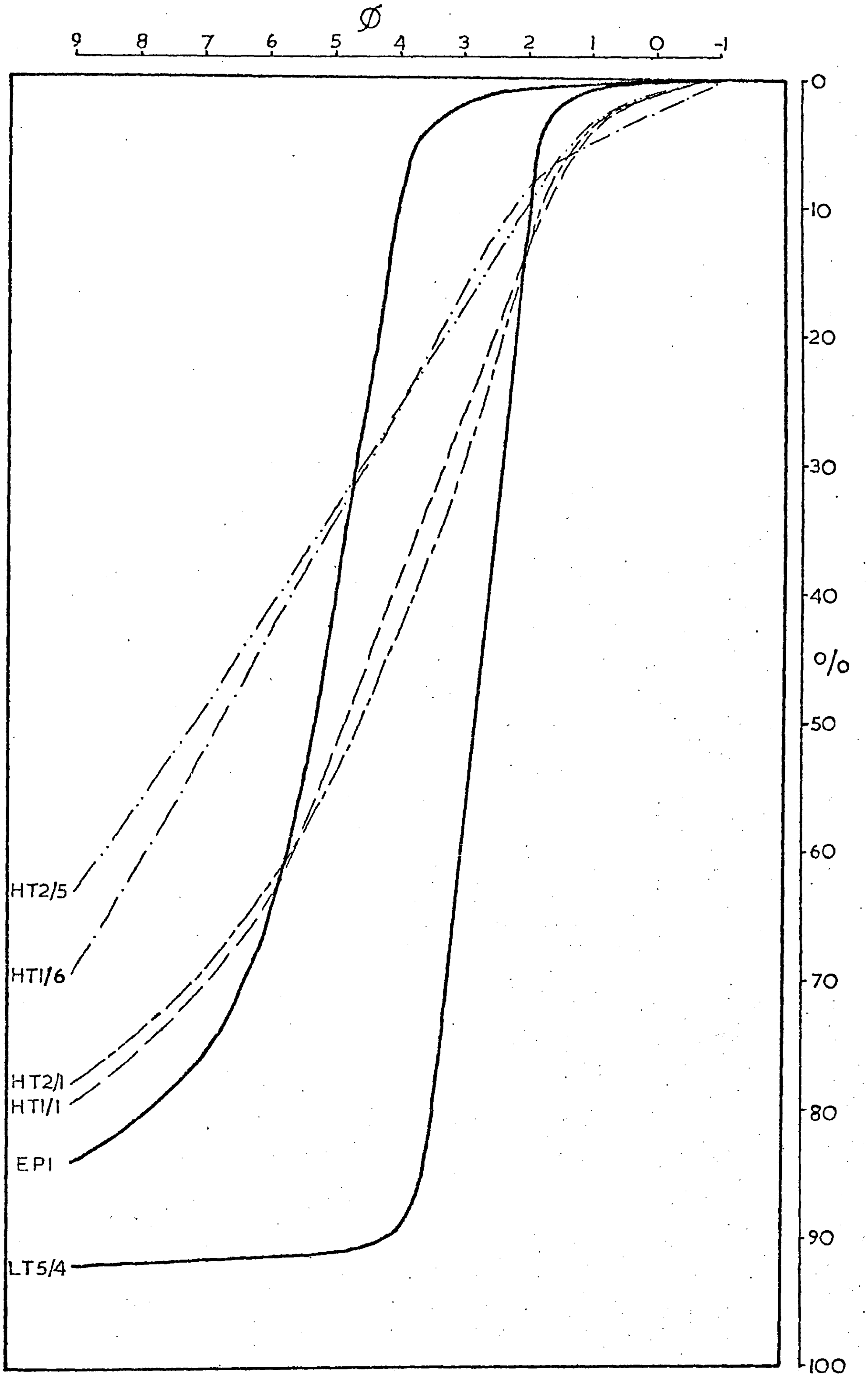


FIGURE 17 CUMULATIVE PARTICLE SIZE ANALYSES TO ILLUSTRATE THE LACK OF CONTAMINATION OF TOP-SOILS (HT1/1 & HT2/1) ON HESSLE & HUNSTANTON TILLS (HT1/6 & HT2/5) BY EITHER LOESSIAL (EP1) OR COVERSAND (LT5/4) MATERIAL

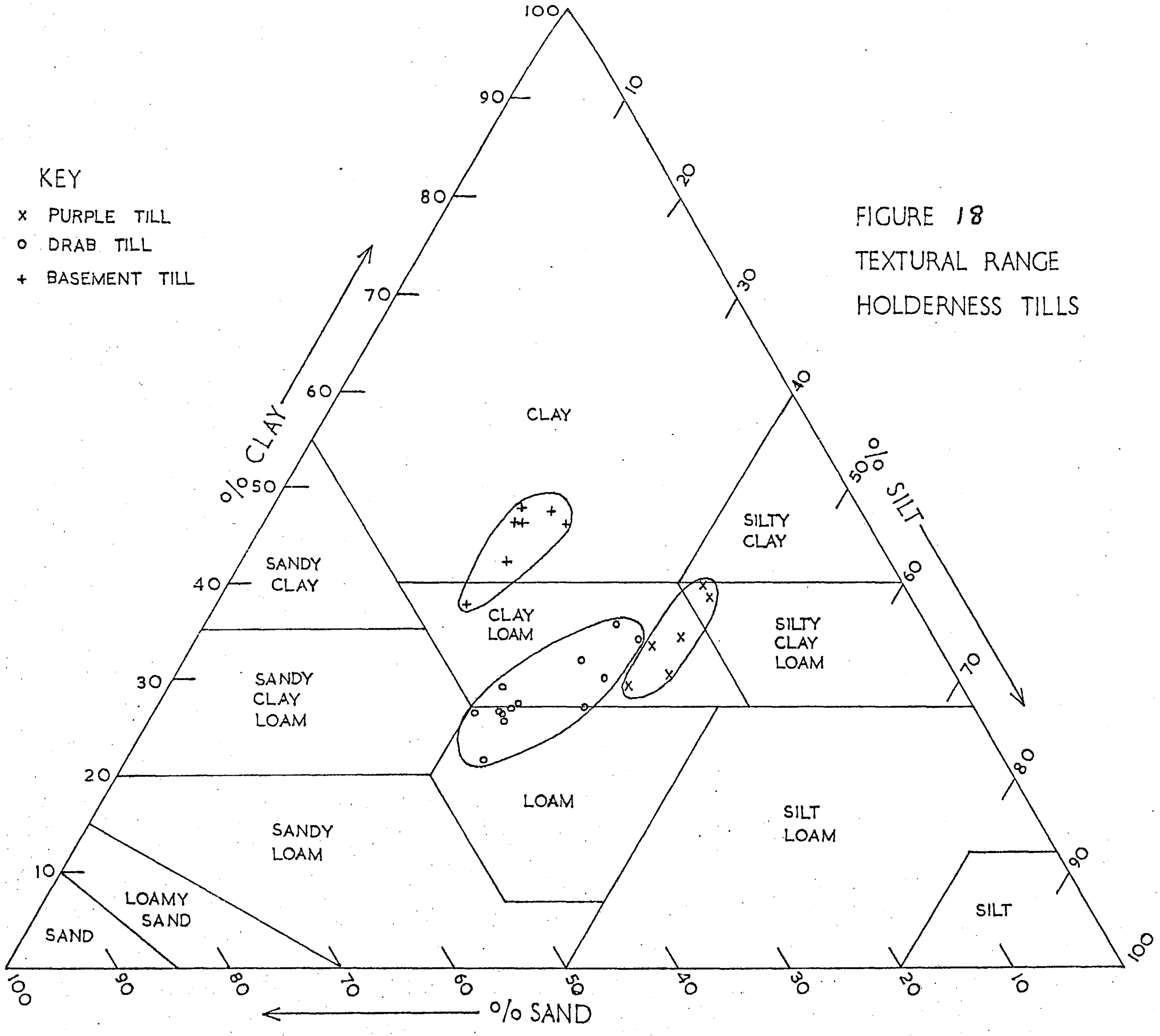


FIGURE 18
TEXTURAL RANGE
HOLDERNESS TILLS

FIGURE 19
TEXTURAL RANGE
HESSLE TILL

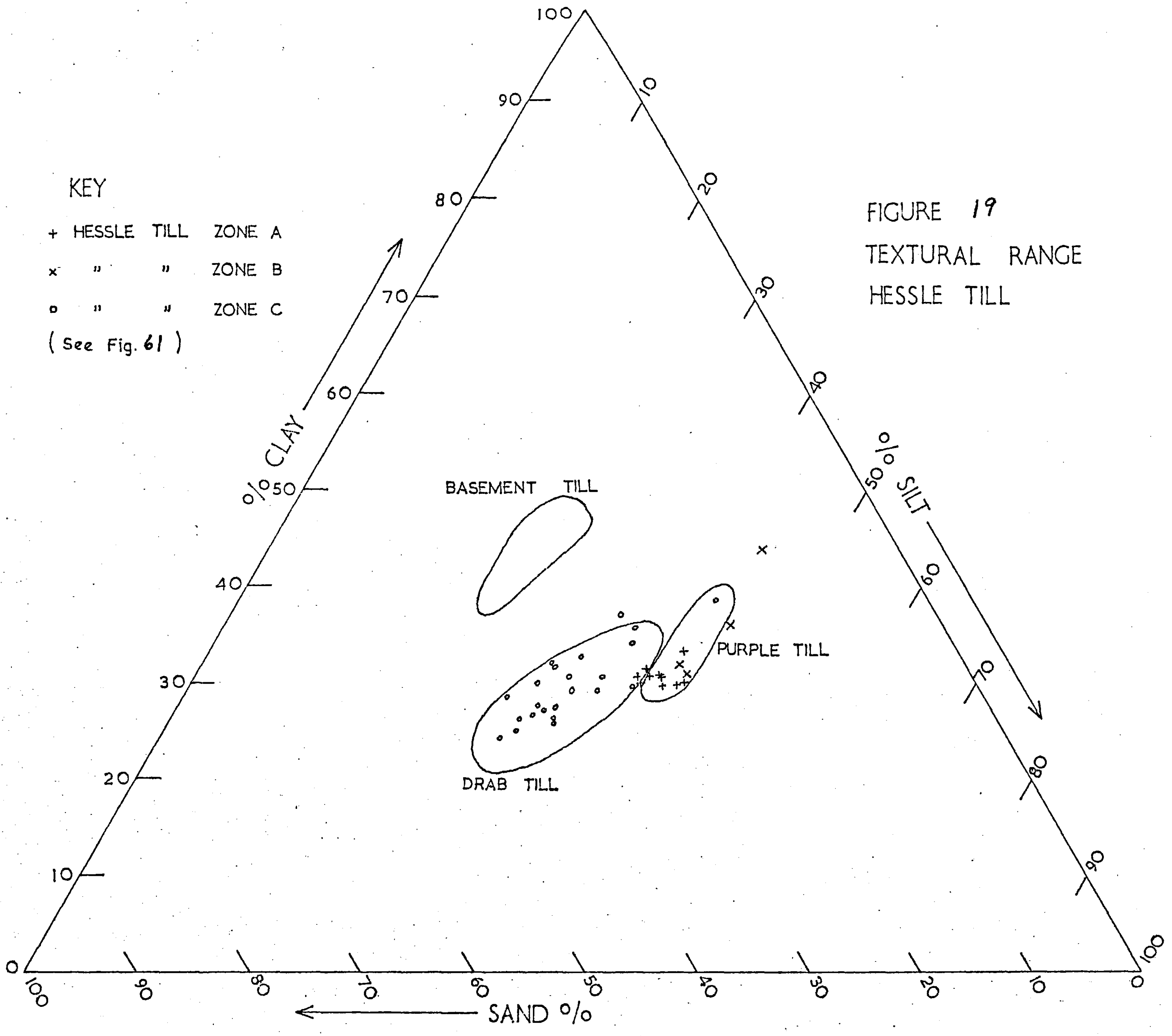
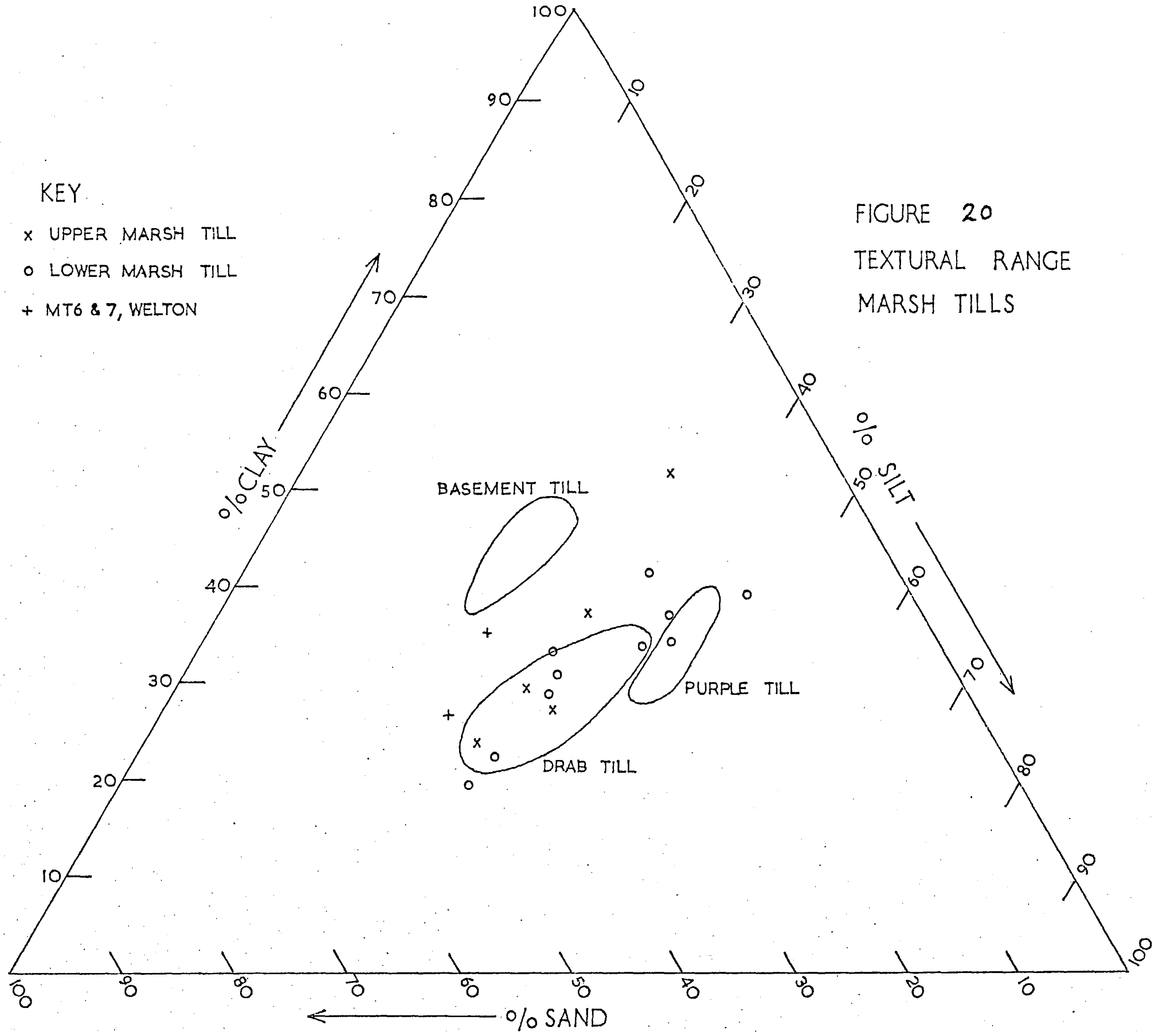


FIGURE 20
TEXTURAL RANGE
MARSH TILLS



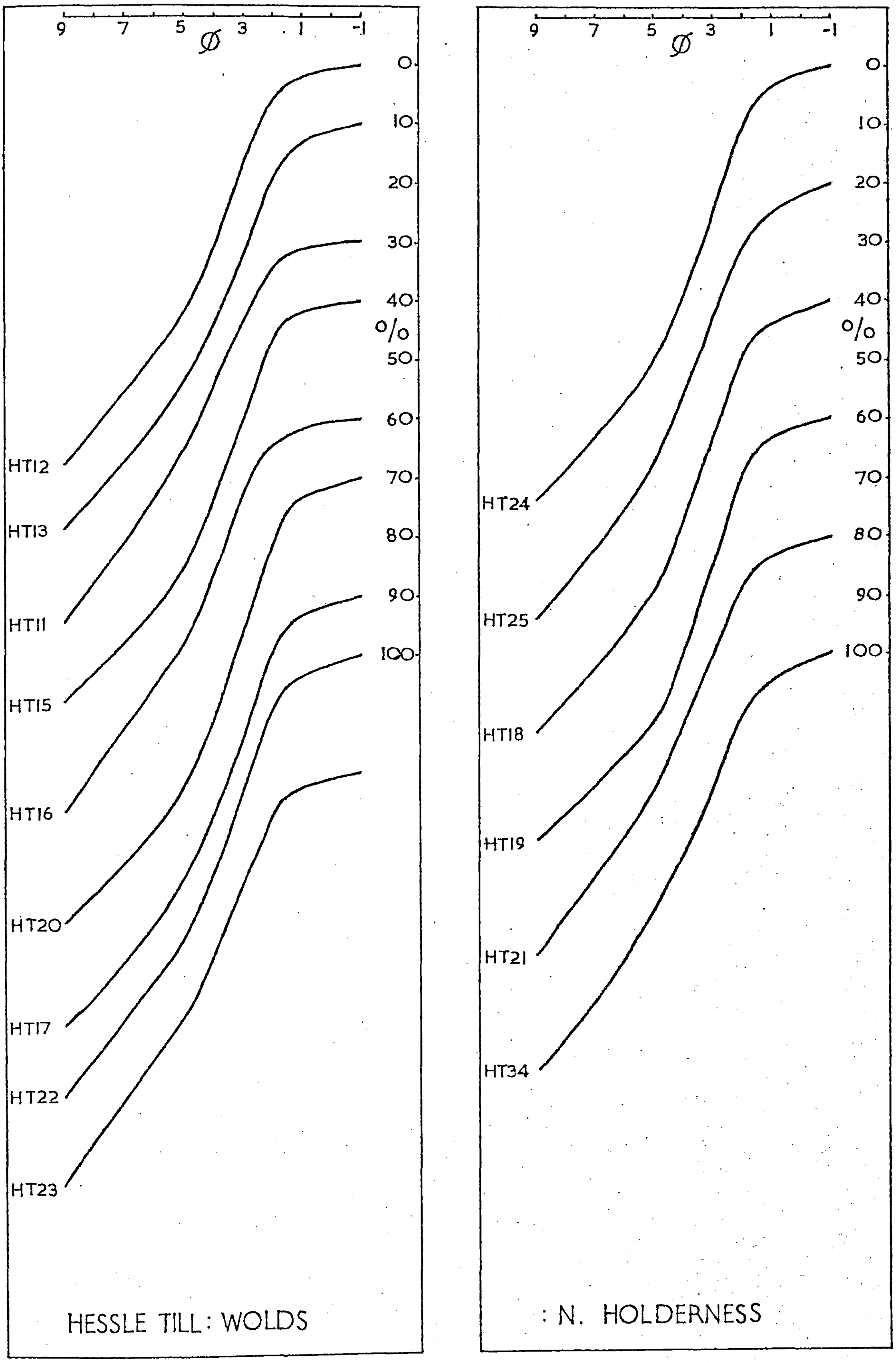


FIGURE 21 CUMULATIVE PARTICLE SIZE ANALYSES

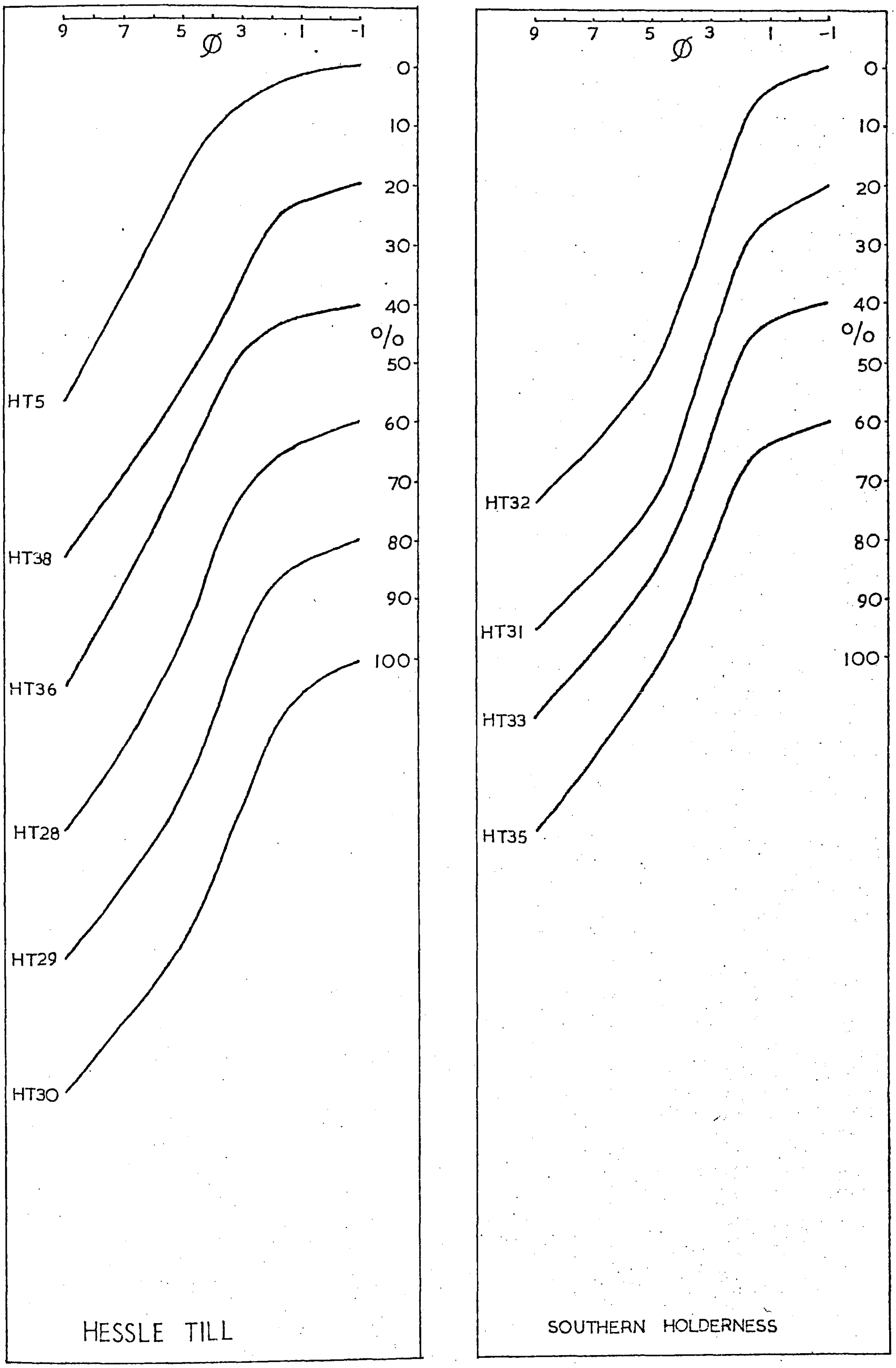


FIGURE 22 CUMULATIVE PARTICLE SIZE ANALYSES

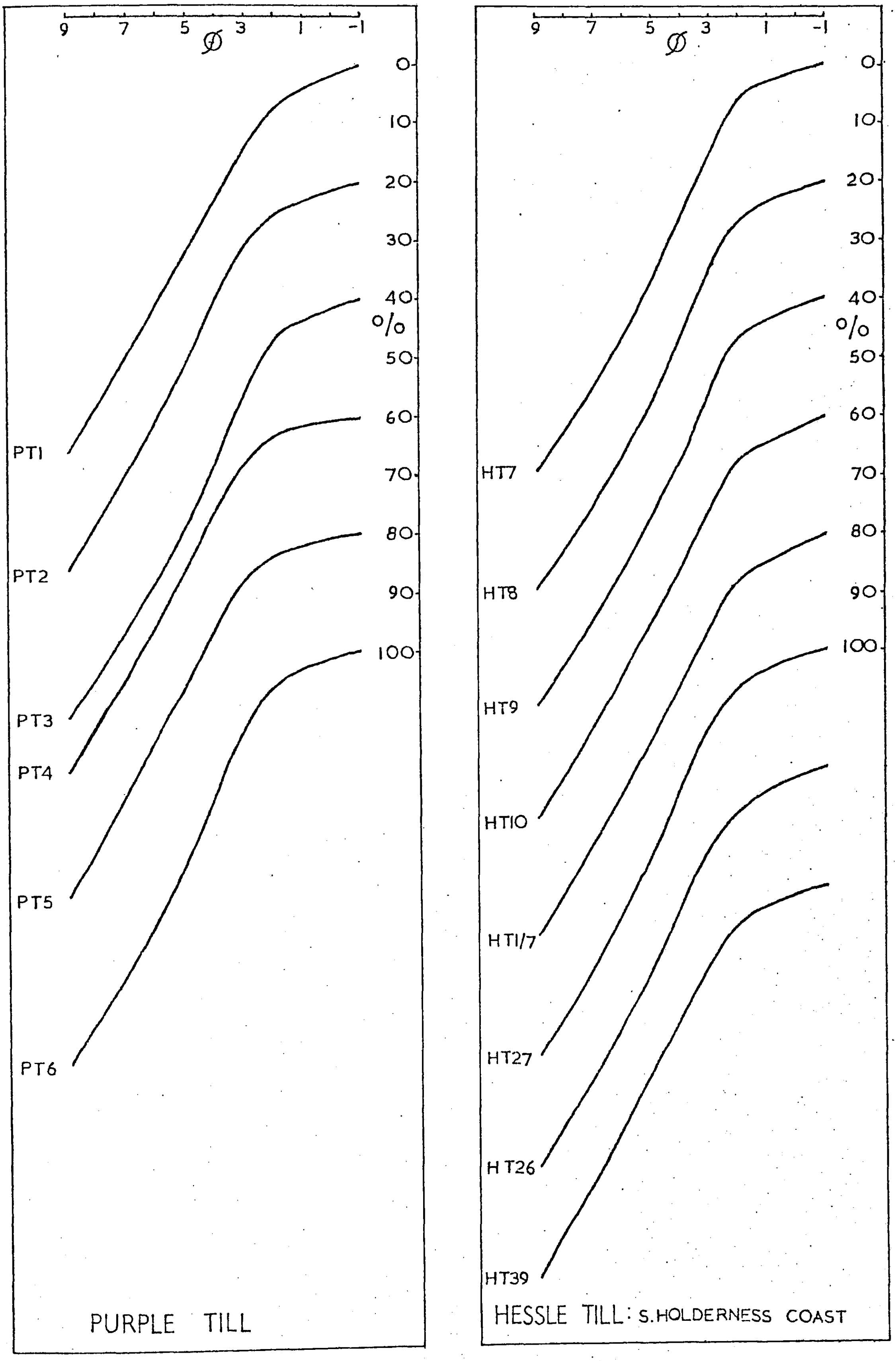


FIGURE 23 CUMULATIVE PARTICLE SIZE ANALYSES

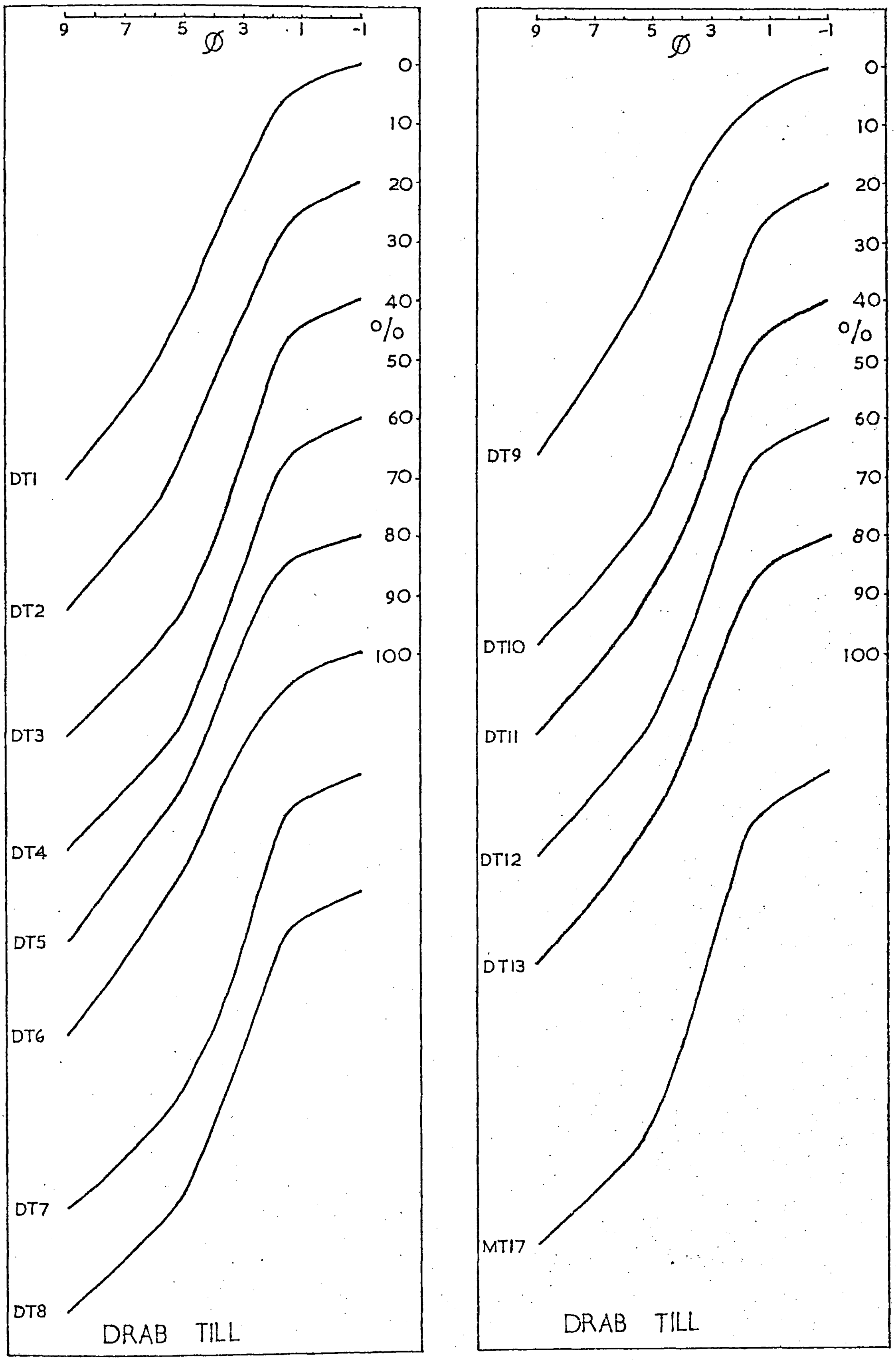


FIGURE 24 CUMULATIVE PARTICLE SIZE ANALYSES

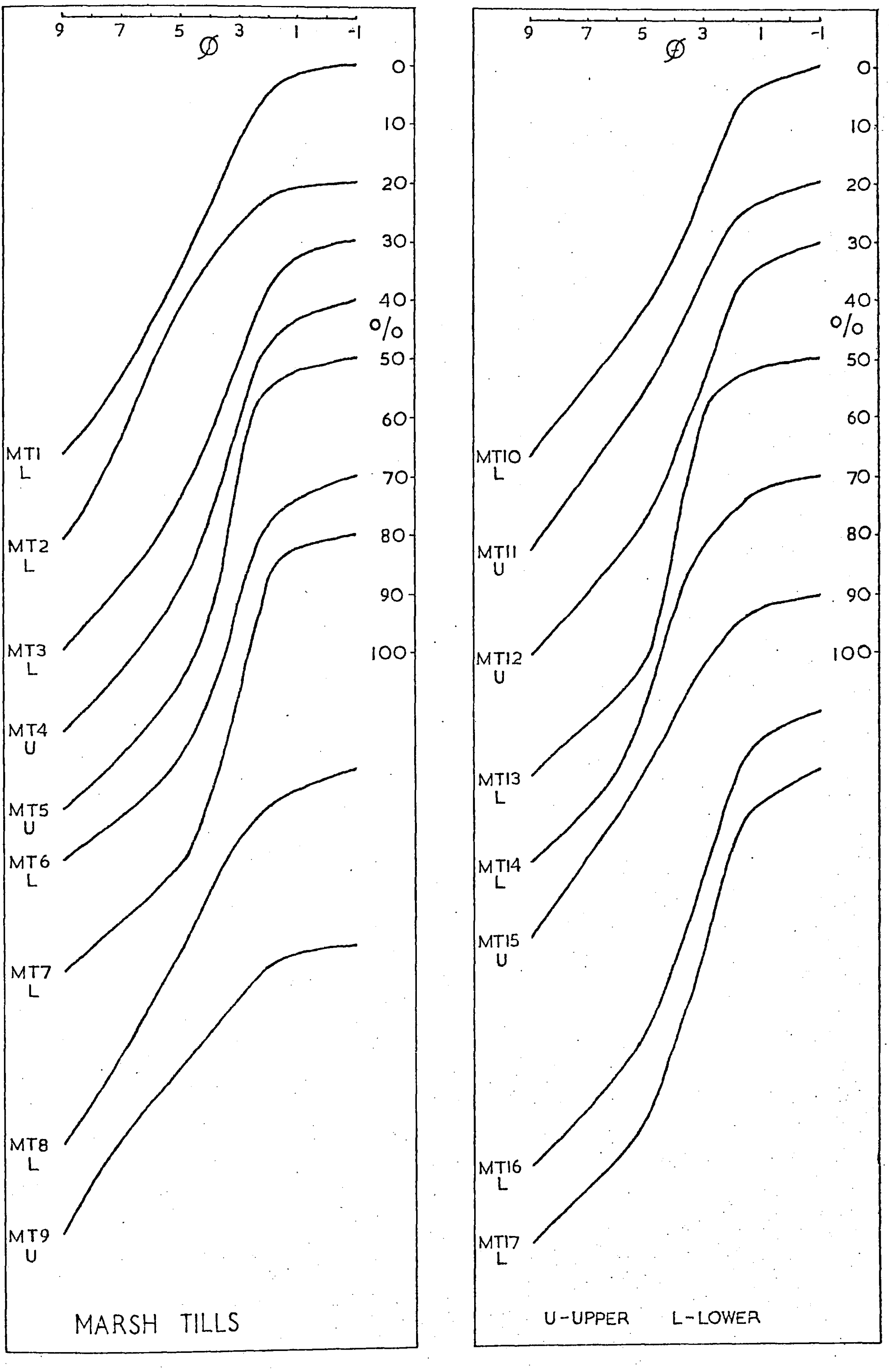


FIGURE 25 CUMULATIVE PARTICLE SIZE ANALYSES

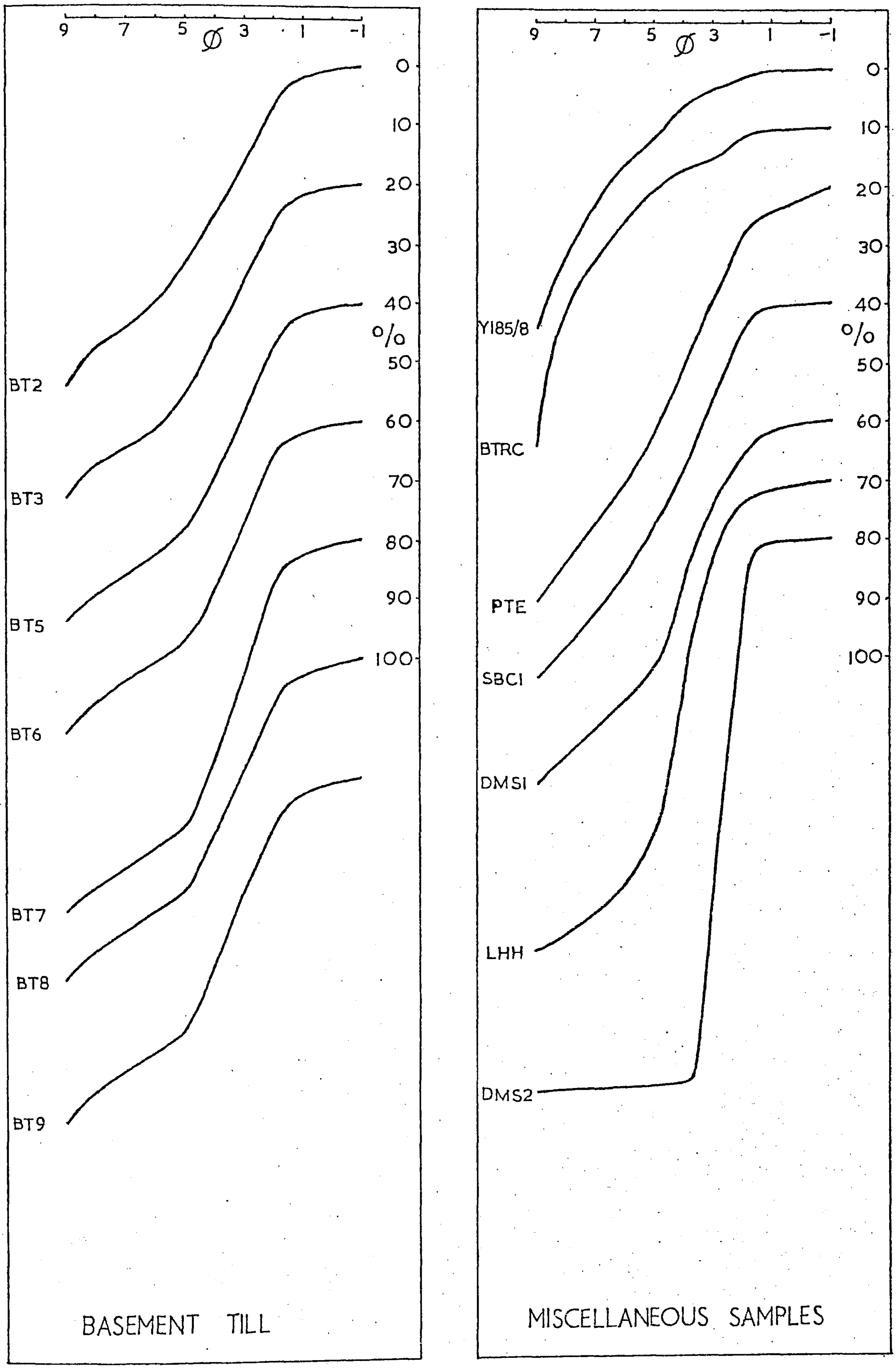
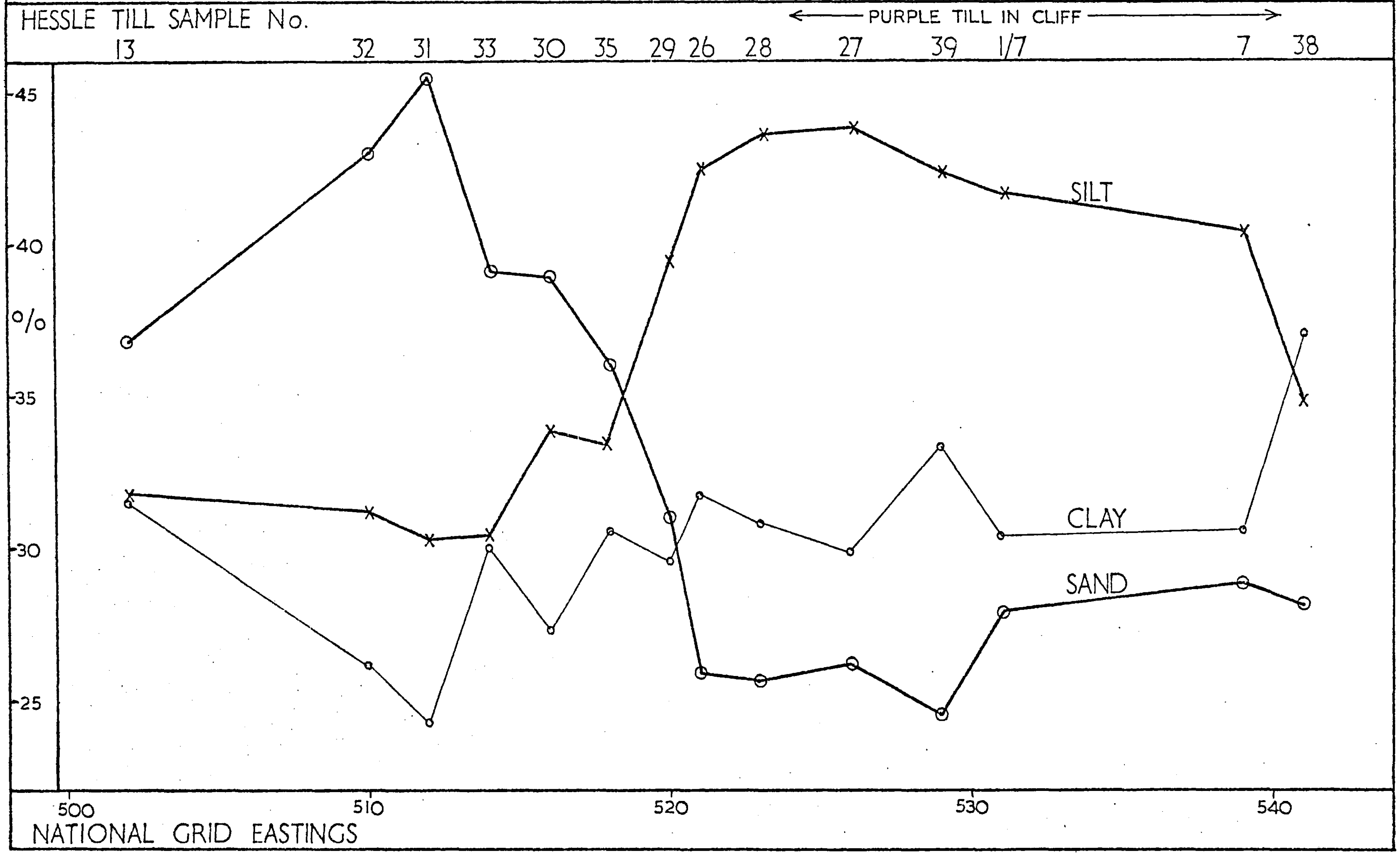


FIGURE 26 CUMULATIVE PARTICLE SIZE ANALYSES

FIGURE 27 TEXTURAL VARIATION IN THE HESSLE TILL ACROSS SOUTHERN HOLDERNESS



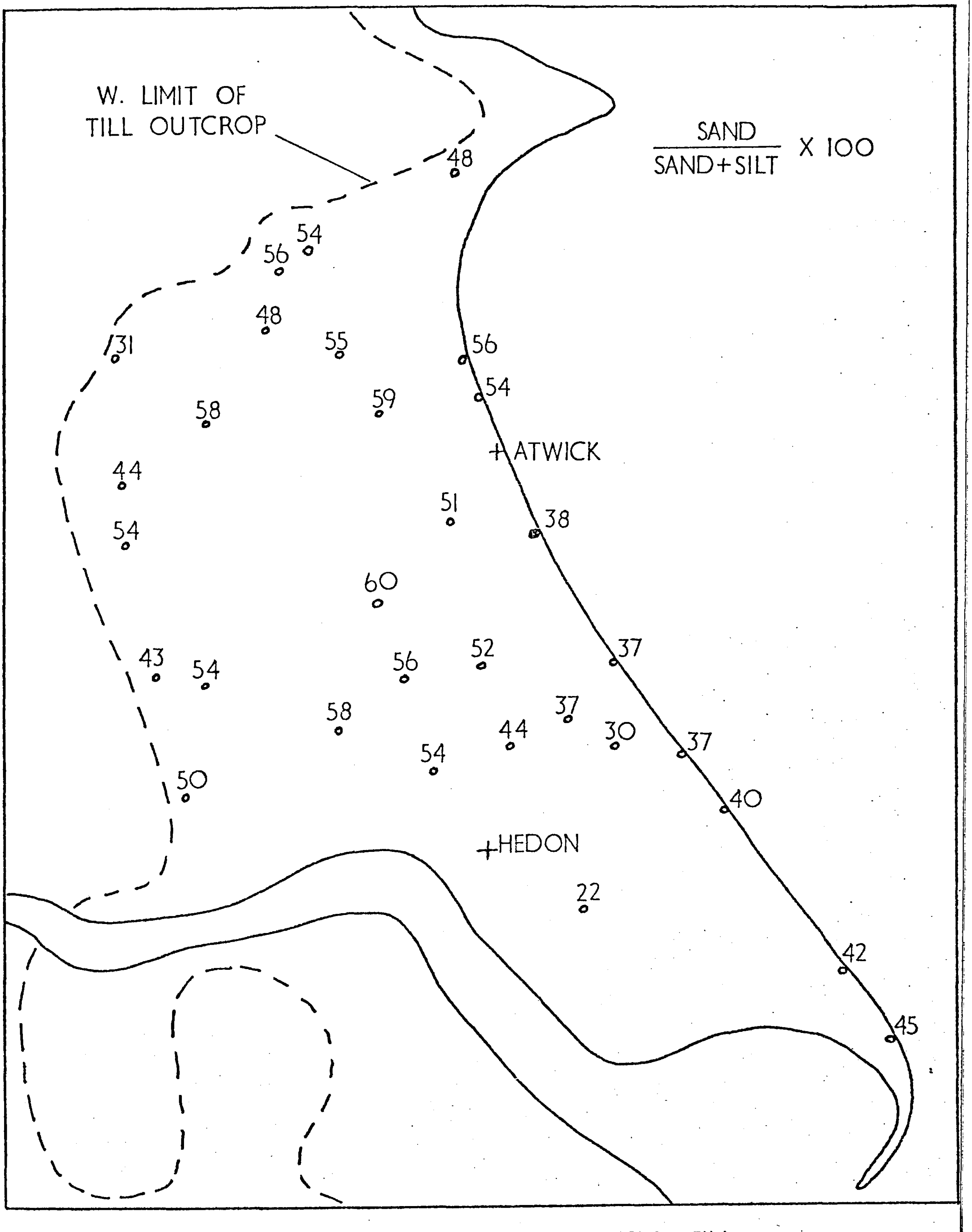


FIGURE 28 TEXTURAL VARIATION IN THE HESSLE TILL

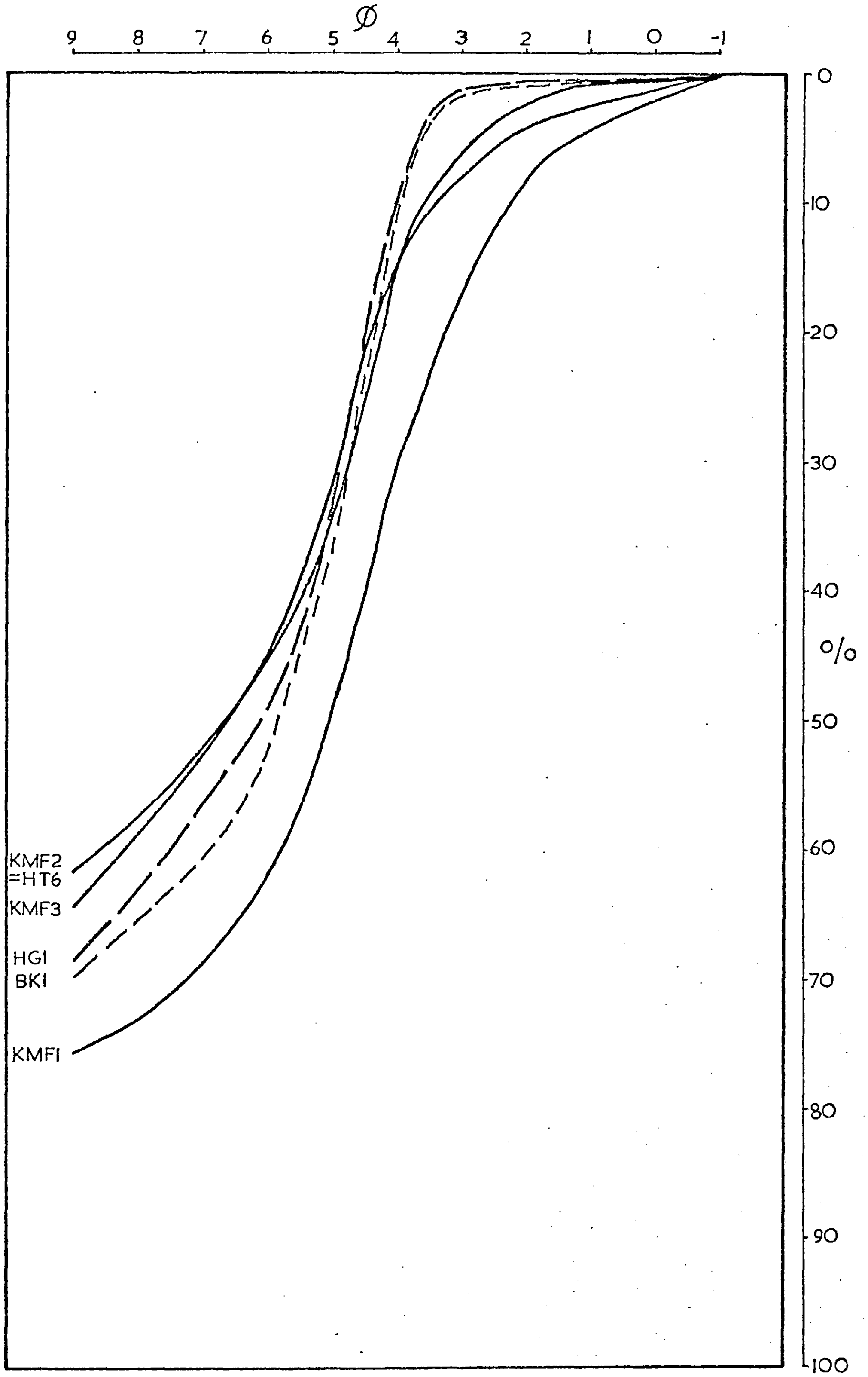


FIGURE 29 CUMULATIVE PARTICLE SIZE ANALYSES
TO ILLUSTRATE PROBABLE CONTAMINATION OF TILL SAMPLE HT6
BY LOESSIAL SILT (HG1, BK1)

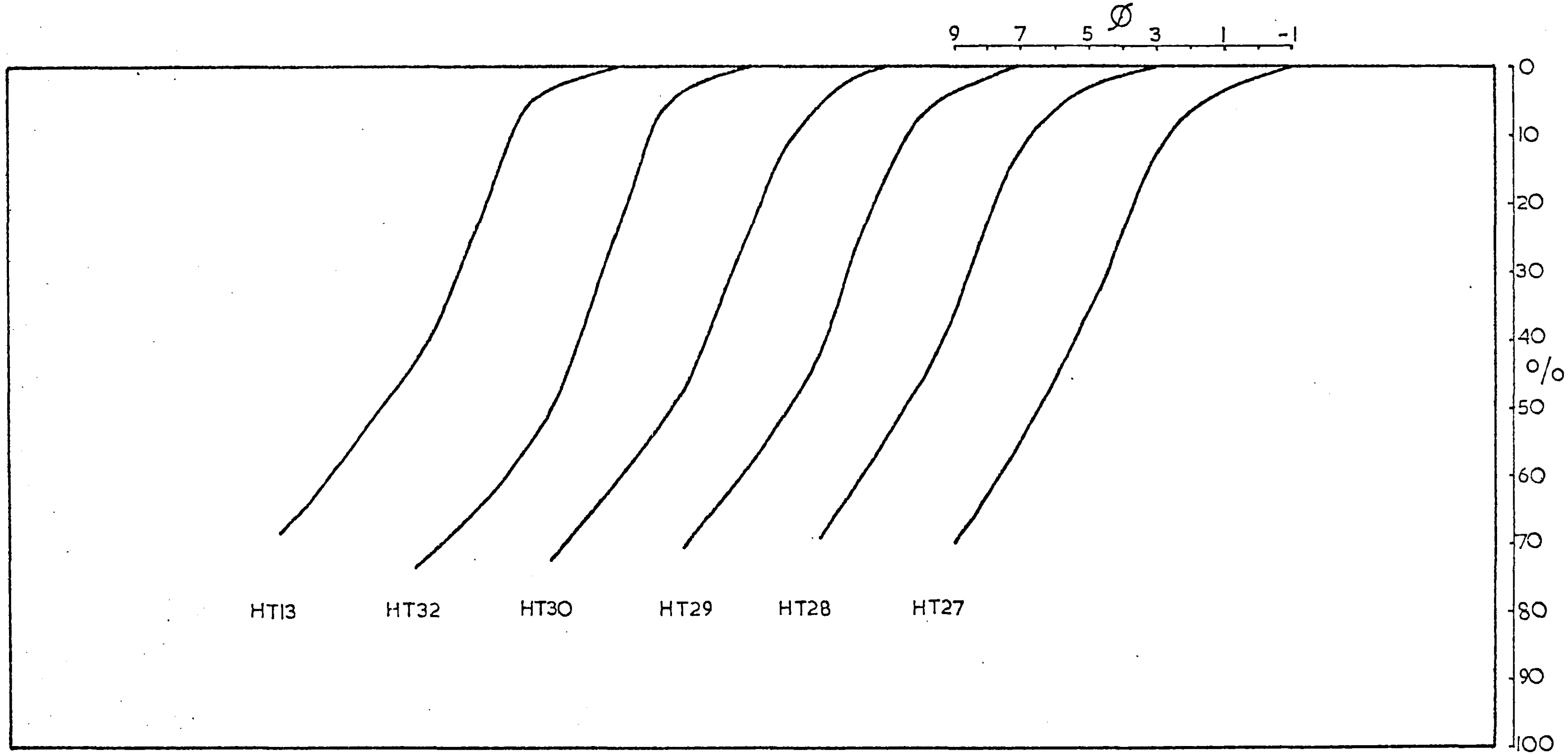


FIGURE 30 CUMULATIVE PARTICLE SIZE ANALYSES HESSLE TILL TRANSECT EAST-WEST ACROSS SOUTHERN HOLDERNESS

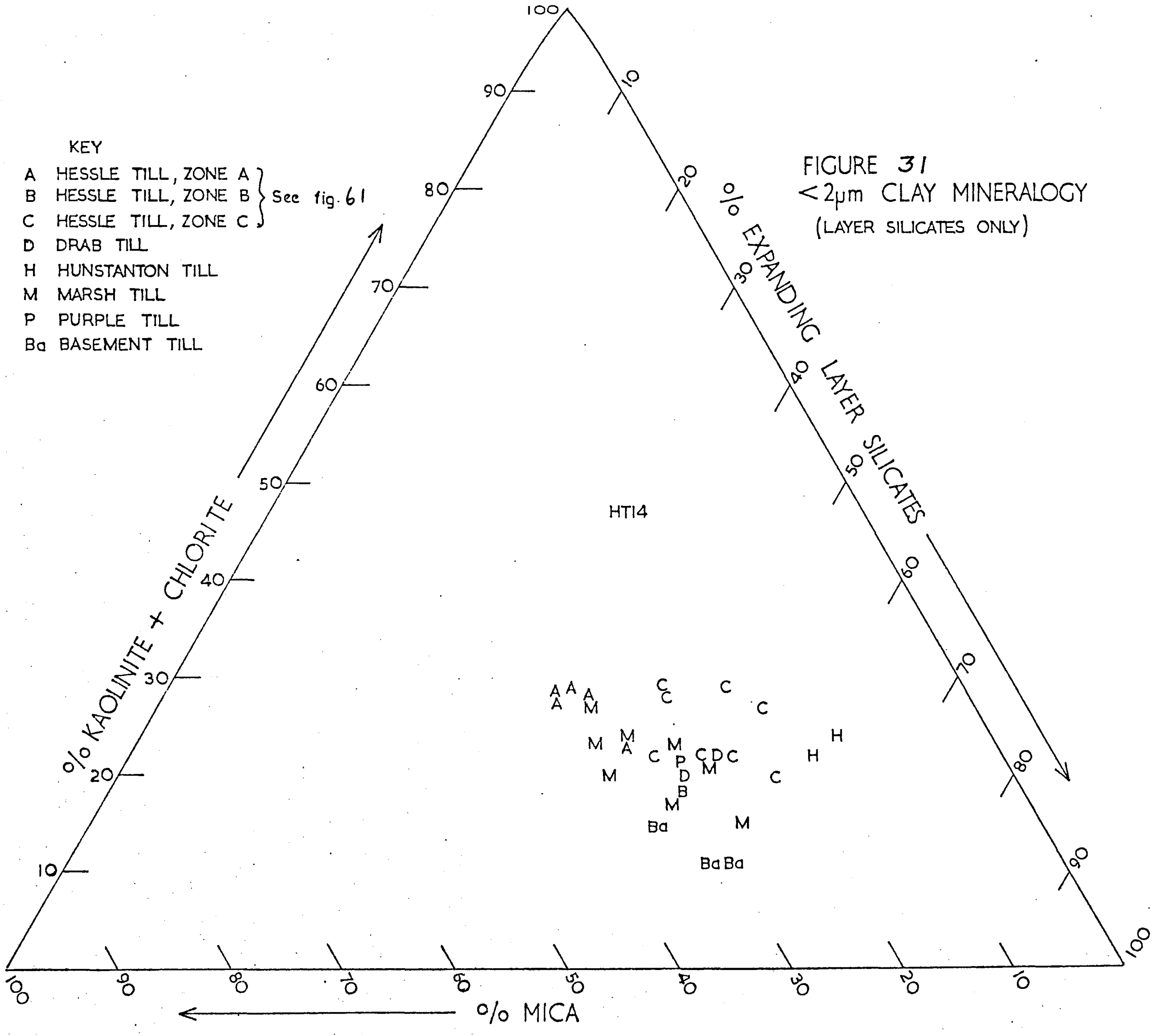


FIGURE 31
<2µm CLAY MINERALOGY
(LAYER SILICATES ONLY)

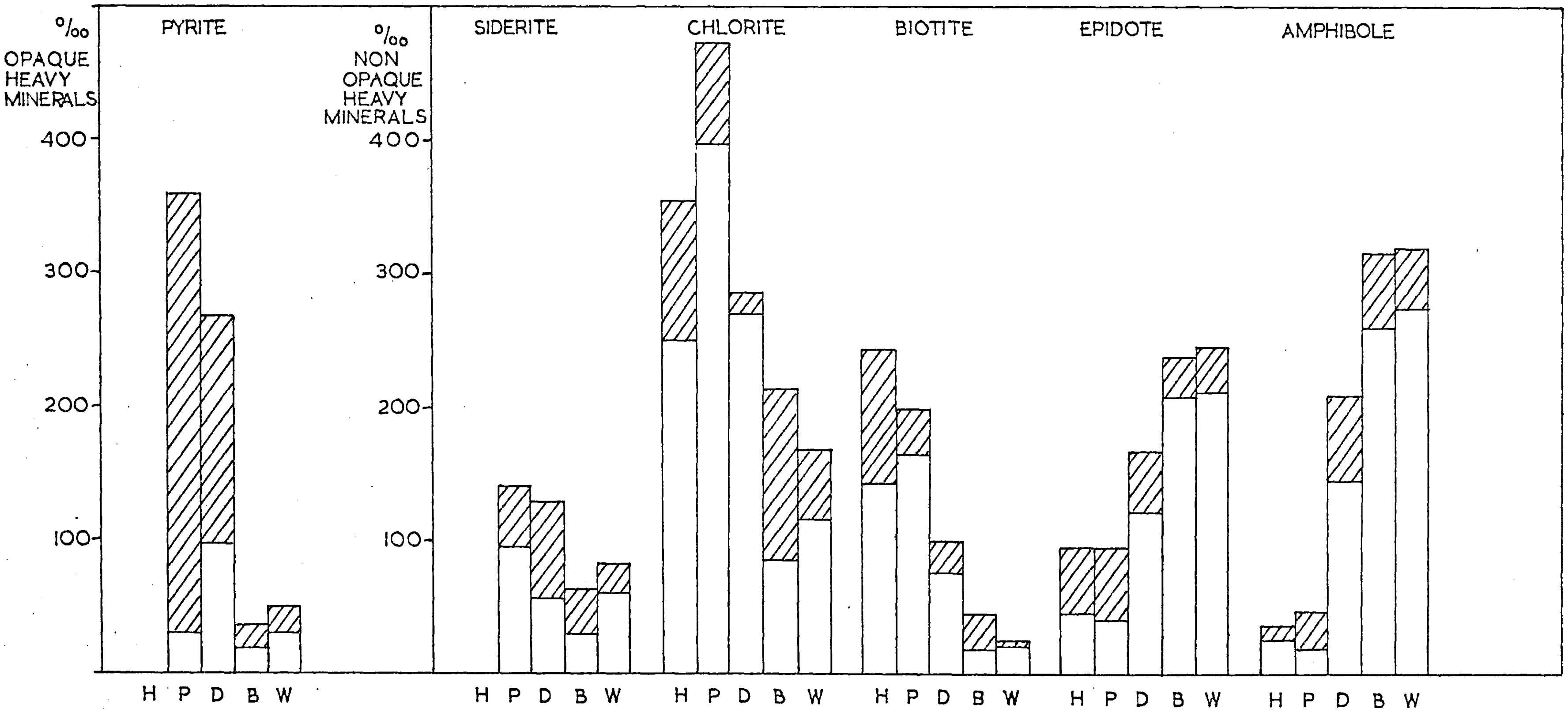


FIGURE 32 20–53µm FRACTION: HEAVY MINERALOGY
MAJOR DIFFERENCES BETWEEN TILLS, DIMLINGTON

FIGURE 33
20-53µm FRACTION
HEAVY NON-OPAQUE MINERALS

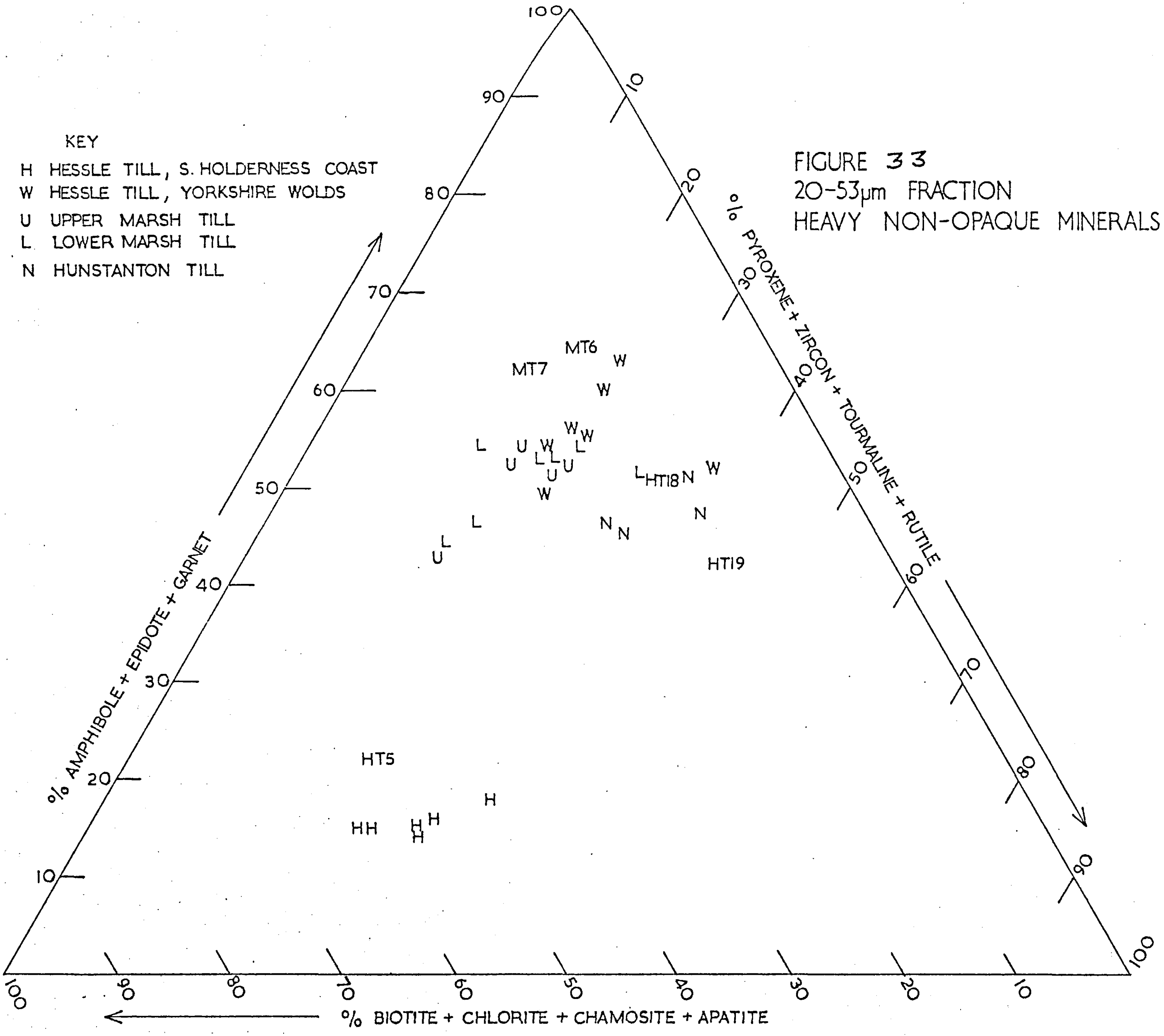


FIGURE 34
20-53µm FRACTION
HEAVY NON-OPAQUE MINERALS
SIDERITE-FREE BASIS

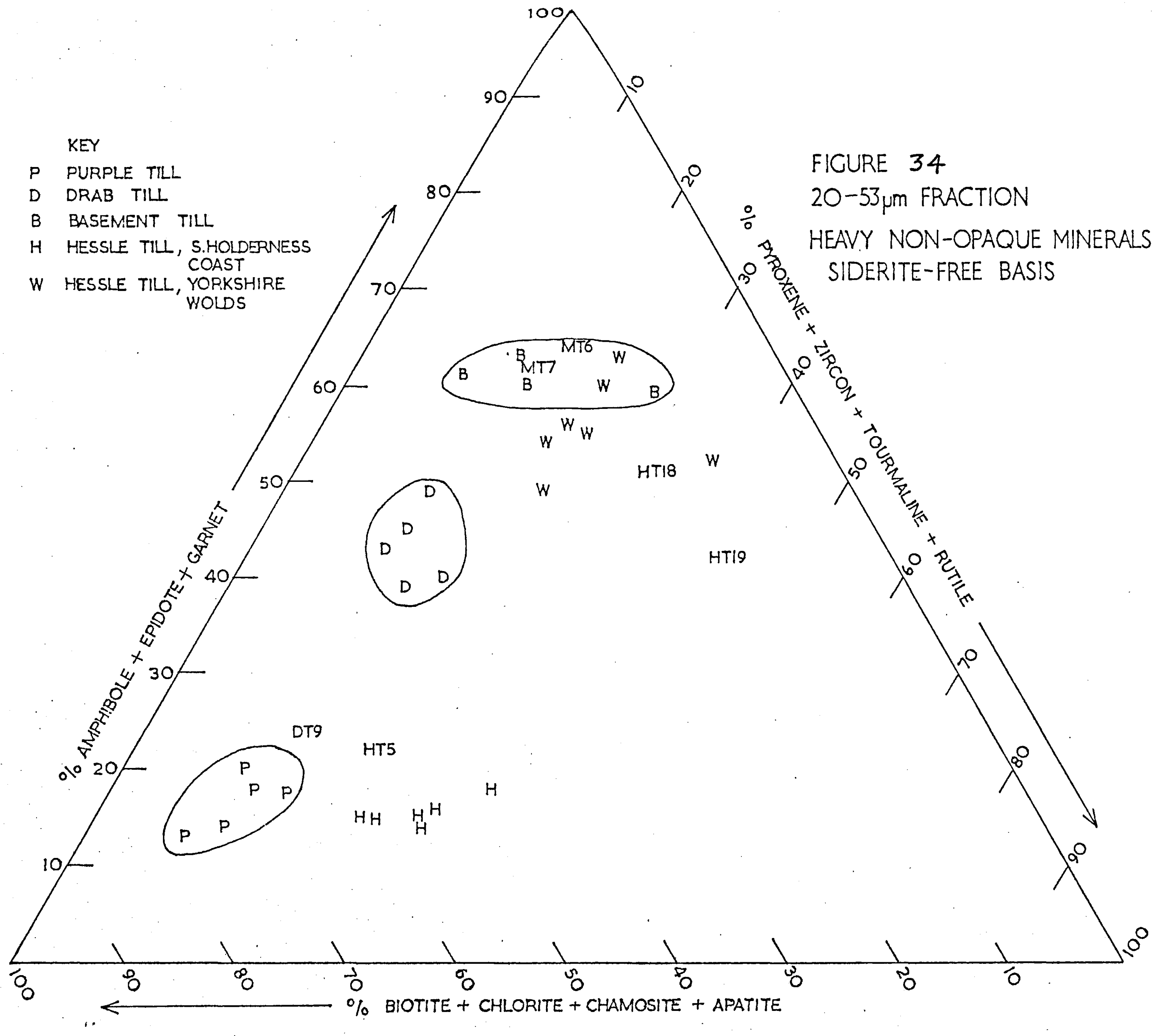
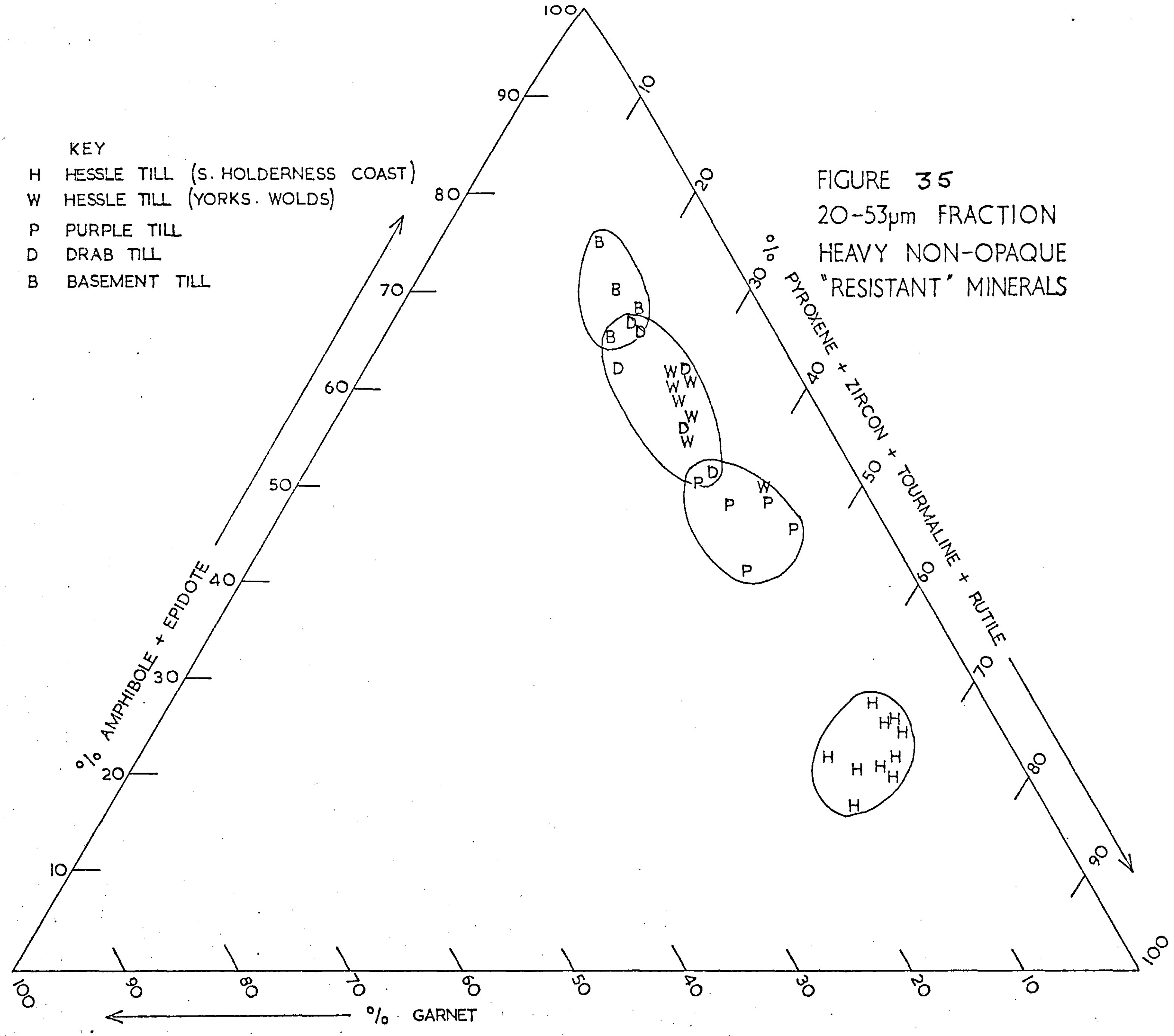


FIGURE 35
20-53μm FRACTION
HEAVY NON-OPAQUE
"RESISTANT" MINERALS



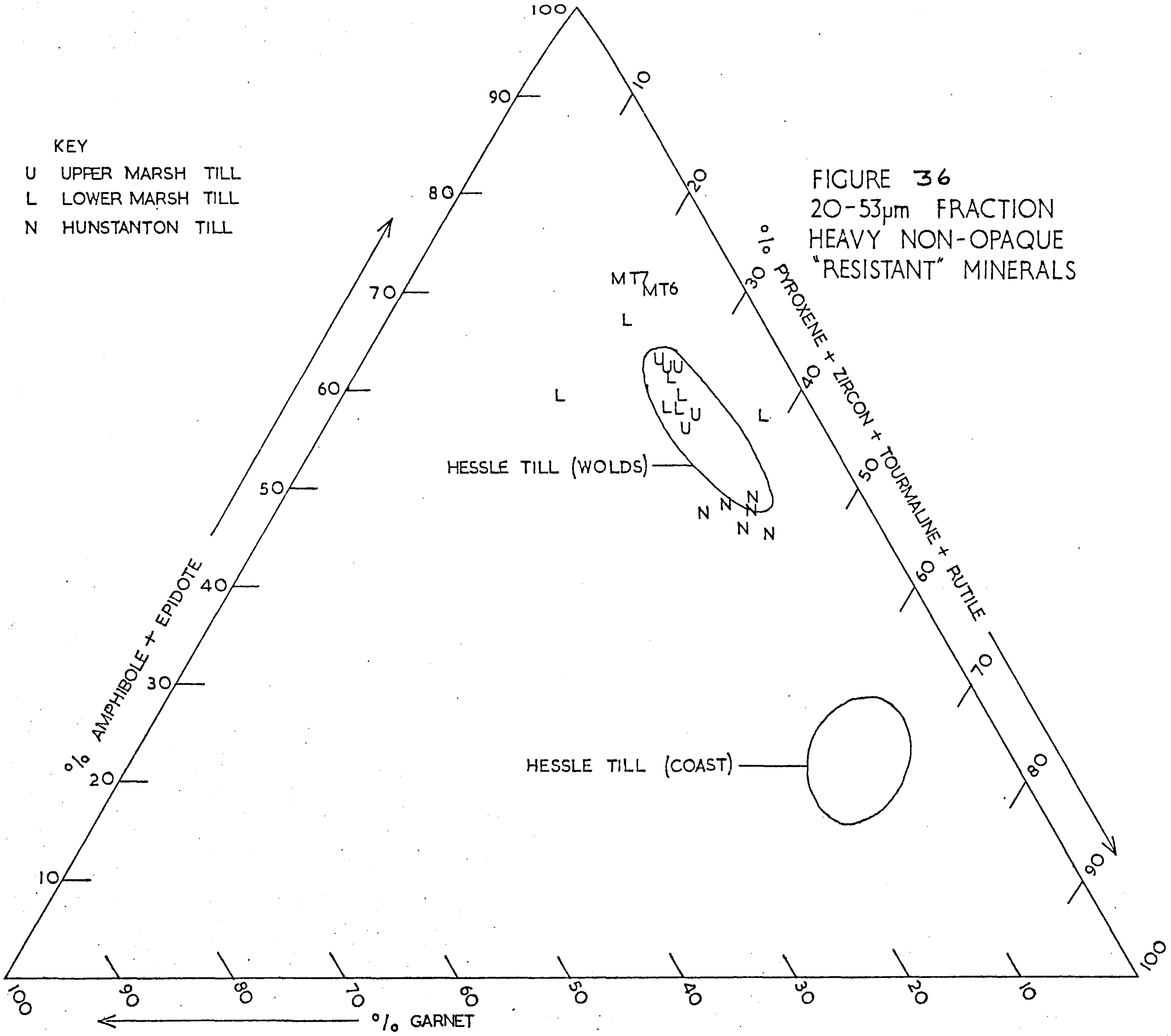


FIGURE 36
20-53µm FRACTION
HEAVY NON-OPAQUE
"RESISTANT" MINERALS

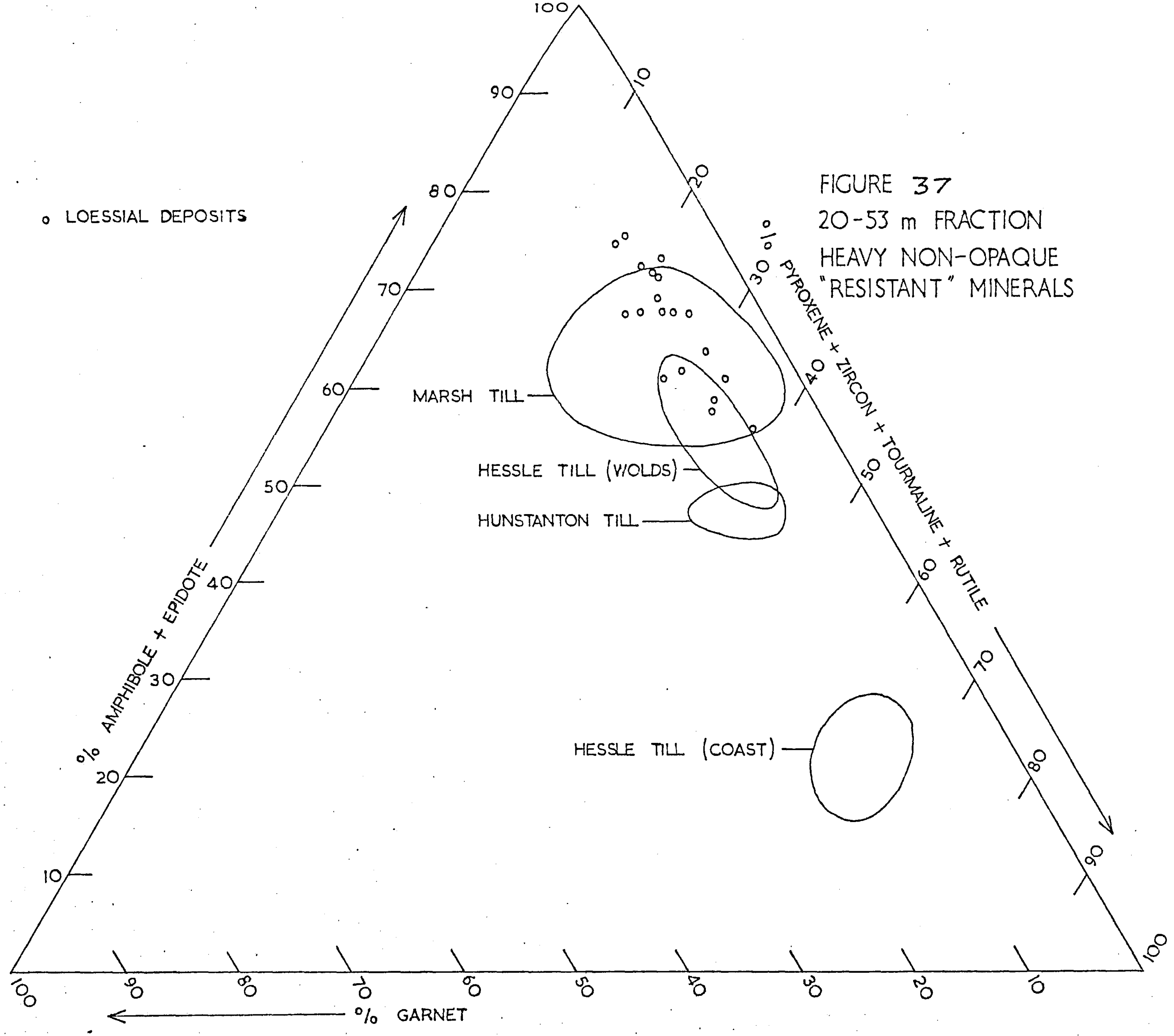
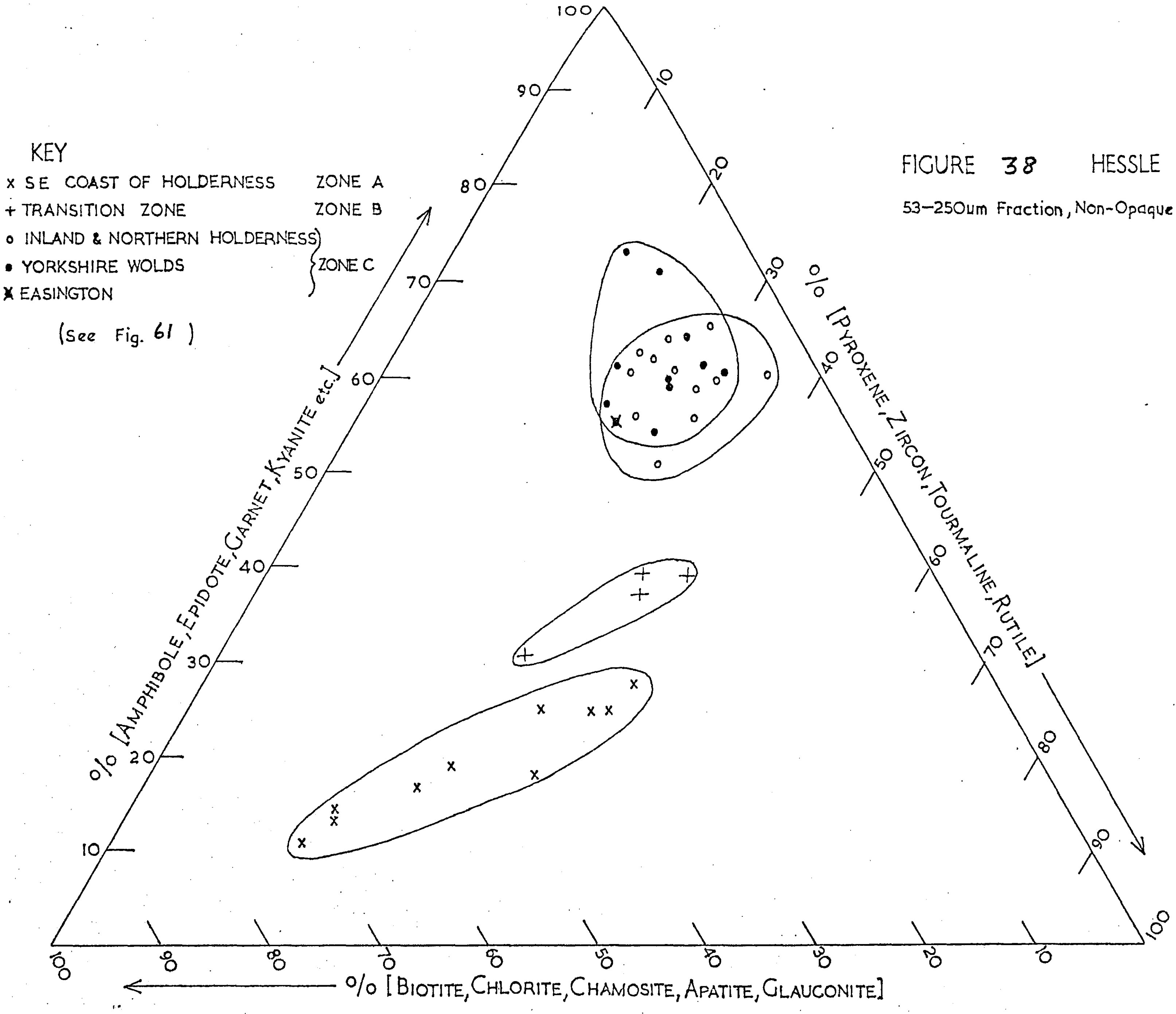


FIGURE 37
20-53 m FRACTION
HEAVY NON-OPAQUE
"RESISTANT" MINERALS

FIGURE 38 HESSLE TILL

53–250um Fraction, Non-Opaque Heavy Minerals



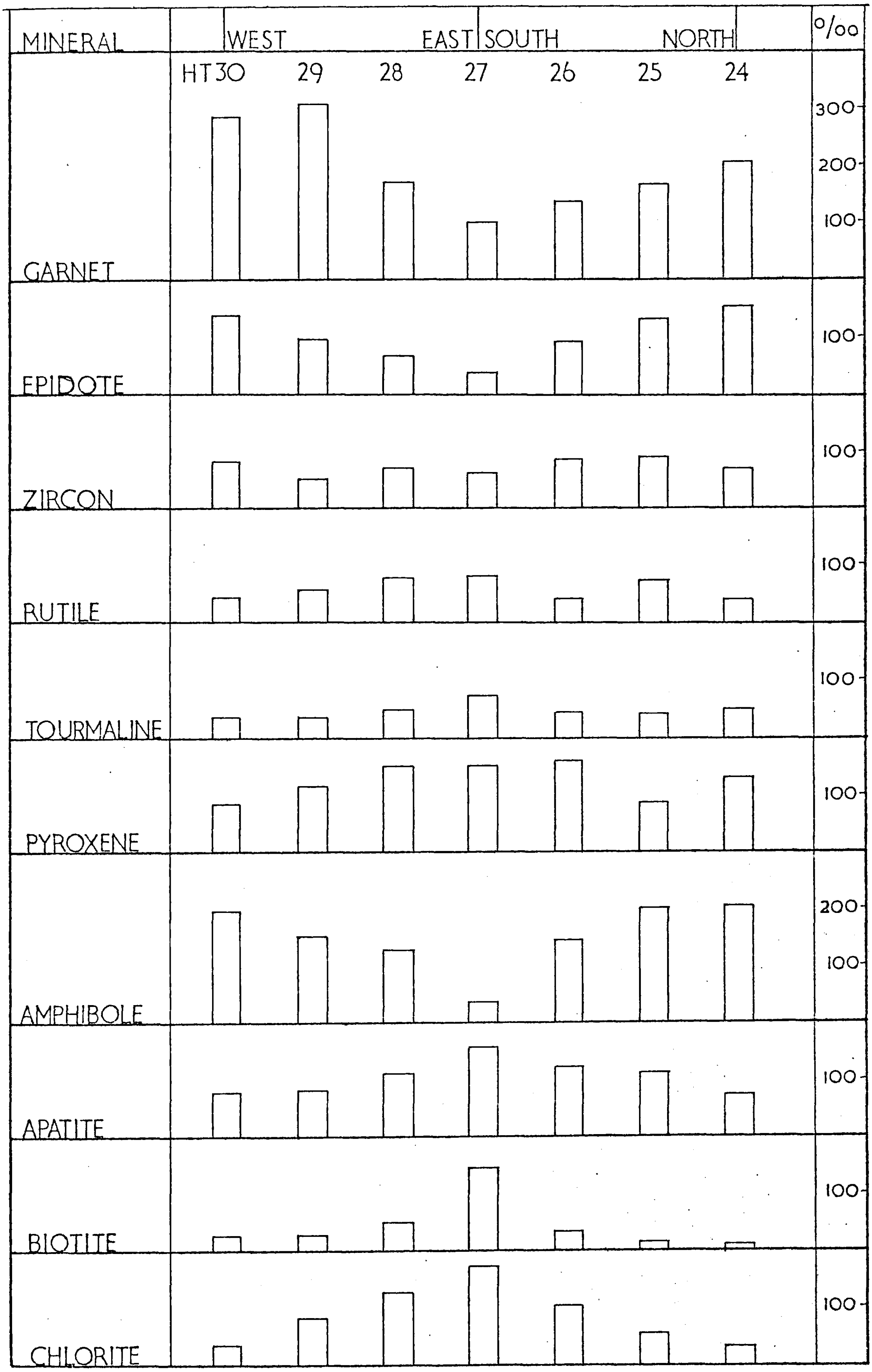


FIGURE 39 53-250μm FRACTION : HEAVY NON-OPAQUE MINERALS LATERAL VARIATION IN THE HESSLE TILL, HOLDERNESS

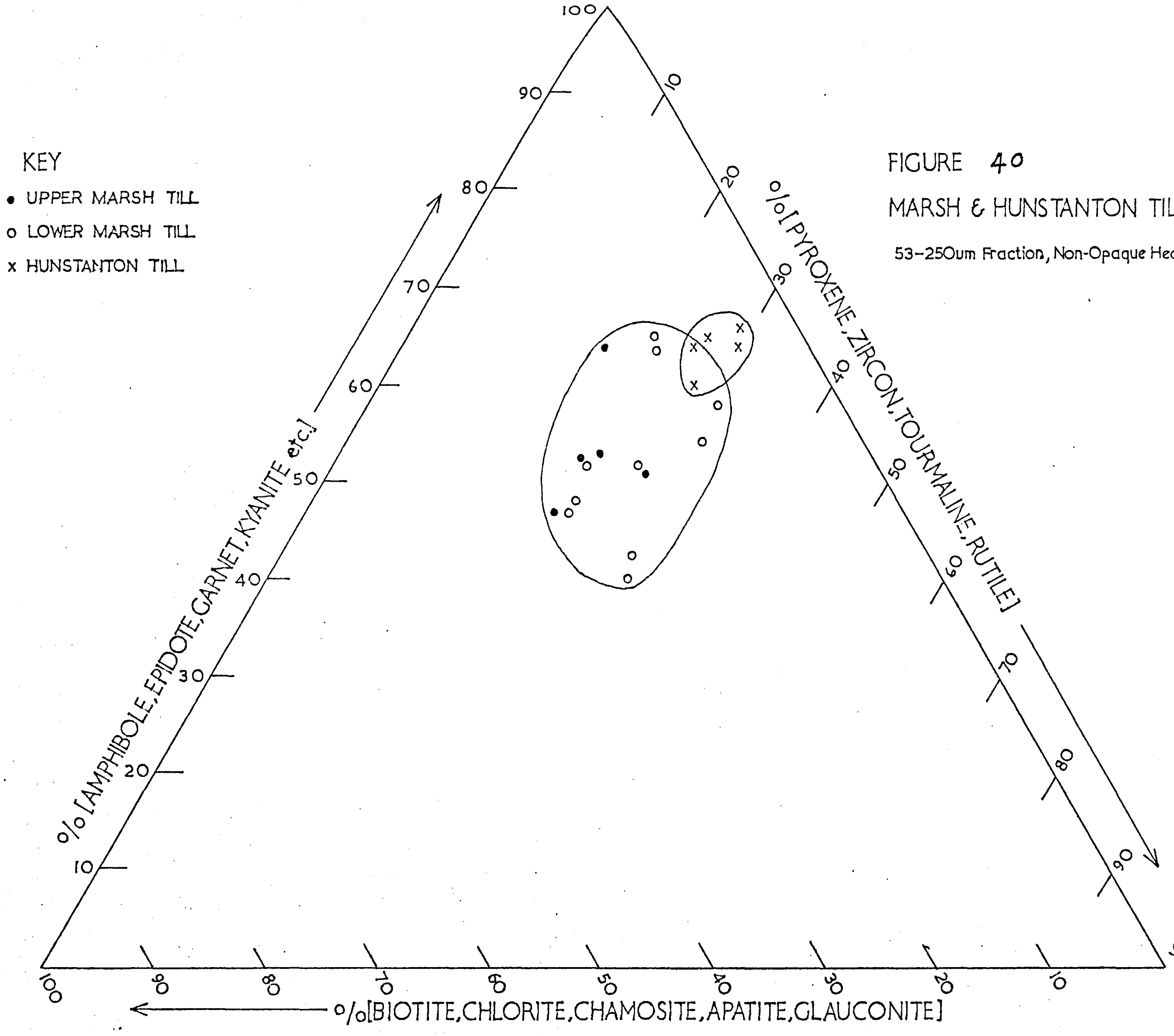


FIGURE 40

MARSH & HUNSTANTON TILLS

53-250um Fraction, Non-Opaque Heavy Minerals

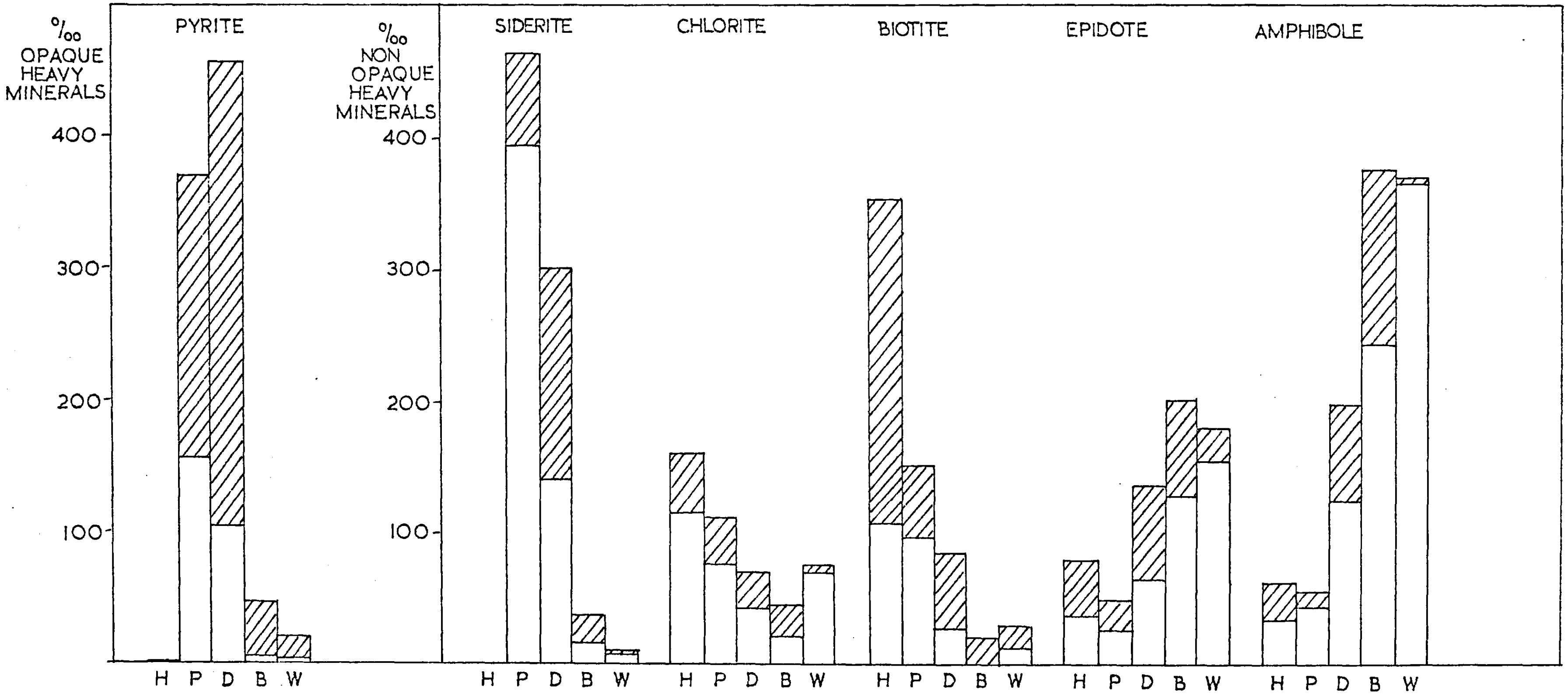


FIGURE 41 53-250μm FRACTION: HEAVY MINERALOGY

MAJOR DIFFERENCES BETWEEN TILLS, DIMLINGTON

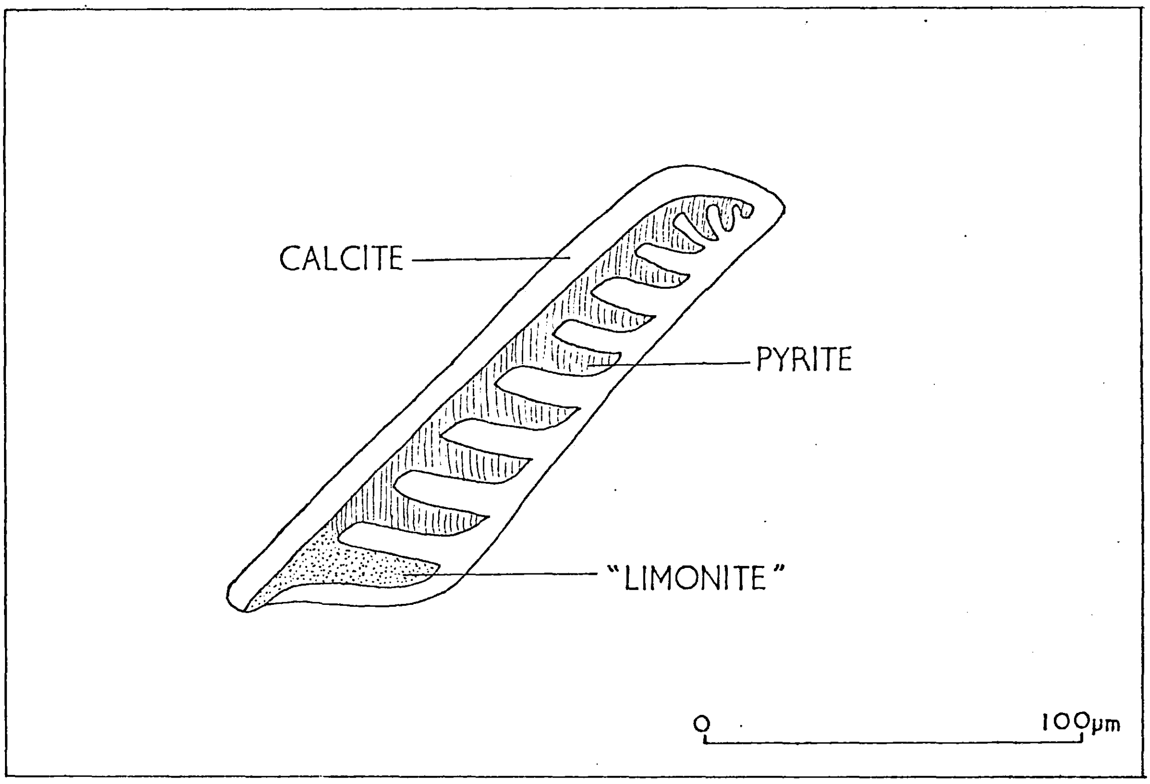
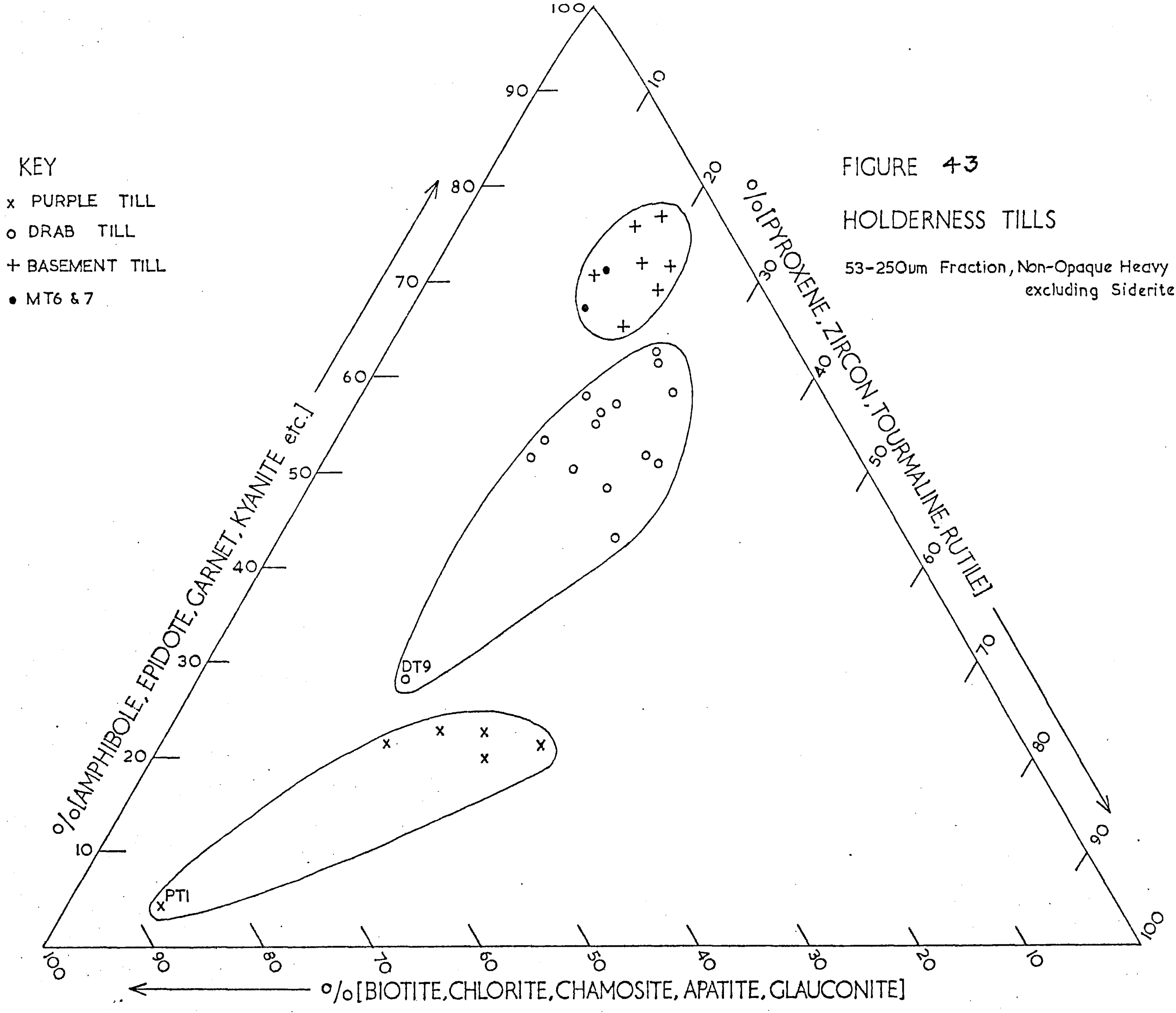


FIGURE 42 PARTIAL OXIDATION OF PYRITE INFILLING OF FORAMINIFERAL SHELL, FINE SAND FRACTION, SAMPLE HT28

FIGURE 4-3

HOLDERNESS TILLS

53-250um Fraction, Non-Opaque Heavy Minerals excluding Siderite



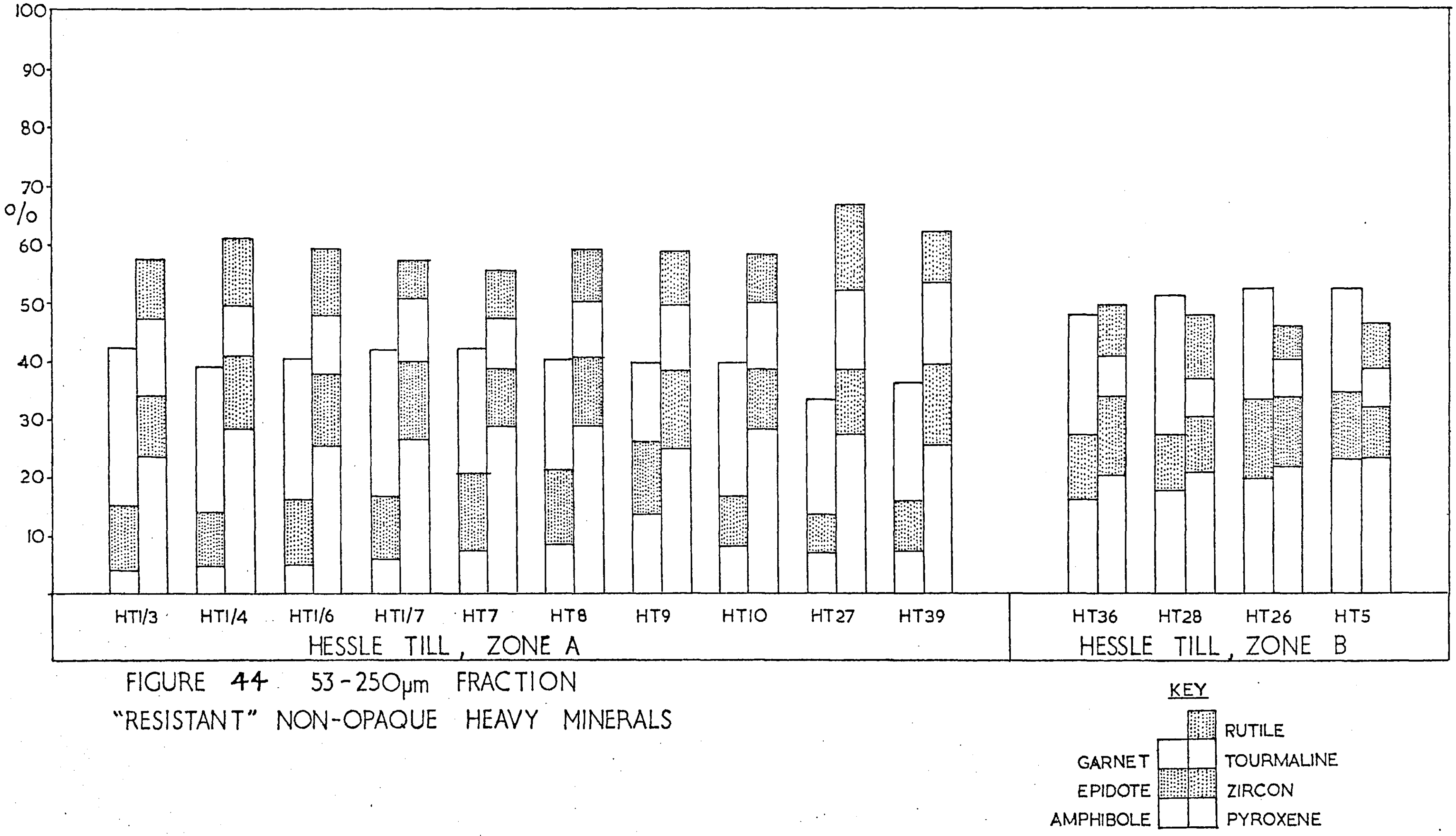


FIGURE 44 53-250µm FRACTION
"RESISTANT" NON-OPAQUE HEAVY MINERALS

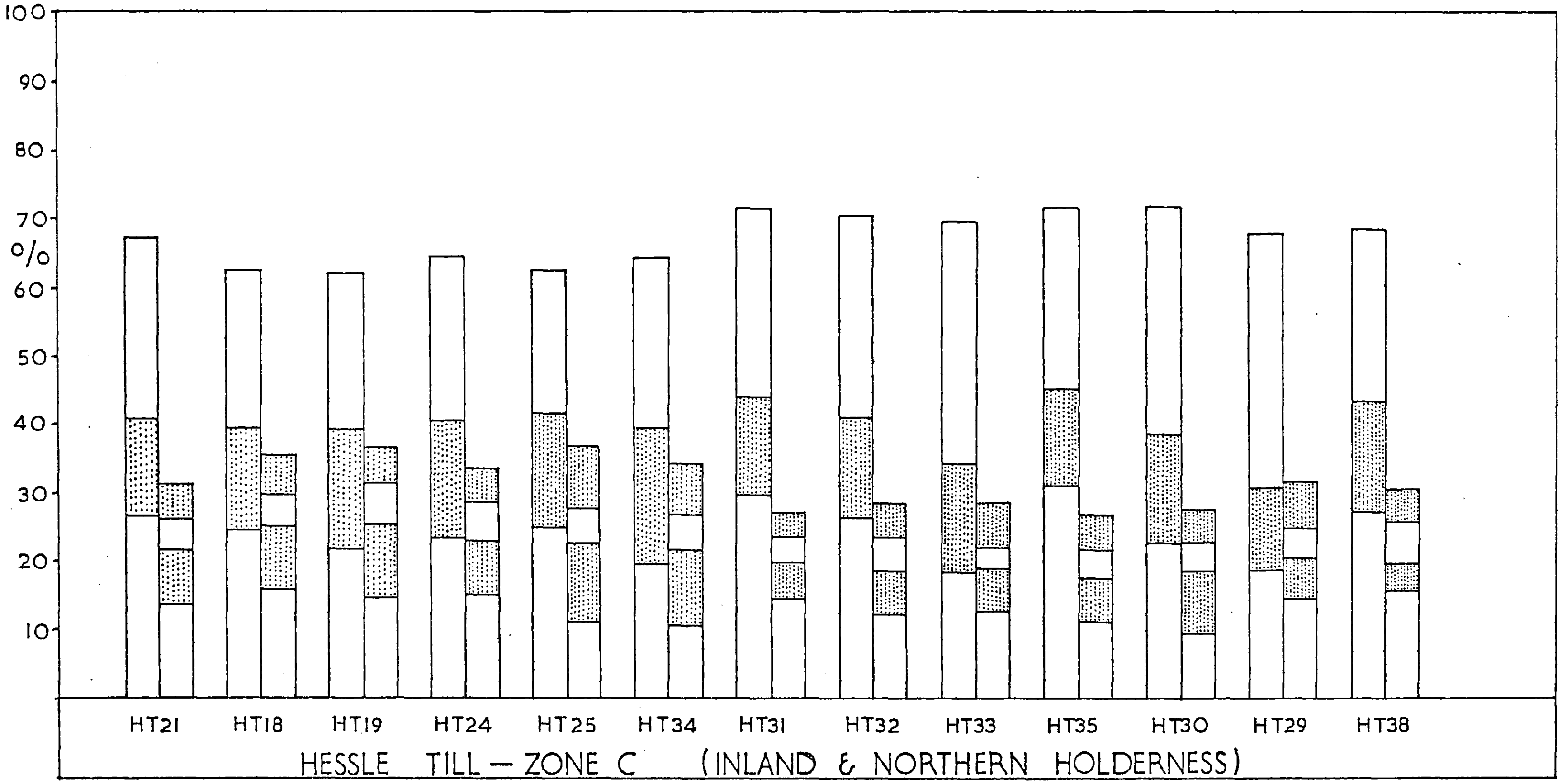


FIGURE 45 53-250μm FRACTION

"RESISTANT" NON-OPAQUE HEAVY MINERALS

KEY – AS FOR FIGURE 44

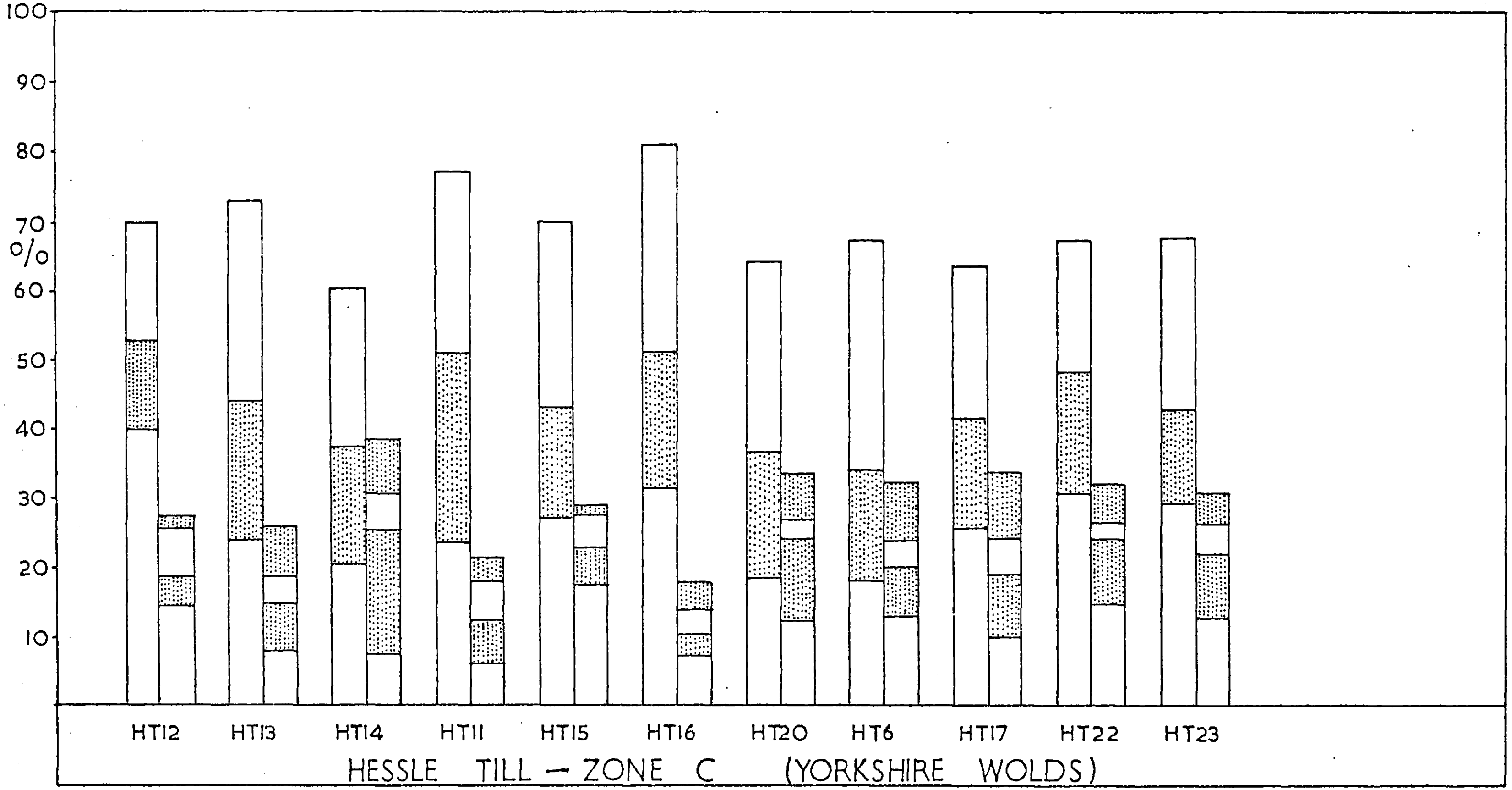


FIGURE 46 53-250μm FRACTION
"RESISTANT" NON-OPAQUE HEAVY MINERALS

KEY – AS FOR FIGURE 44

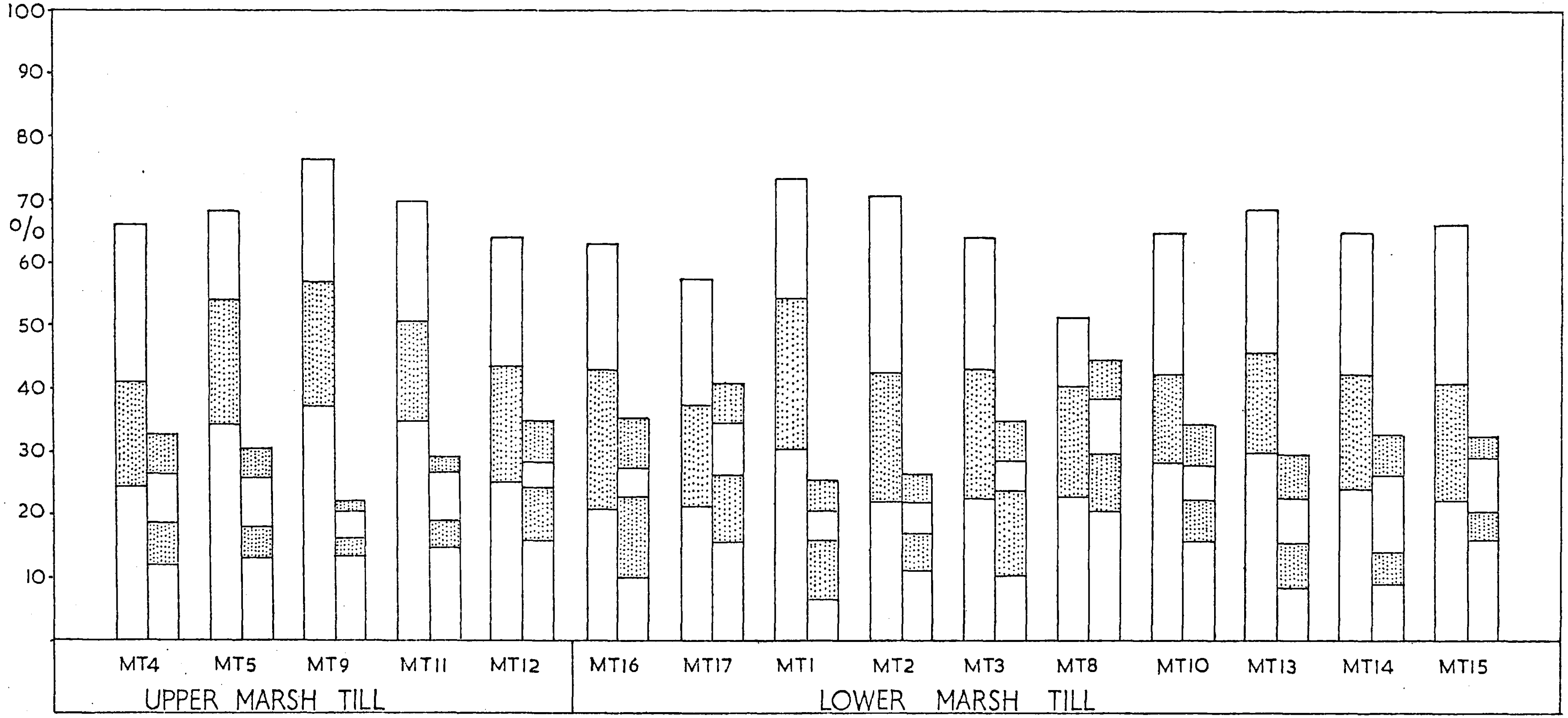


FIGURE 47 53 - 250μm FRACTION
"RESISTANT" NON-OPAQUE HEAVY MINERALS

KEY – AS FOR FIGURE 44

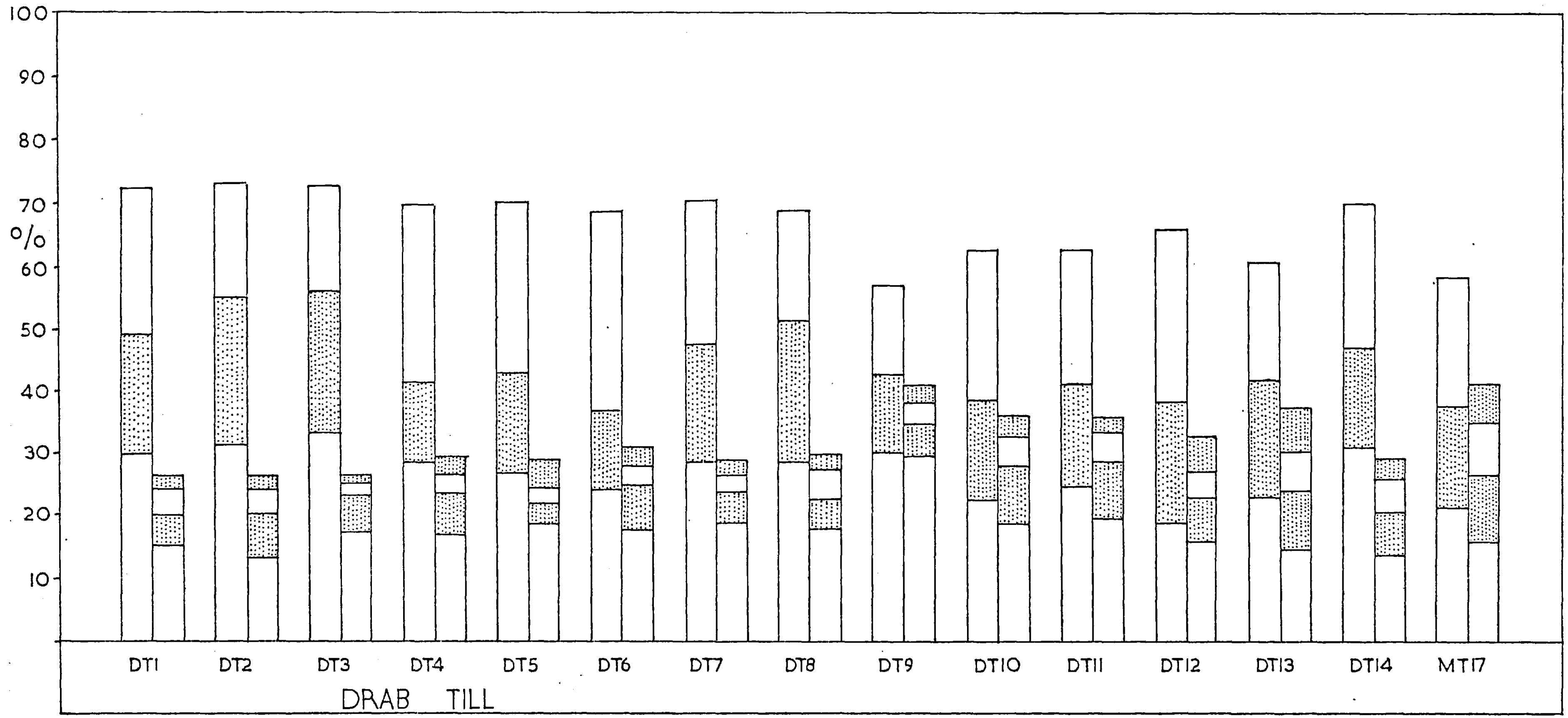


FIGURE 48 53-250μm FRACTION
"RESISTANT" NON-OPAQUE HEAVY MINERALS

KEY - AS FOR FIGURE 44

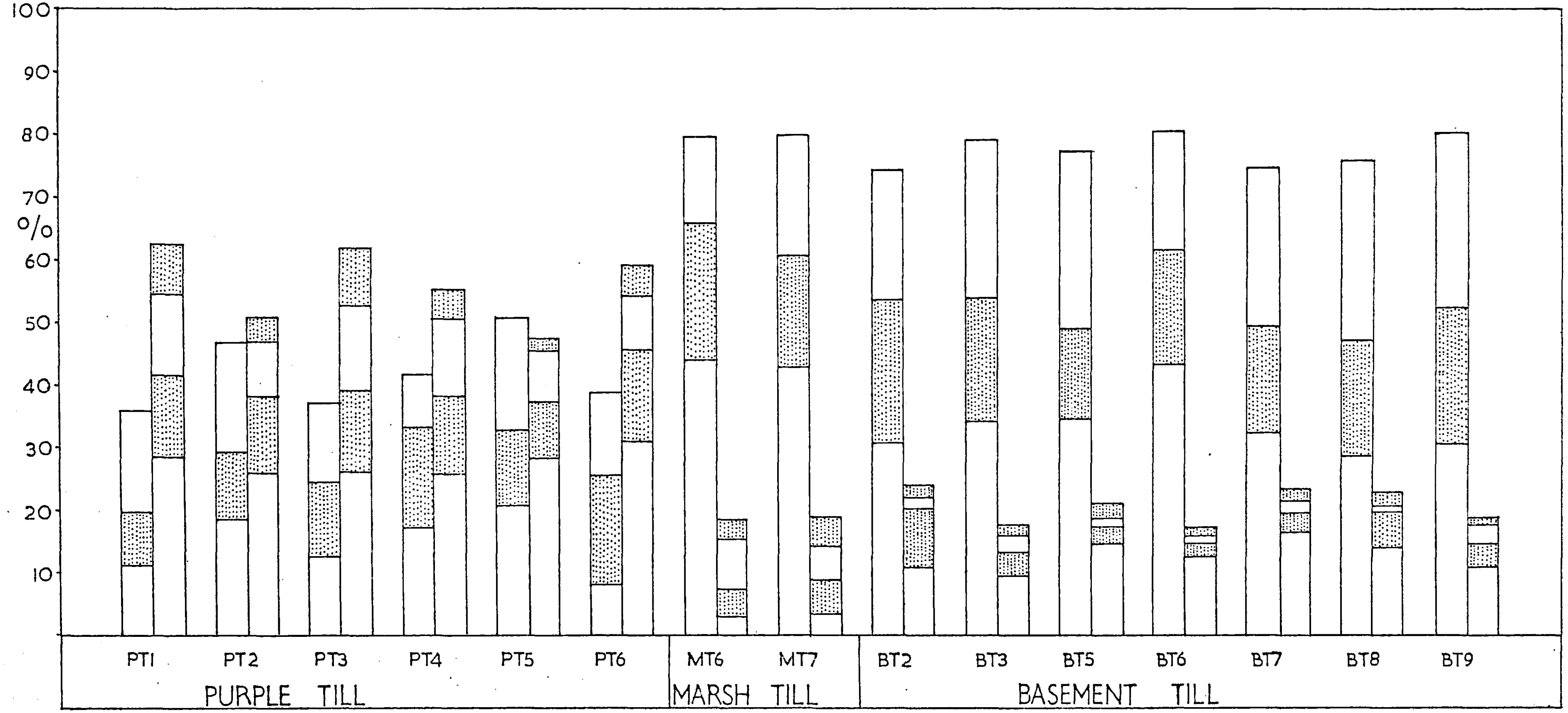


FIGURE 49 53-250μm FRACTION
"RESISTANT" NON-OPAQUE HEAVY MINERALS

KEY – AS FOR FIGURE 44

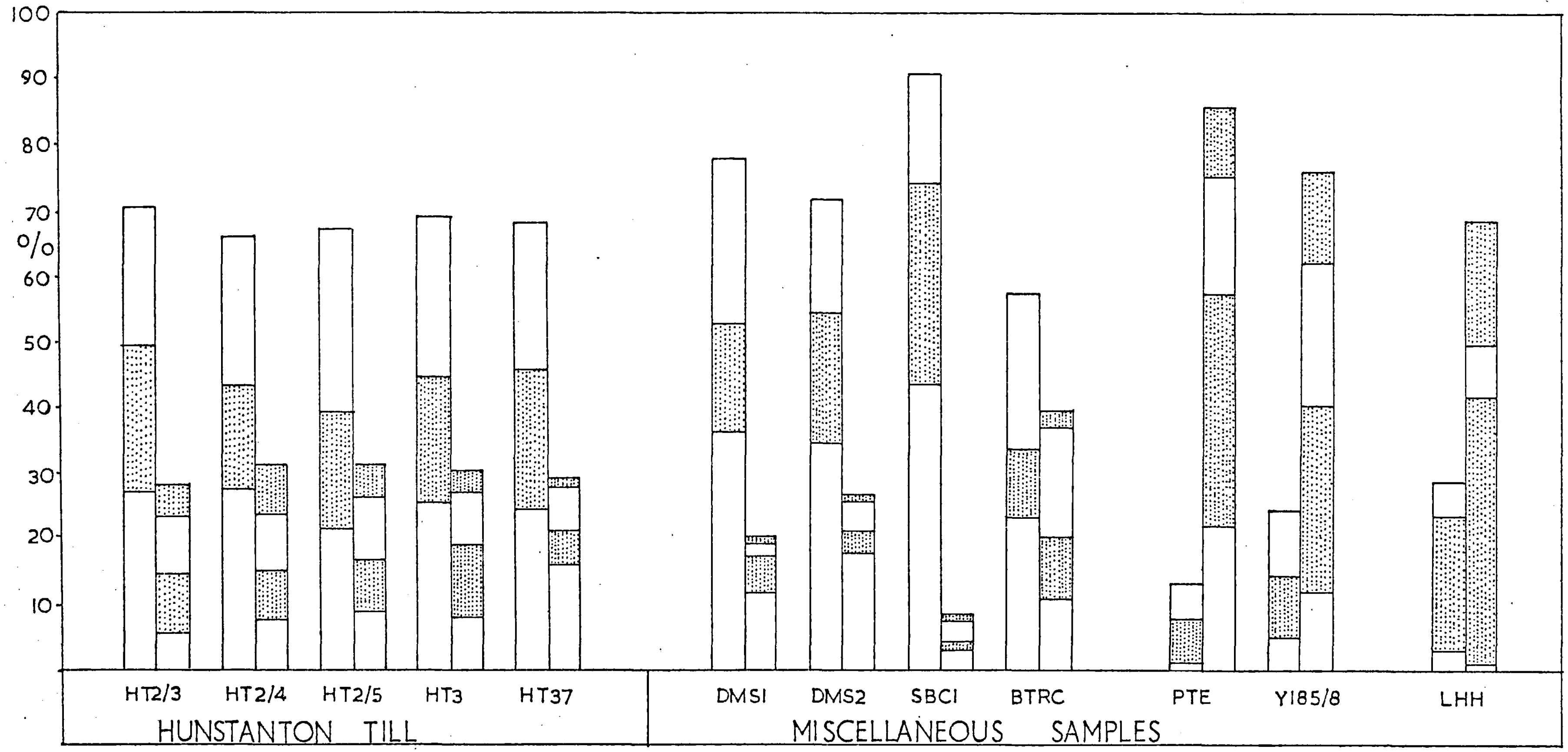


FIGURE 50 53–250μm FRACTION
"RESISTANT" NON-OPAQUE HEAVY MINERALS

KEY — AS FOR FIGURE 44

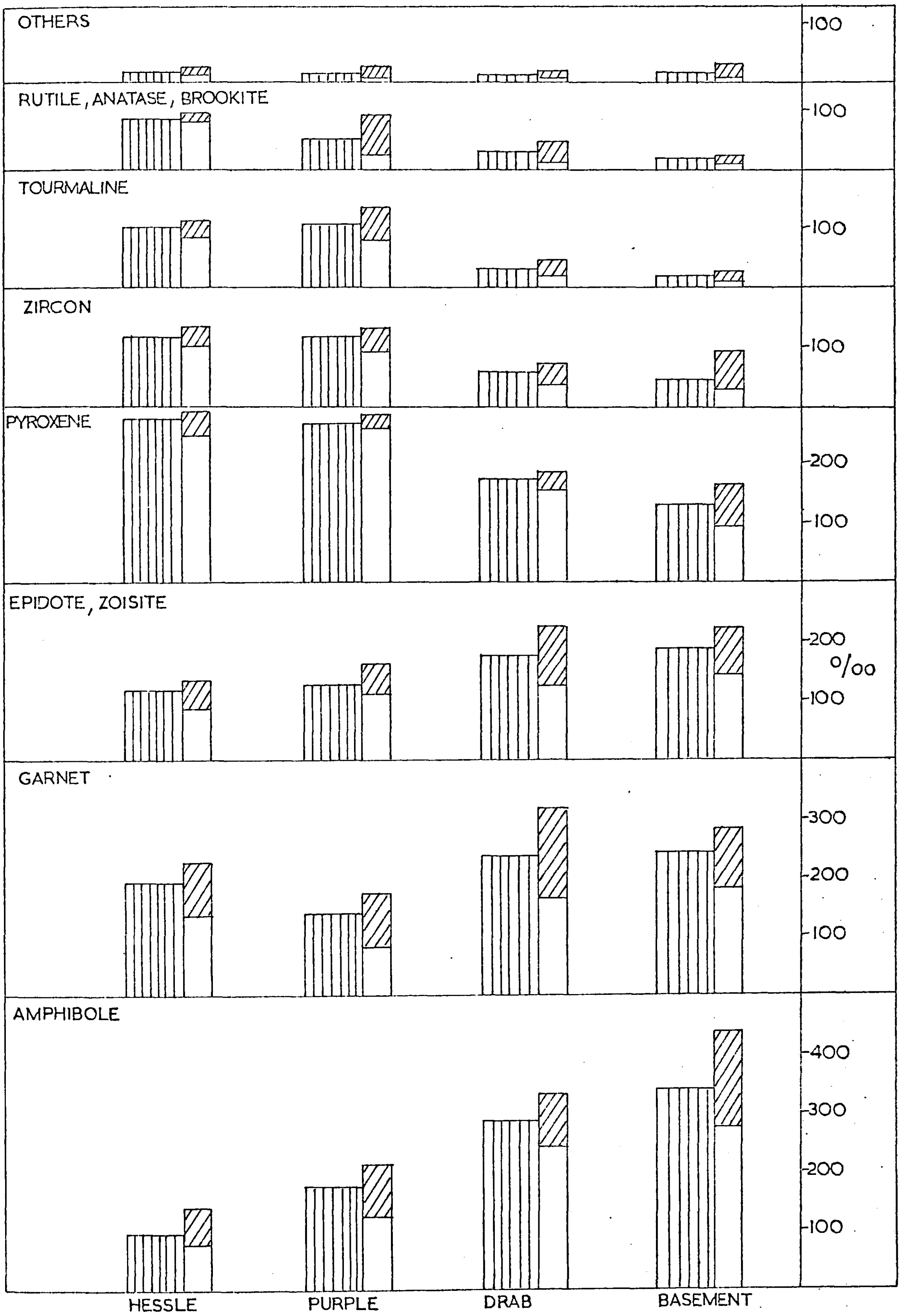


FIGURE 51 NON-OPAQUE "RESISTANT" HEAVY MINERALS

53-250µm FRACTION TILL SAMPLES FROM DIMLINGTON

VERTICAL SHADING : MEAN COMPOSITION
OBLIQUE SHADING : RANGE OF COMPOSITION

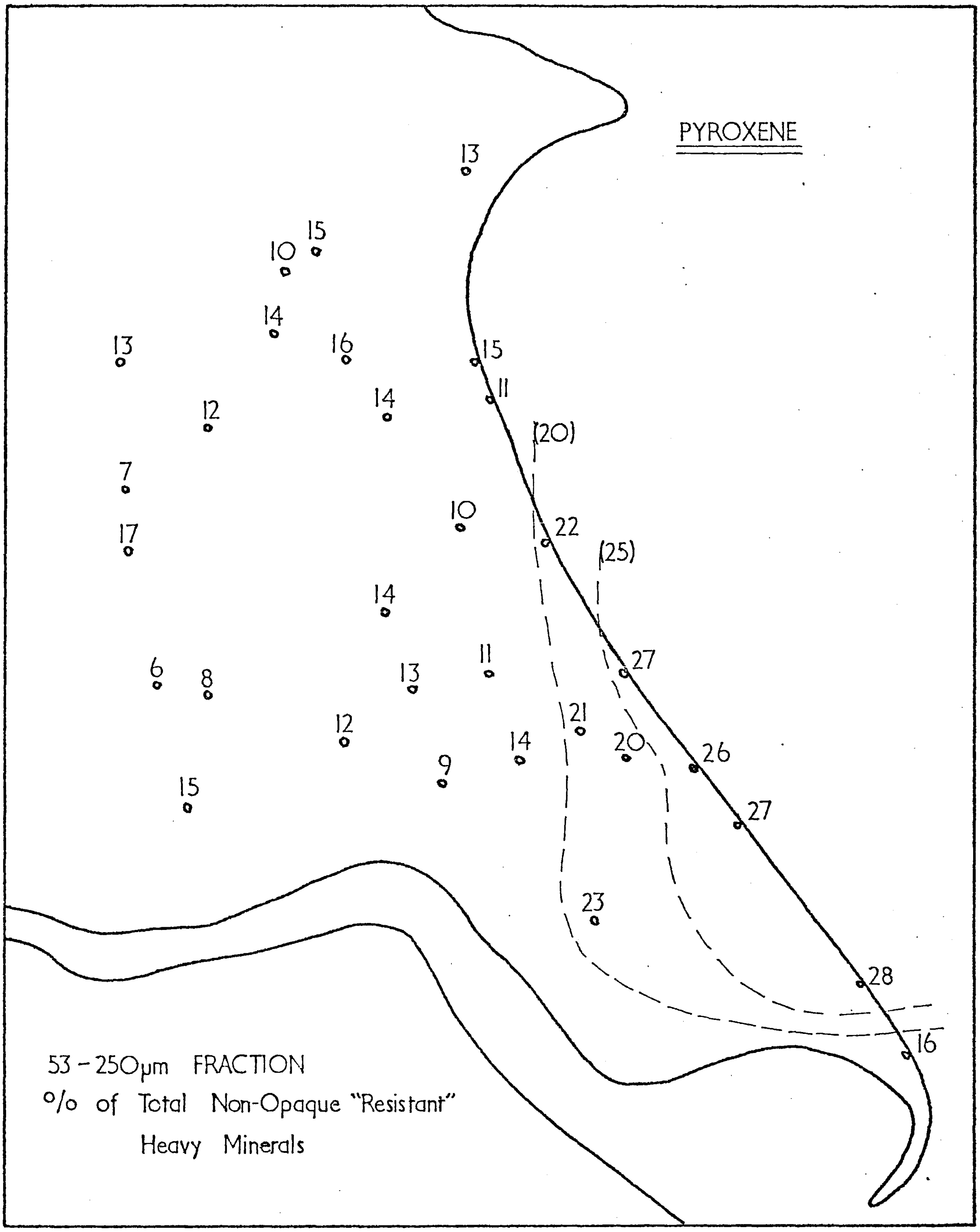


FIGURE 52 MINERALOGICAL VARIABILITY OF THE HESSLE TILL

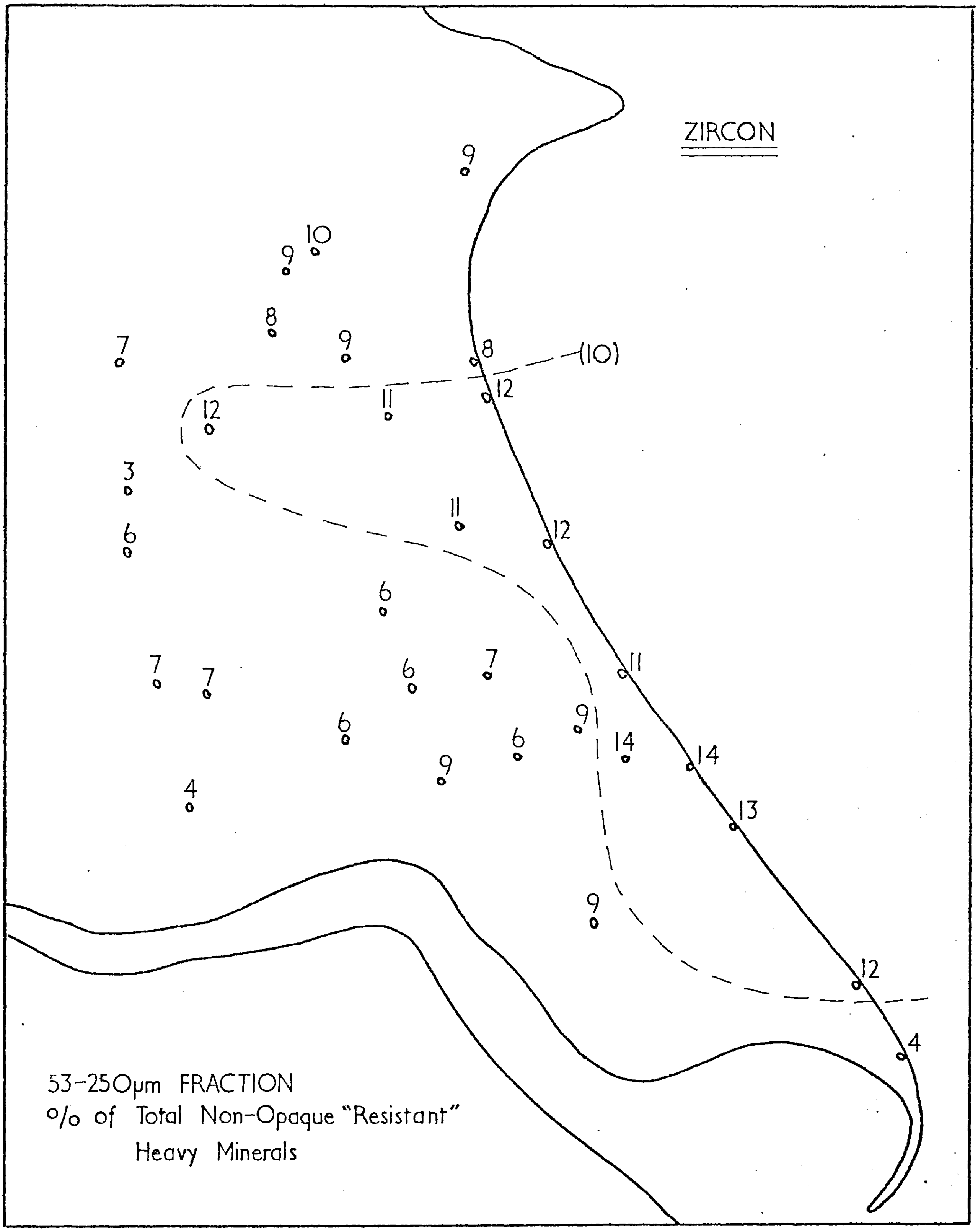


FIGURE 53 MINERALOGICAL VARIABILITY OF THE HESSLE TILL

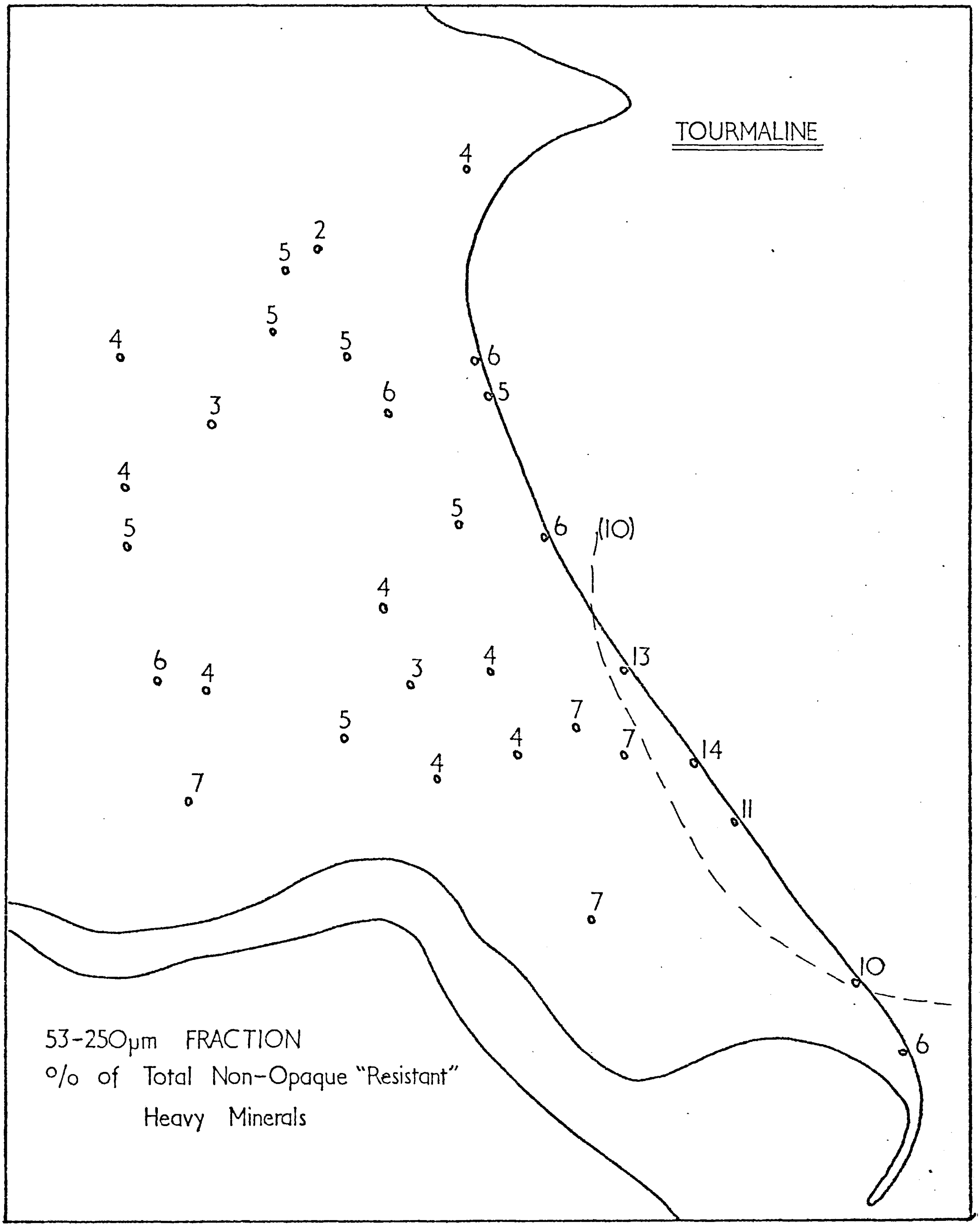


FIGURE 54 MINERALOGICAL VARIABILITY OF THE HESSLE TILL

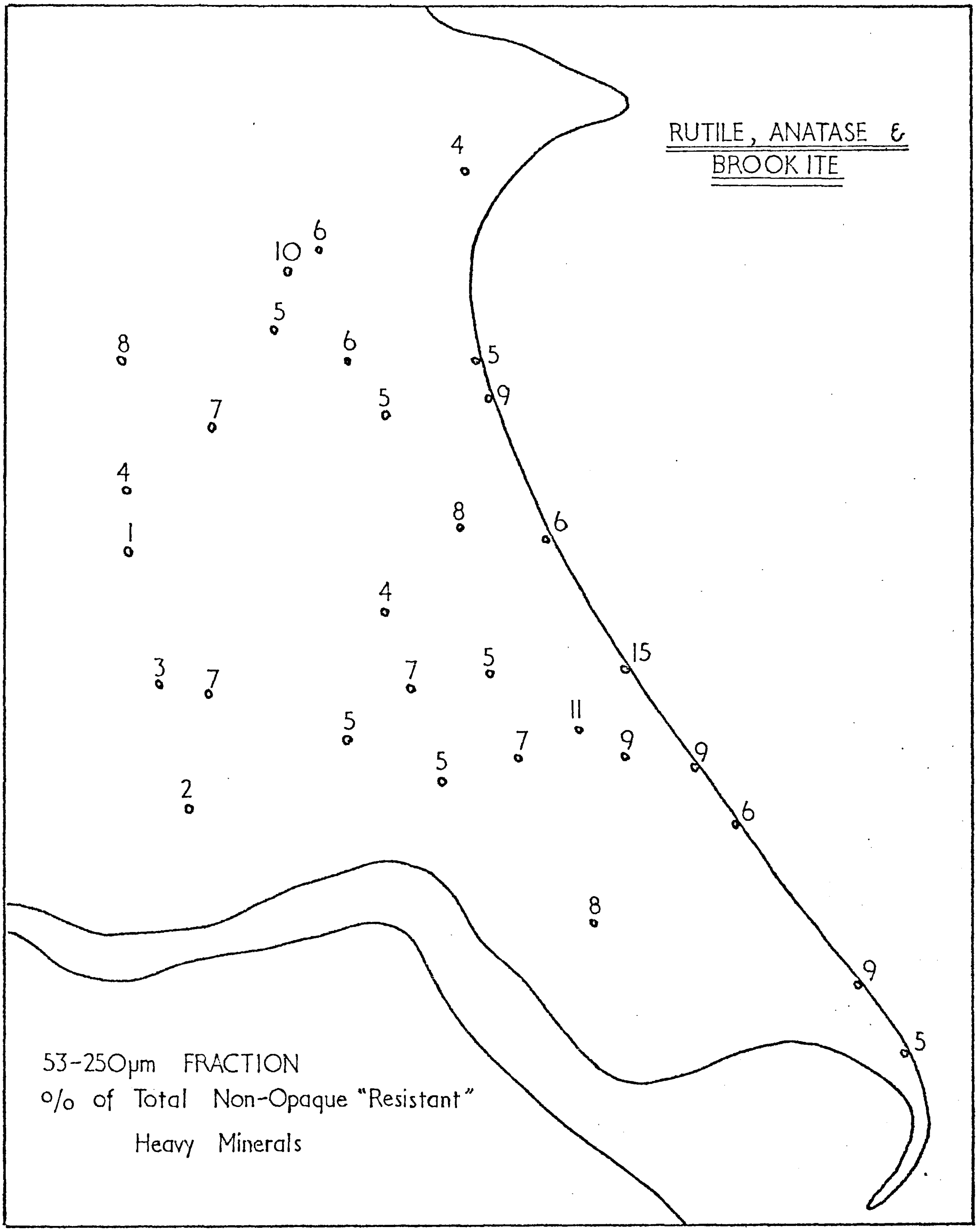


FIGURE 55 MINERALOGICAL VARIABILITY OF THE HESSLE TILL

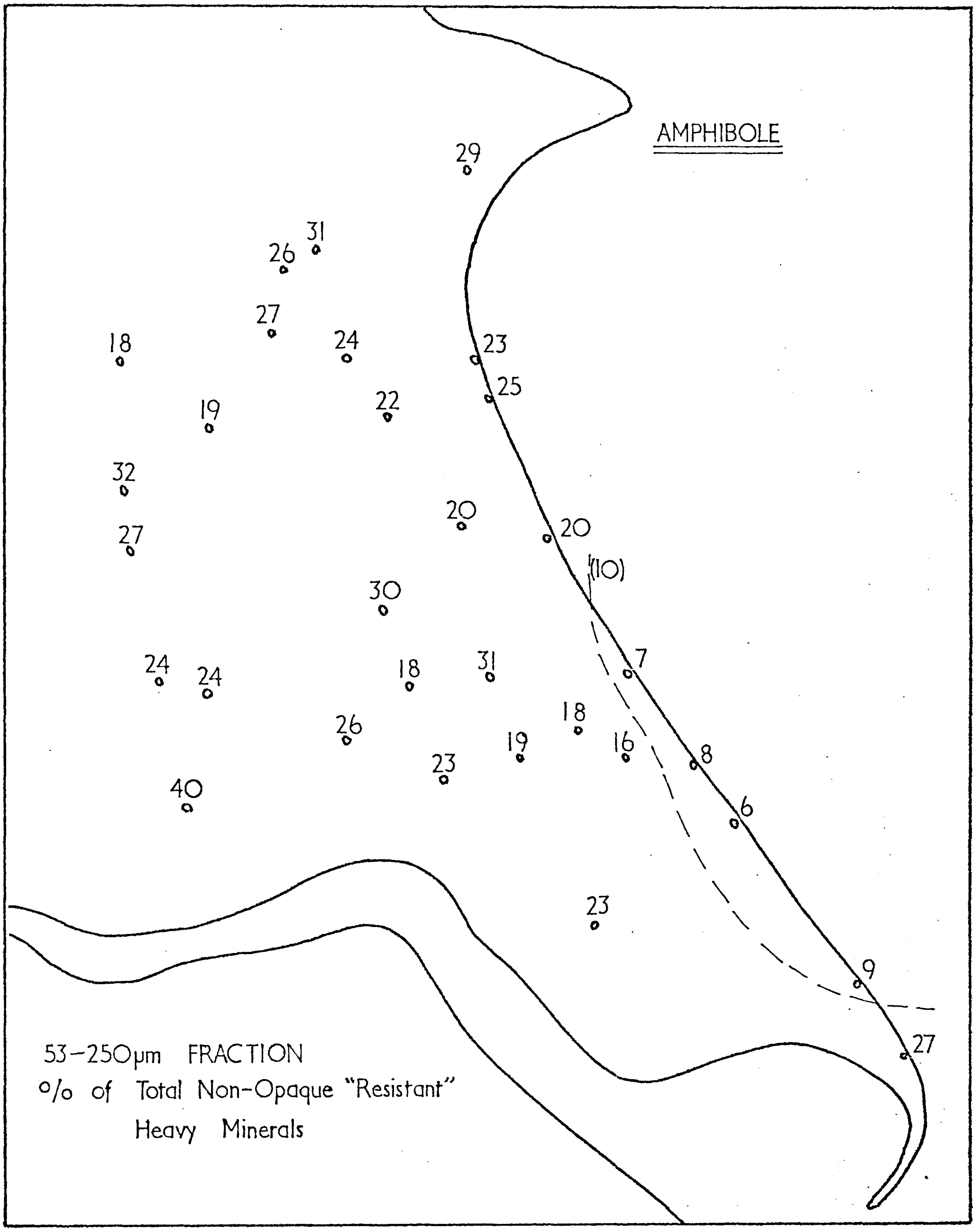


FIGURE 56 MINERALOGICAL VARIABILITY OF THE HESSLE TILL

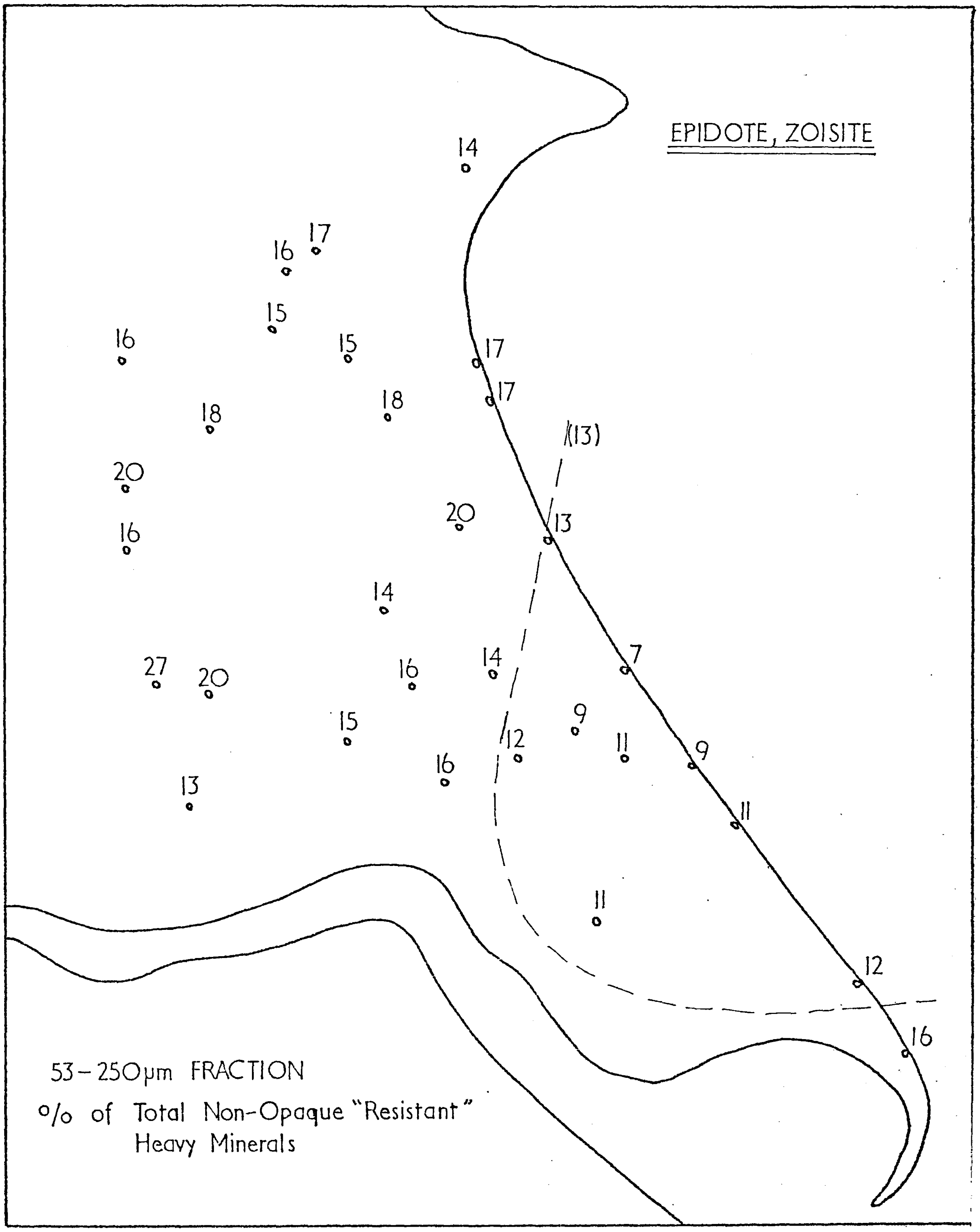


FIGURE 57 MINERALOGICAL VARIABILITY OF THE HESSLE TILL

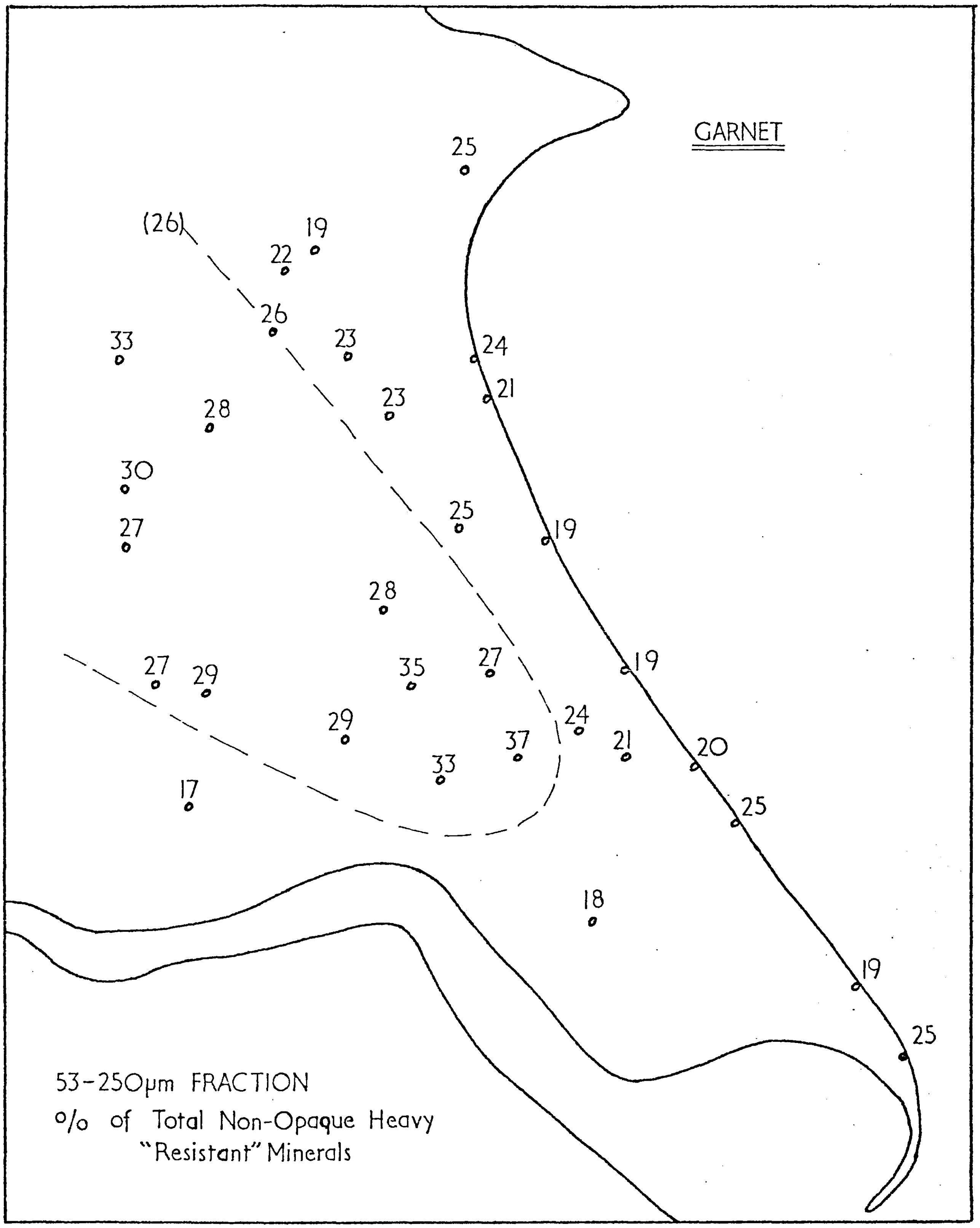


FIGURE 58 MINERALOGICAL VARIABILITY OF THE HESSLE TILL

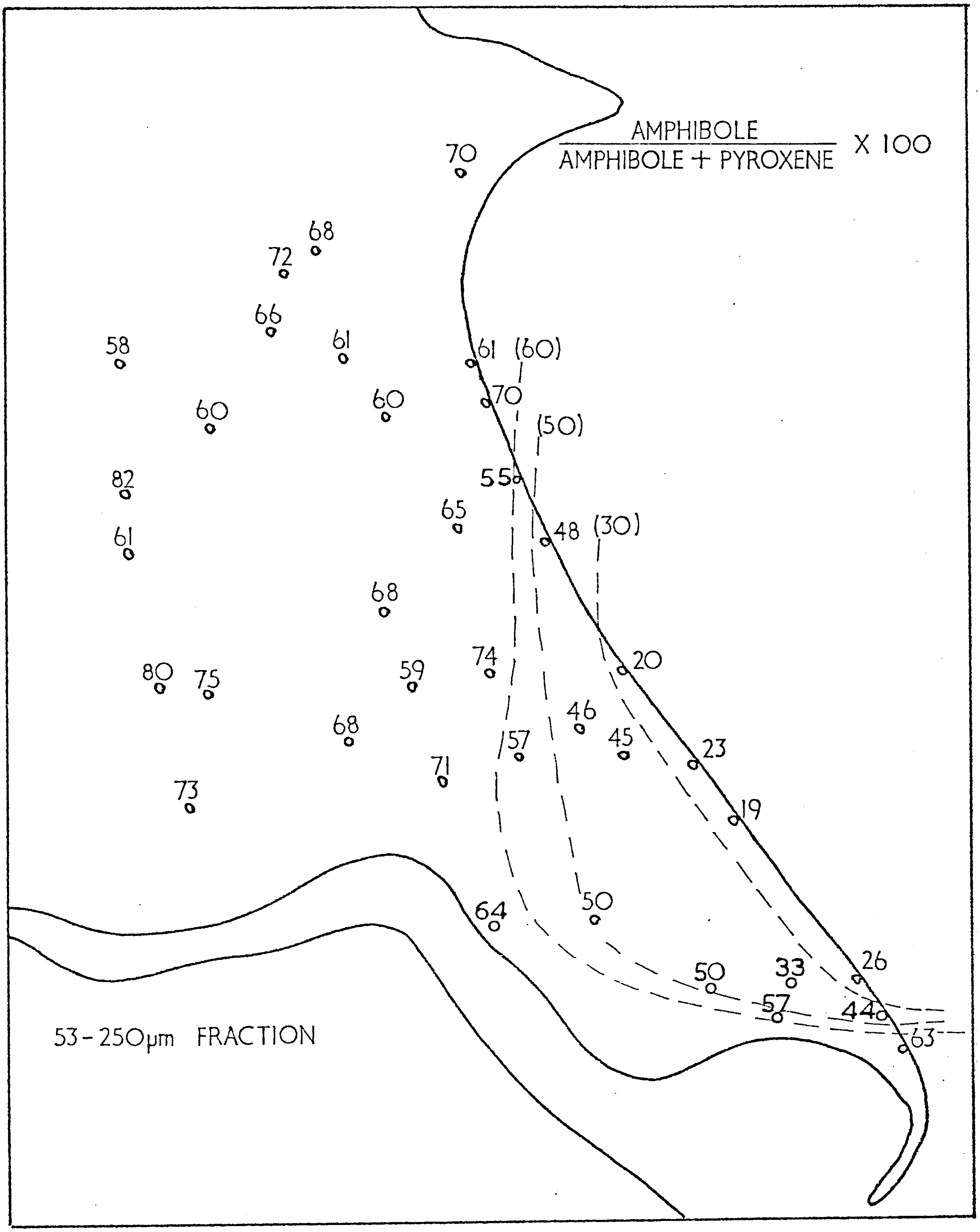


FIGURE 59 MINERALOGICAL VARIABILITY OF THE HESSLE TILL

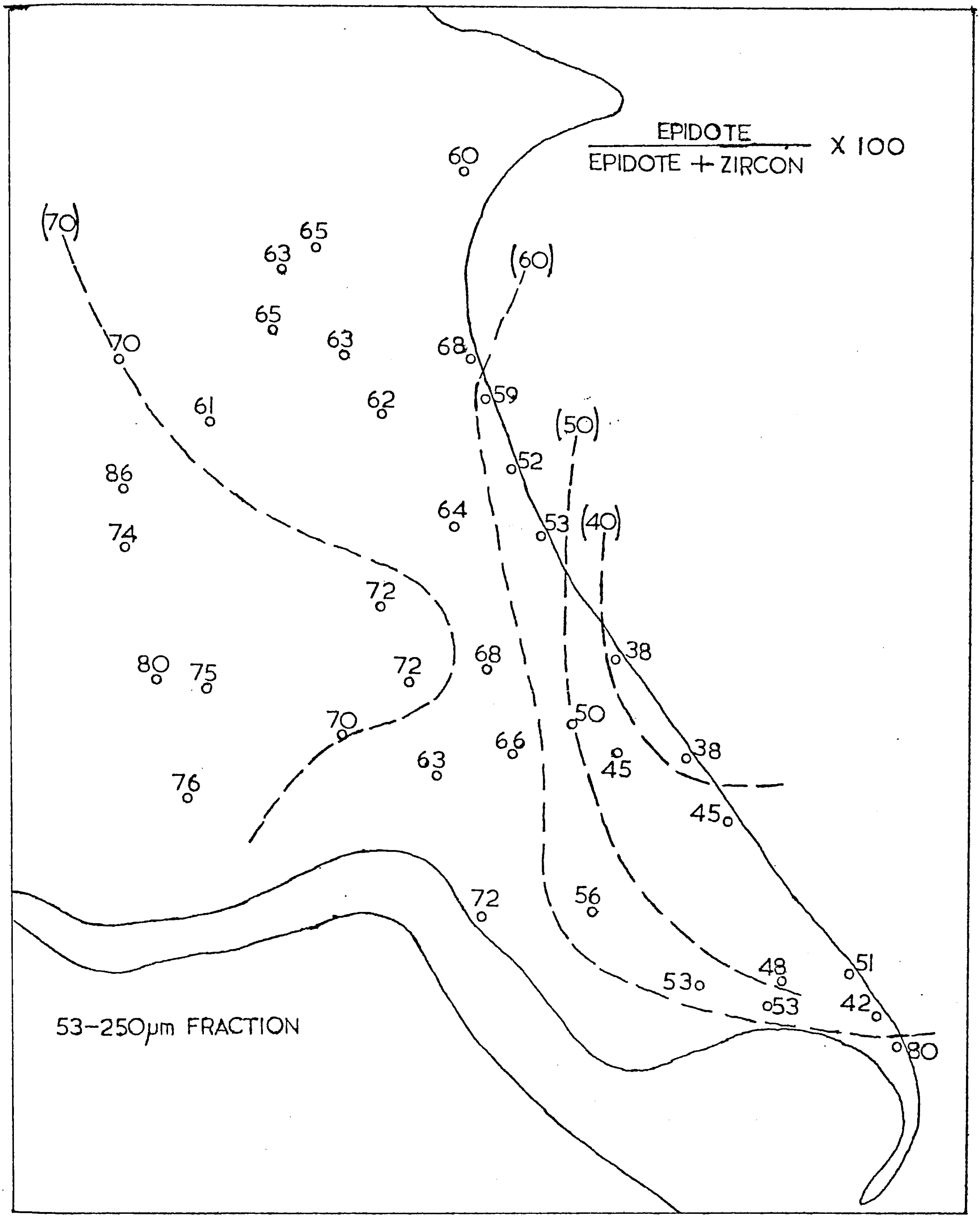


FIGURE 60 MINERALOGICAL VARIABILITY OF THE HESSLE TILL

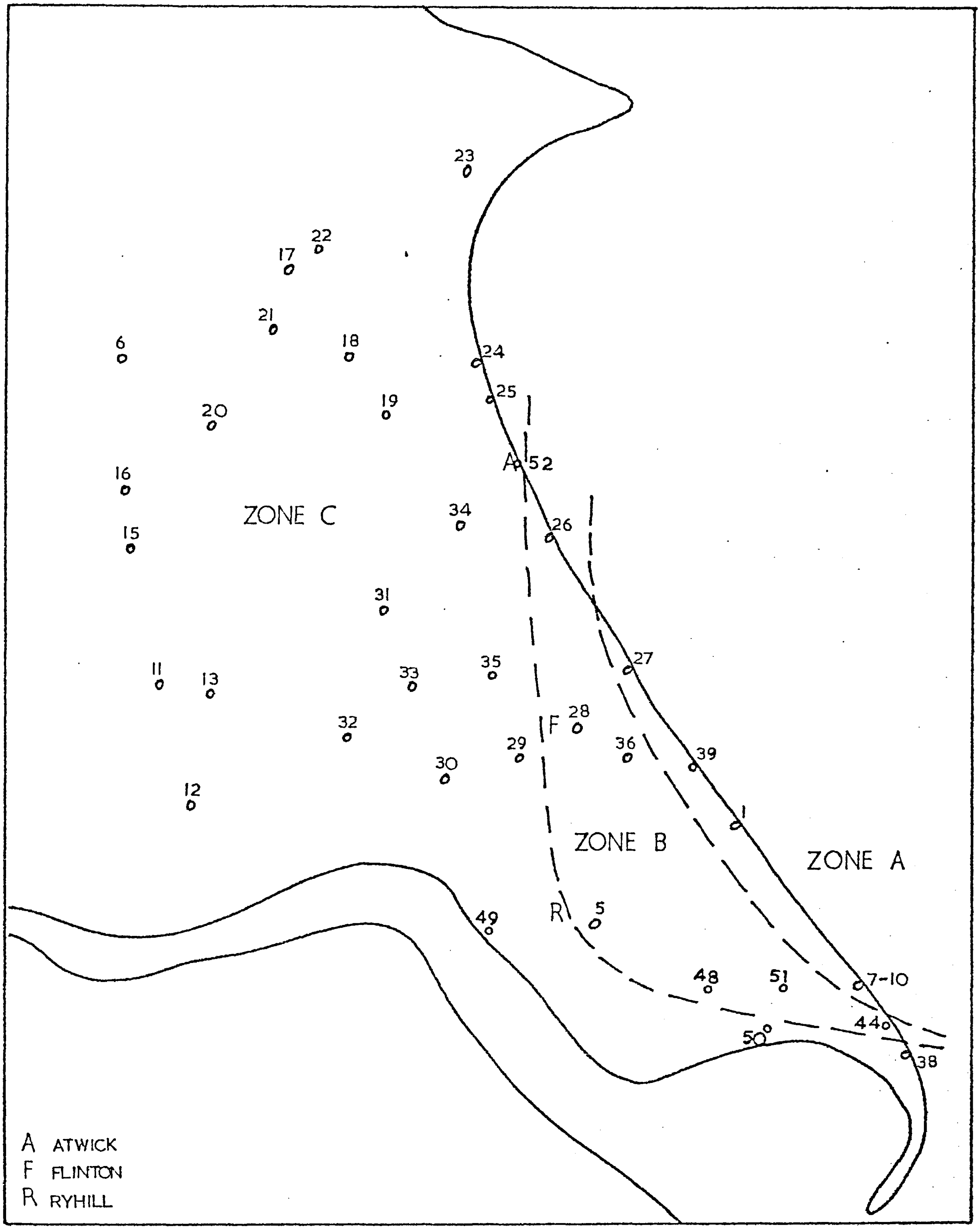


FIGURE 61 GEOGRAPHICAL ZONATION OF HESSLE TILL SAMPLES BASED ON TEXTURAL AND MINERALOGICAL VARIATIONS

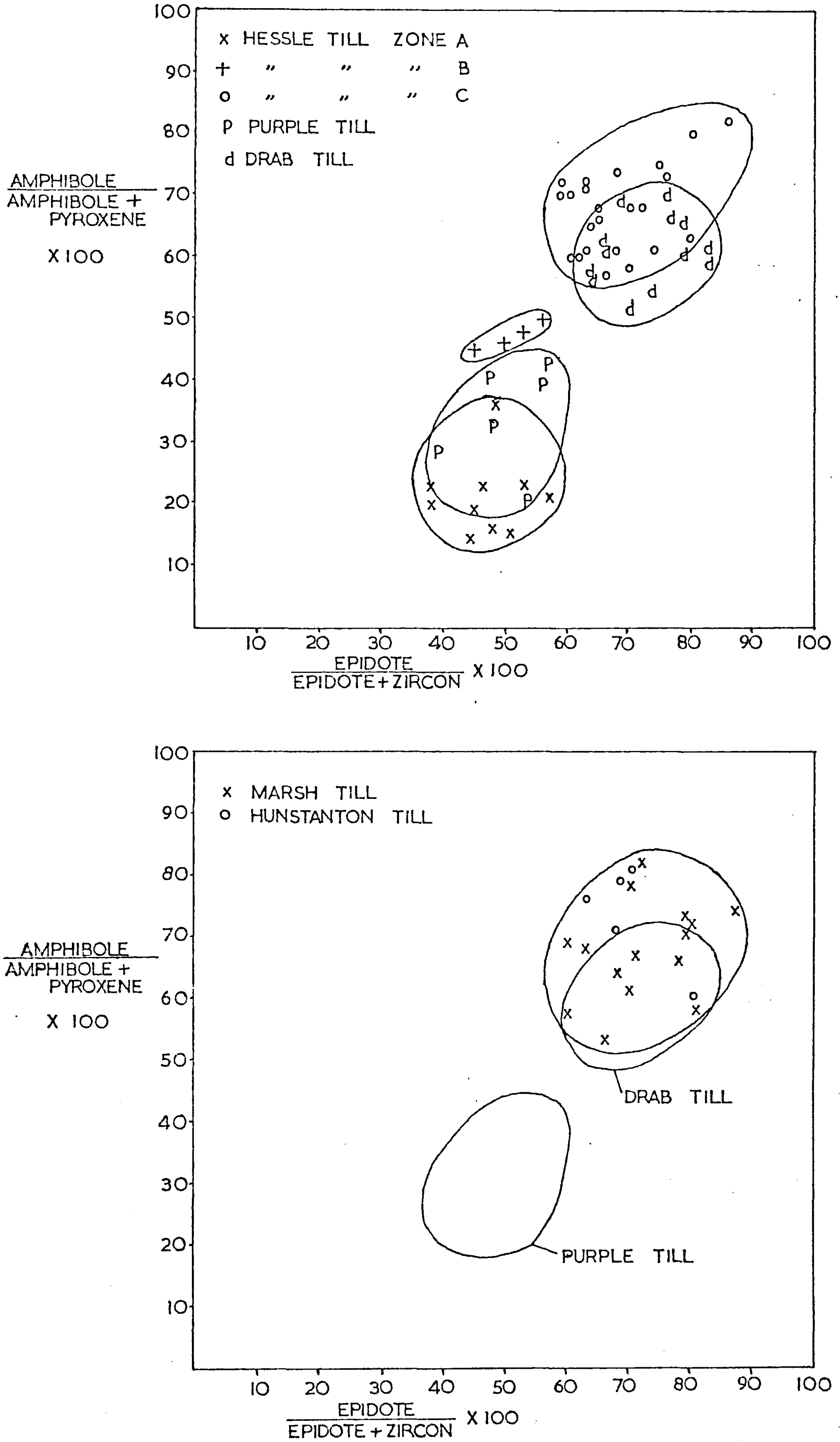
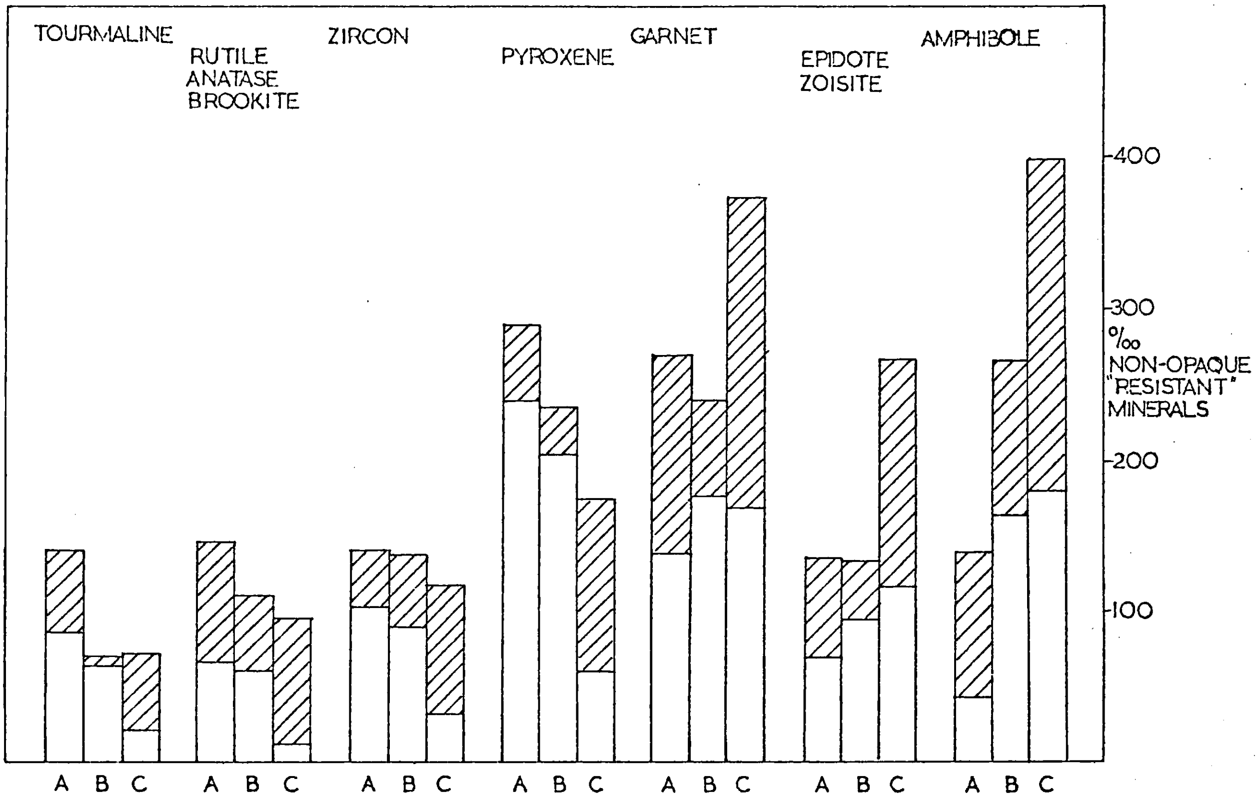


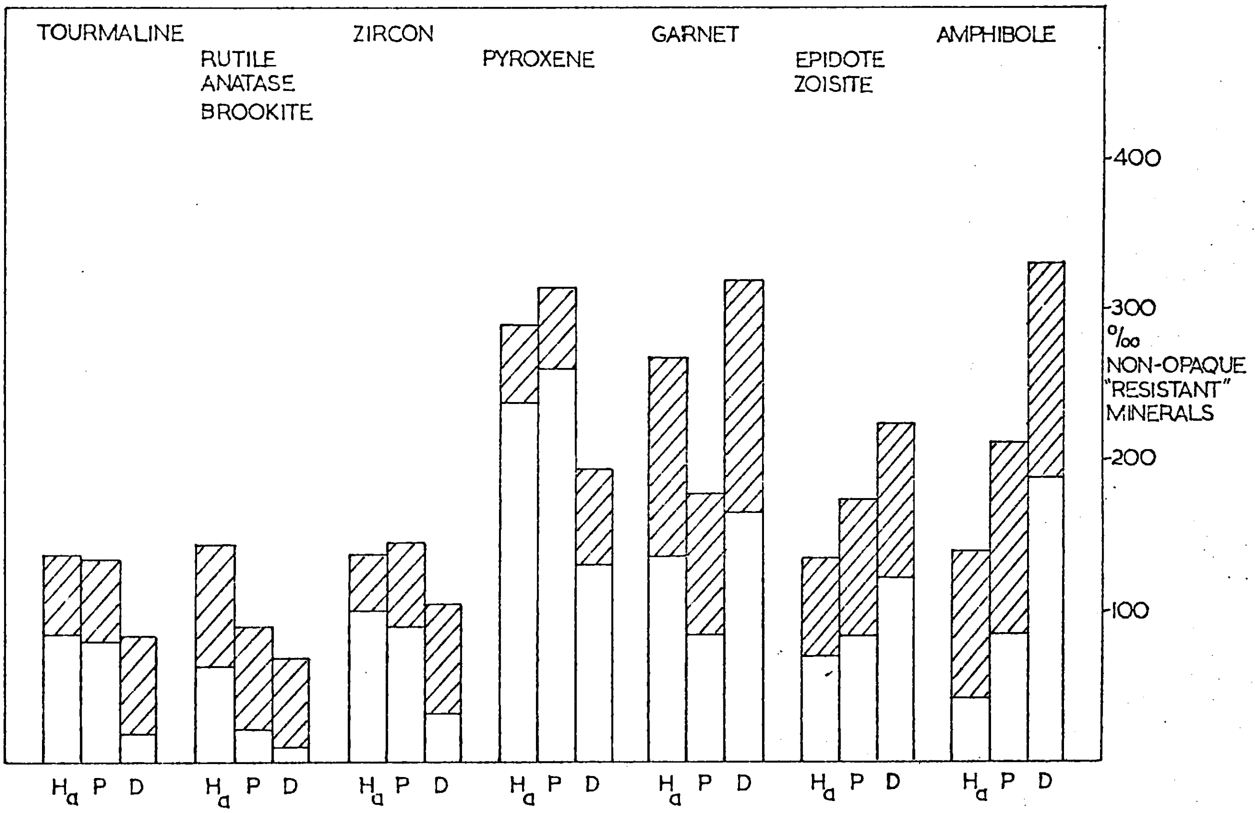
FIGURE 62 53–250μm FRACTION

RELATIONSHIPS BETWEEN TILLS SHOWN BY MINERAL RATIOS



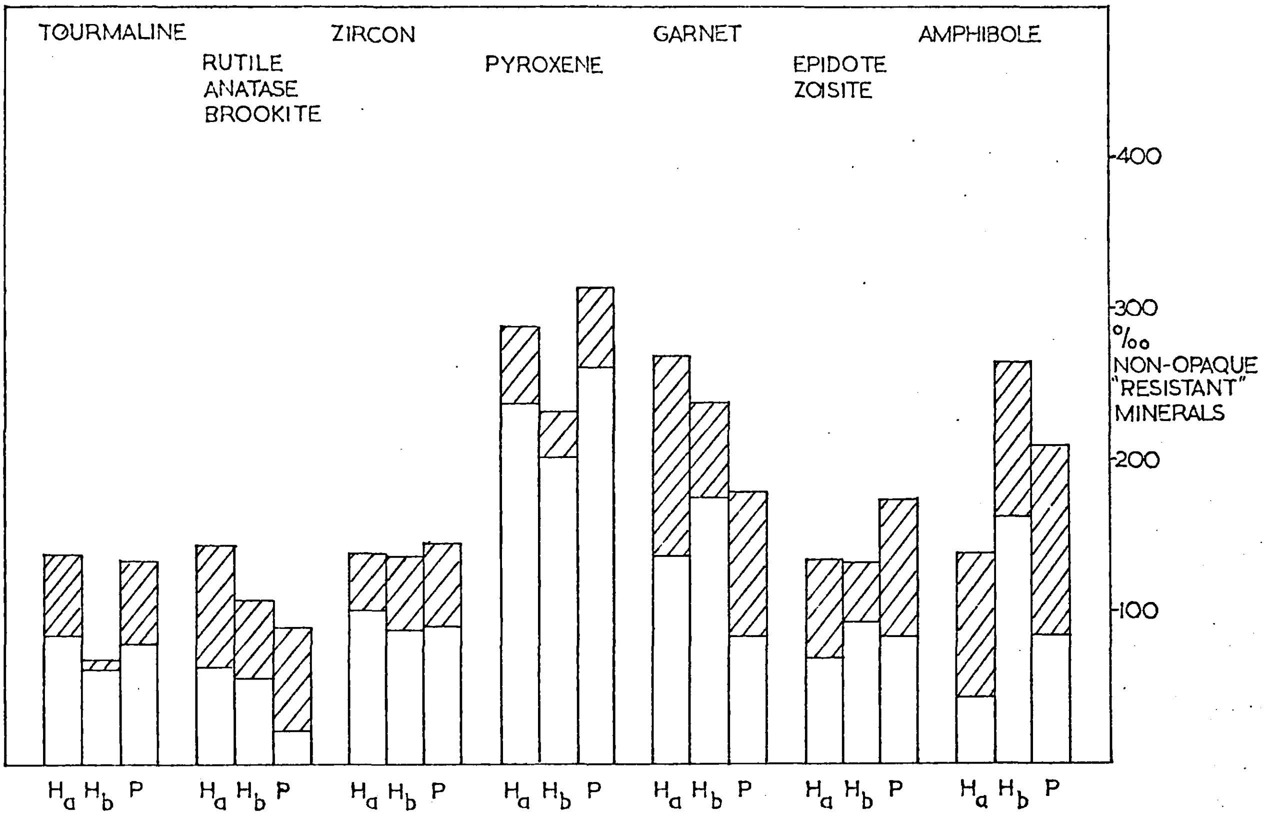
HESSLE TILL : ZONES A,B & C

COMPOSITIONAL RANGES SHADED



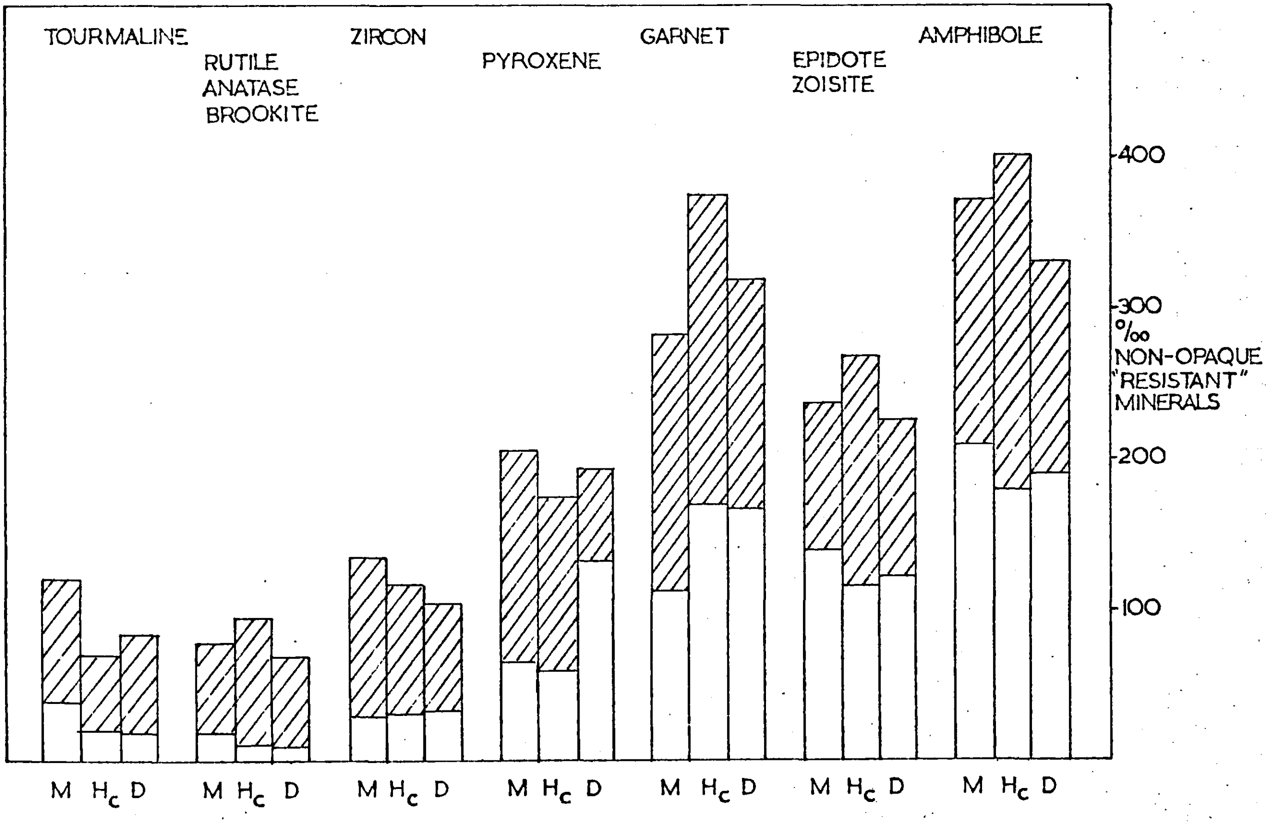
HESSLE (ZONE A), PURPLE, & DRAB TILLS

FIGURE 63 53 250µm FRACTION : HEAVY MINERALS
HORIZONTAL & VERTICAL RELATIONSHIPS IN HOLDERNESS



RELATIONSHIP OF HESSLE TILL (ZONES A & B) TO PURPLE TILL

COMPOSITIONAL RANGES SHADED



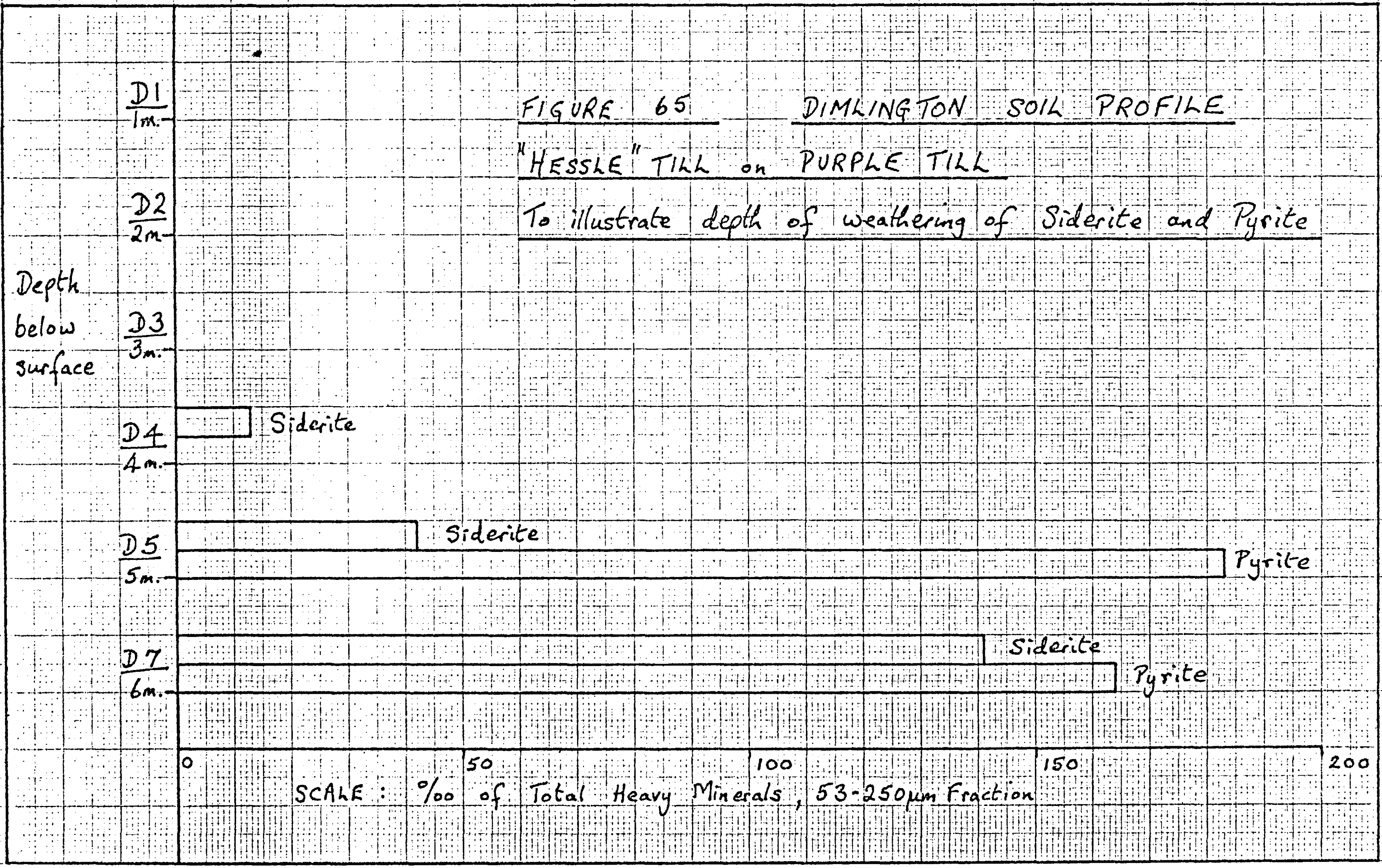
RELATIONSHIP OF MARSH TILLS & HESSLE TILL (ZONE C) TO DRAB TILL

FIGURE 64 53-250µm FRACTION : HEAVY MINERALS

FIGURE 65 DIMLINGTON SOIL PROFILE

"HESSLE" TILL on PURPLE TILL

To illustrate depth of weathering of Siderite and Pyrite



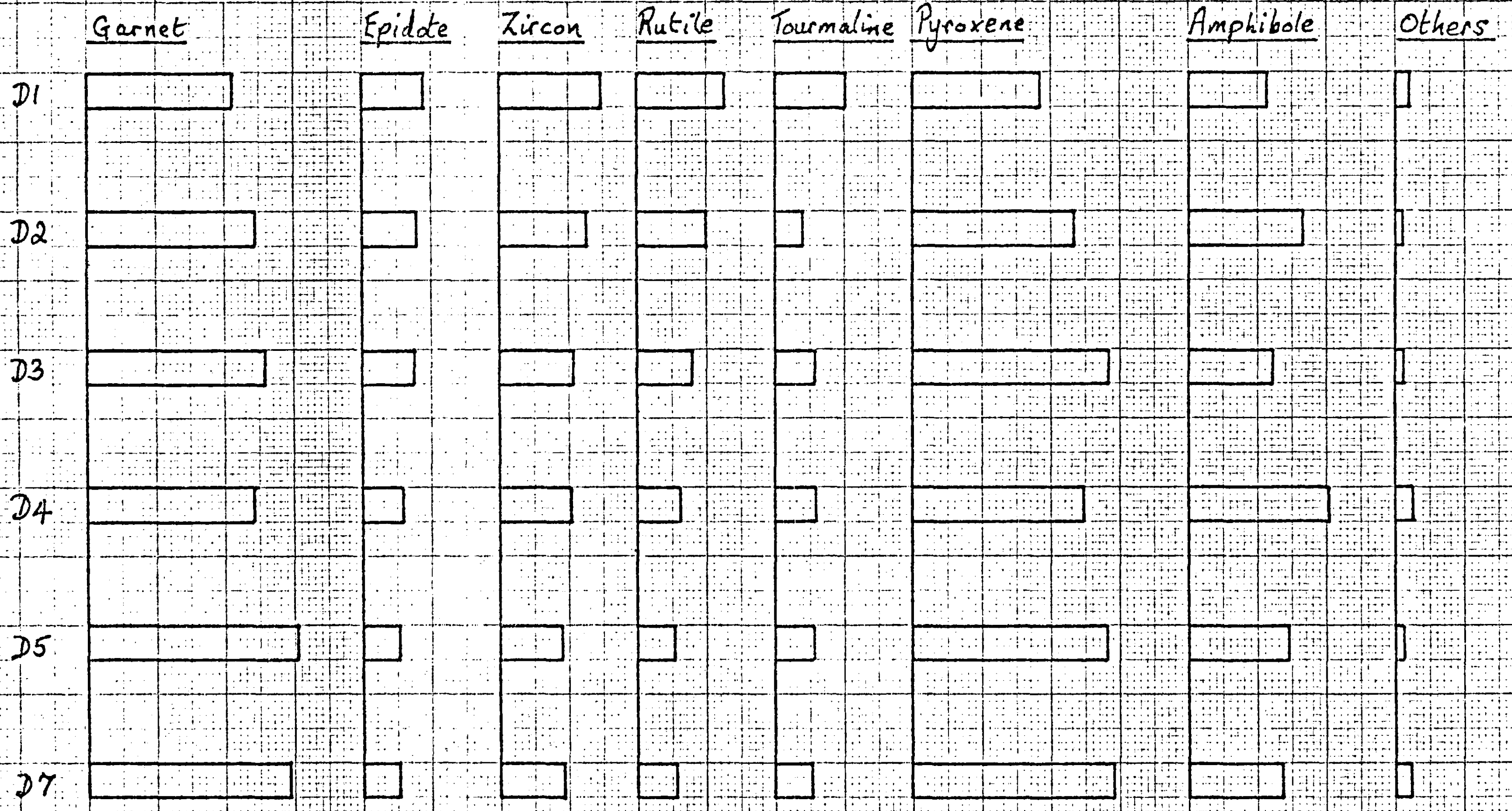


FIGURE 66 DIMLINGTON SOIL PROFILE, "HESSLE" TILL on PURPLE TILL

53-250µm FRACTION

"Resistant" Non-Opaque Heavy Minerals

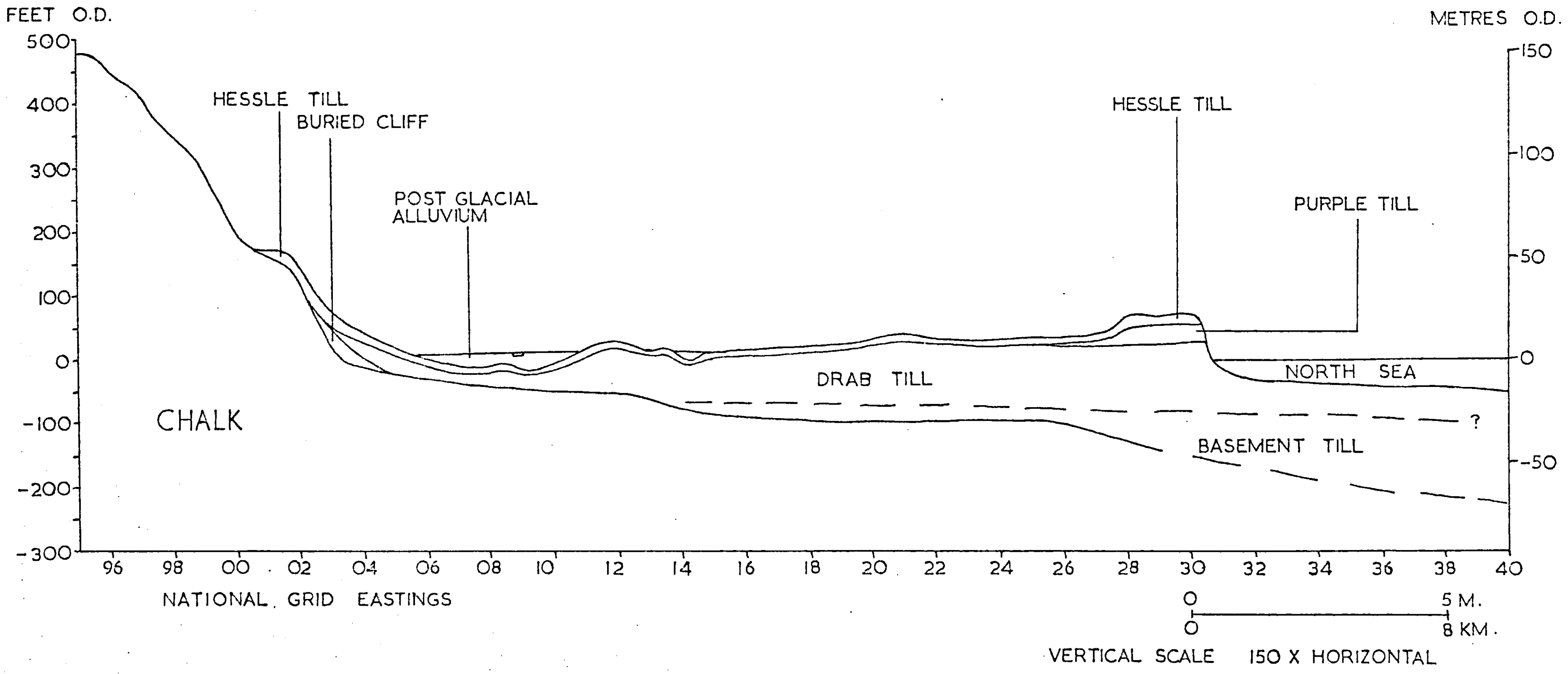


FIGURE 67 SECTION EAST WEST Across HOLDERNESS along National Grid Northing TA 330
STRATIGRAPHY OF CATT & PENNY (1966)

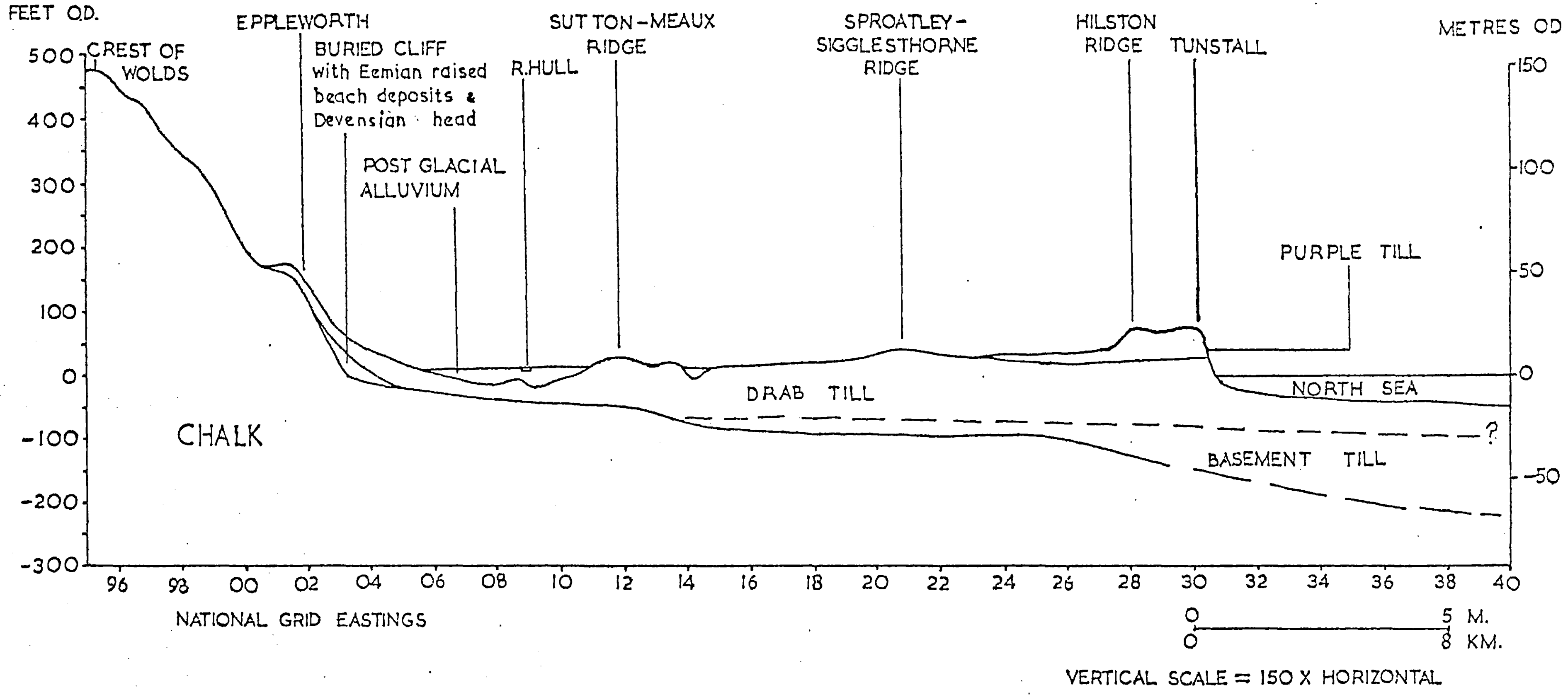


FIGURE 68 SECTION EAST-WEST Across HOLDERNESS along National Grid Northing TA 330
REVISED STRATIGRAPHY

CHAPTER 6 DISCUSSION OF RESULTS: SOIL GENESIS STUDY

6.1 Introduction

Chapters 1 and 3 gave the reasons for studying soils developed on the Devensian tills of eastern England, and the investigations reported in Chapter 5 indicate that these tills are petrographically fairly uniform, although small textural and mineralogical differences occur between the tills recognised in the Devensian succession of south-eastern Holderness. Most of the till samples analysed are in the clay loam textural class; very few contain more than 40 % or less than 25 % clay, and the average clay content of 58 calcareous samples was 30.7 %. As clay is pedologically the most important size fraction of soils, being relatively mobile and susceptible to alteration, the Tunstall profile, which contains 30.4 % clay in horizon 6 (the presumed parent material), can be regarded as a representative profile, at least in the textural sense, for soil development on the Devensian tills of eastern England.

Mineralogically, however, the Tunstall profile is strictly representative only of soils on the Purple Till of south-eastern Holderness, which contains more chlorite, chamosite, biotite, apatite and augite in fine sand and coarse silt fractions than does the Devensian parent material of soils in other parts of eastern Yorkshire, east Lincolnshire and north Norfolk (the Drab Till). Also, the clay fraction of HT 1/6, parent material of the Tunstall profile, contains more mica than most other clay fractions analysed. However, these differences are an advantage in a weathering study, because the minerals that are more abundant in the Tunstall than in other profiles are those which would be expected to weather more readily, so that weathering changes should be more easily detected.

The following discussion concerns mainly the results for the Tunstall profile, and all details refer to this unless otherwise stated. The profile developed in the Hunstanton (= Drab) Till at Holkham, Norfolk, is discussed where appropriate, to enable comparisons to be drawn with the widespread soils developed on the less micaceous Drab Till.

6.2 Field Characteristics

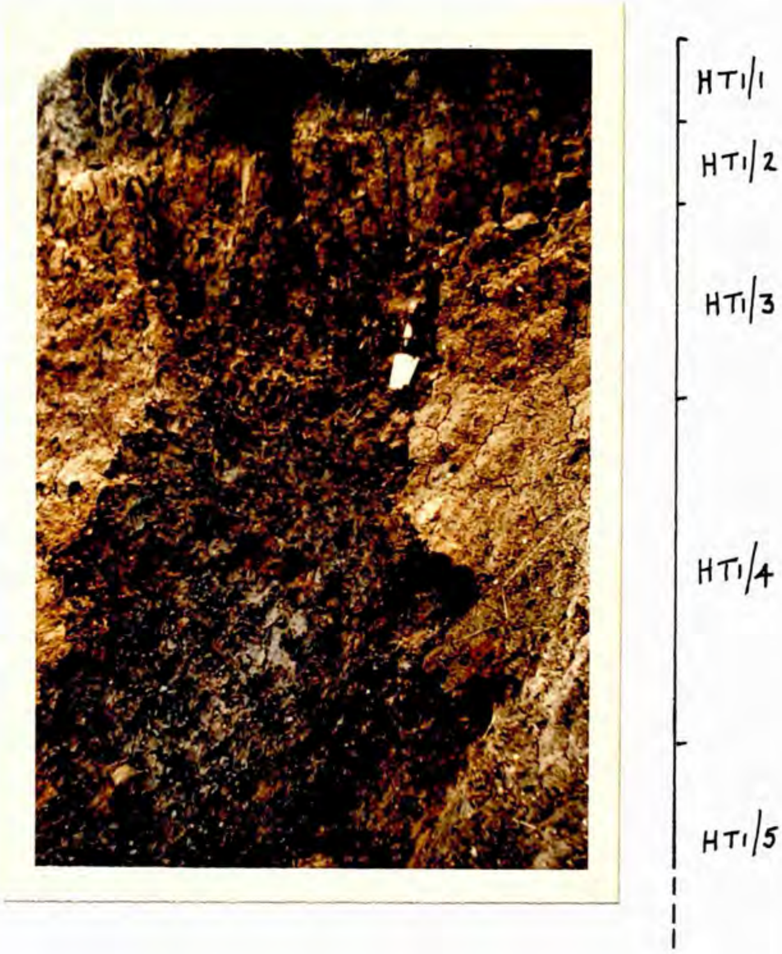
Soil characteristics readily observable in the field include structure, colour and gleying phenomena, and depth of decalcification. Details of these are given in the full profile descriptions (Tables 22, 61), and the main features of the Tunstall profile are shown in Fig. 69.

6.2.1 Structure

A coarse prismatic structure is typical of the upper 1-3 m of profiles on the Devensian tills throughout eastern England, and has been regarded by some authors (e.g. Suggate and West, 1959) as characteristic of the "Hessle" Till. In the Tunstall profile the prismatic structure is best developed in horizons 2 and 3 (20-71 cm), which are decalcified; the reduction in volume on decalcification may account partly for this. However, when a large pit, 2 m deep, was dug for demonstration purposes in the cliff top at Dimlington, the prismatic structure below 20 cm was much less evident in the moist state than after the soil had dried out for 2-3 days; as horizons 2 and 3 are usually drier than deeper layers, their well developed structure may thus reflect only relative moisture contents.

Robinson (1949) suggested that prismatic structures result from shrinkage consequent upon drying of originally dispersed clays, and that the structural units (peds) persist through recurrent cycles of wetting and drying. If this is so, the prismatic structure of these profiles was

FIGURE 69



TUNSTALL SOIL PROFILE ON "HESSLE" (PURPLE) TILL

HT1/1	Top - Soil	
HT1/2	Prominent prismatic peds	
HT1/3	Decalcified; gleyed; maximum clay accumulation	
HT1/4	Horizon of secondary carbonate accumulation; gleyed	
HT1/5	Gleyed; oxidised; otherwise unaltered till	
HT1/6	Oxidised; otherwise unaltered till	not shown
PT1	Unaltered parent material : Purple Till	

probably the first pedological feature to develope after deposition of the tills and retreat of the ice.

6.2.2 Soil Colour

The dark reddish brown colours (5YR 3/4) shown by the lower horizons of the Tunstall profile are probably inherited from the parent material. In Chapter 5 it was concluded that the "Hessle" Till of south-east Holderness was, in its original unoxidised state, similar to the underlying Purple Till, which has a dark brown colour (7.5YR 3/2) when moist, probably due to incorporation of much Triassic material (Catt and Penny, 1966). Similar reasons have been given for the reddish brown colours of till soils in the Vale of York (Crompton and Matthews, 1969) and the West Midlands (Mackney and Burnham, 1964), though details of these profiles were given only to 1 - 1.5 m depth, which by comparison with the Holderness profiles, is probably well within the zone of oxidation and colour change.

At Tunstall the change from the dark brown colour of the Purple Till to the dark reddish brown of the "Hessle" probably results from oxidation, in particular of pyrites and siderite in the silt and sand fractions. In other parts of Holderness, the oxidation of the Drab Till gives a more distinct colour change from very dark greyish brown (10YR 3/2) to reddish brown (5YR 4/4) or less frequently to brown (7.5YR 4/4). From the evidence presented in Chapter 5, it is thought that the reddish brown colour of the Marsh Tills in Lincolnshire and the Hunstanton Till in Norfolk also results from oxidation of a till that was originally very dark greyish brown (10YR 3/2), though till of this colour was seen at depth only at South Ferriby and South Elkington.

The change of hue apparent in the two uppermost horizons of the Tunstall profile (HT 1/1 and 1/2) may result from the partial leaching of free iron oxides (see Table 43), though humus probably contributes to the dark colour of the surface horizon. Horizon 2 has distinct mottles, mainly strong brown (7.5YR 5/8) in colour; segregations of iron oxide are probably responsible for these, as iron oxide cemented concretions occur in the coarse sand and stone fractions of this horizon (Table 31). Mottles with low chromas, which are regarded as indicative of gleying, do not occur until horizon 3, where faint fine olive grey (5Y 5/2) mottles are common within peds, and dark grey (5Y 4/1) and neutral grey (N 4/1) patches occur on some ped faces. These pale mottles persist through horizon 4, and are present to a lesser extent in horizon 5, but are absent below.

Grey (5GY 5/1) ped faces become prominent in horizon 4, and persist through horizon 5, but below this are restricted to a few fissures, some of which extend however to 5 m depth. These grey fissures were once regarded as characteristic of the "Hessle" Till, but as Catt and Penny (1966) pointed out they are a pedological feature affecting whichever till happens to occur at the surface. Close investigation shows they are composite features, involving both thin pale coloured deposits lining the walls of the fissures and discoloration of the immediately adjacent till. A sample of the material lining a fissure (HT 1/8) was analysed and compared with a sample of unaffected till (HT 1/9) from the interior of an adjacent ped; both were from a depth of 1.5 m (i.e. within horizon 5). The carbonate content of the grey fissure lining was significantly greater than that of the unaffected till (Table 23), and the dithionite extractable iron considerably smaller (Table 43), but the only difference in particle size distribution was a slightly larger percentage of fine clay in the grey material lining the fissure. The only difference shown by X-ray diffraction of the coarse and fine clay fractions from each sample was a slightly larger proportion of expanding minerals in the coarse clay of the grey fissure lining compared with the coarse clay of the unaffected till, and a similarly small decrease in the amount of mica. These observations support the composite origin suggested for the grey structural faces. The pale colour of the till immediately adjacent to the ped faces results from reduction of ferric iron compounds to mobile ferrous forms, much of which are leached out in water passing down the fissures. The pale colour is enhanced by secondary carbonate, presumably redeposited after being leached from higher soil horizons. However, there is little evidence for redeposition of translocated clay in the fissures, at least at 1.5 m depth.

The Holkham profile (HT 2) is better drained than the Tunstall profile, overlying gravel at approximately 1.5 m, and consequently has less well developed gley features. Profiles over Chalk on the Yorkshire and Lincolnshire Wolds are also better drained.

6.2.3 Carbonate content

The Tunstall profile is carbonate free to a depth of 71 cm (Table 23), except that a little chalk, mostly of gravel size, occurs in the top 20 cm; this probably results from past agricultural treatment, and the topsoil would almost certainly have been carbonate free in the natural state. Below 71 cm chalk and hard limestone particles, up to several cm across, are frequent, and the till contains 8–9 % carbonate by weight, this being distributed between all size fractions.

Light reddish brown (5YR 6/4) secondary carbonate concretions, up to 2 cm across, are abundant in horizon 4 (71–140 cm). Analysis of these nodules showed that they contain an average of 63 % $CaCO_3$, with a residue of silt and clay. Thin sections of horizon 4 showed the nodules grew <u>in situ</u>, incorporating part of the till matrix. Separation of nodules from sample HT 1/4 showed that they comprise 0.8 % by weight of the horizon, and as they contain 63 % $CaCO_3$, this is equivalent to 0.5 % $CaCO_3$ in the horizon as a whole, which is precisely the difference between the total carbonate contents of HT 1/4 and HT 1/5 (8.7 and 8,2 % respectively).

The simplest explanation of the changes in carbonate content through the Tunstall profile is that leaching by percolating rainwater has removed the carbonate from the uppermost 71 cm, and that part has been redeposited at greater depths to form discrete nodules and ped face coatings. Assuming the non-carbonate soil material is immobile, and no changes in horizon thicknesses have occurred, the total amount of carbonate leached from surface horizons and the total amount deposited beneath can be calculated as follows. Horizons 5 and 6 both contain 8.2 % carbonate, and horizon 4 contains 8.7 %, of which 0.5 % is redeposited; it may therefore be assumed that the original till contained 8.2 %. Using the bulk density values given in Table 23, the upper 71 cm of a column of till 1m square would have lost 115.8 kg carbonate, whereas the amount gained in the zone of secondary carbonate deposition is only 3.6 kg. The net loss of 112.2 kg/m^2, 97 % of that originally present, represents carbonate carried away in the groundwater as dissolved calcium ions.

The Holkham profile (HT 2) is decalcified to a slightly greater depth than the Tunstall profile, probably because the underlying gravel allows more rapid drainage. Pink secondary carbonate concretions occur in horizon 5, similar to those in horizon 4 of the Tunstall profile. These seem to be ubiquitous in the uppermost calcareous zone of profiles on the Devensian tills in eastern England. The observed depth of decalcified soil ranges from 0.55 to 2.0m; the deeper decalcified profiles occur over permeable substrata, in particular the Chalk of the Wolds, and the thinnest decalcified layers (e.g. HT 12 at Eppleworth and HT 32 at Wawne) are on the upper slopes of valleys, where erosion has probably removed part of the decalcified till.

6.3 Laboratory Studies

6.3.1 pH measurements

The Tunstall profile has a slightly alkaline reaction throughout (Table 13), the pH increasing slightly with depth to a maximum in horizon 4, the zone of carbonate accumulation. The slightly more alkaline reaction of the topsoil compared with horizon 2 results from the chalk added for agricultural purposes, which, by being leached down the profile, has probably made the sub-surface horizons also slightly more alkaline than they would be under natural conditions. Horizons 1-3 may therefore have been acid at earlier stages of profile development, and mineralogical changes within these horizons could have resulted from acidity.

6.3.2 Organic matter

Roots penetrate the Tunstall profile to a depth of about 1m, though they are abundant only within the highest 20 cm; they comprise about 0.1 % of horizon 1, 0.04 % of horizon 2, 0.01 % of horizon 3 and 0.001 % of horizon 4. Horizon 1 contains nearly 2 % organic carbon (Table 13), most of which must therefore occur in finely disseminated humus. Appreciable quantities (0.6 %) of organic carbon also occur in horizons 2 and 3; these may be partly in translocated organic matter derived from decomposing surface litter, but probably also represent the decomposed remains of roots which penetrated to these horizons.

6.3.3 Bulk density

Published bulk densities of calcareous tills from depths of up to about 2m range from 1.86 to 1.99 g/cm^3 (Smeck <u>et al</u>., 1968; Bushue <u>et al</u>., 1970). The calcareous parent material of the Tunstall profile is at the dense end of this range (Table 13), and the overlying decalcified soil horizons decrease in density upwards.

Bulk density measurements are used in the quantitative estimation of mineralogical and other changes during profile development. However, the density values were measured on soil material in its original state (apart from air drying), whereas nearly all the particle size, mineralogical and chemical analyses were done on stone-free, decalcified soil. Therefore the bulk density of this material is required. It was derived by calculating the weight of a unit volume of each horizon, and subtracting from this the weight of stones plus carbonate contained in the same volume. These weights were obtained by multiplying their percentage weight by the overall bulk density of the horizon. As the weight of stone-free, decalcified soil is still contained in the original volume, its bulk density can be calculated from its weight divided by the original volume.

On this basis, horizon 3 of the Tunstall profile is the most dense, and both horizons 2 and 3 are denser than the parent material. Leaching of carbonate would have initially produced a less dense soil material by formation of voids, but subsequently the bulk density would have been increased by compaction of the soil, the weathering and breakdown of stones to form finer material, and possibly also by redeposition of translocated clay.

6.3.4 Particle size distribution

The results of these determinations are given in Tables 24-29 and Figures 70-77. They are discussed as evidence of uniformity of parent material in section 6.4.1, where it is suggested that many changes in particle size distribution in the profile are caused by weathering of susceptible rock fragments in the coarser grades, and of susceptible minerals in finer grades. In the Tunstall profile, the clay grade shows the greatest differences in amount between horizons. This fraction was subdivided at 0.25 μm (12 ϕ) into coarse and fine clay. The latter increases down the profile to a maximum of 22.9 % in horizon 3, below which it decreases to 16.0 - 16.2 % in horizons 5 and 6. The ratio of fine to coarse clay increases continuously up the profile, probably due to the increasing intensity of weathering processes.

6.3.5 Composition of stones

The stone fraction (>2mm) is important in the weathering of the tills, as it contains a large proportion of weatherable rock types, such as shales, weakly cemented sandstones and limestones. To obtain reliable analyses of the stone grades very large samples are required, of the order of 20 kg. Unfortunately, it was not possible to collect such large samples of the different horizons from the original site at Tunstall, as habitations are already fairly close to the cliff at this point, and the residents are understandably anxious that erosion of the cliffs should be minimal. A site was therefore selected at Dimlington, and samples taken at depths comparable to those of the horizons sampled at Tunstall: HT 57 equivalent to HT 1/2; HT 58 to HT 1/3; HT 59 to HT 1/5. The tills at the two sites are virtually identical in texture and mineralogy, and apart from some contamination of the surface horizon at Dimlington, the soil profile characteristics are comparable. Samples of approximately 20 kg weight were collected in large polythene bags.

In the laboratory, after weighing and sub-sampling to obtain a dry weight, the samples were disaggregated in tap water, and separated with a 2 mm sieve. The stones retained by this sieve were washed thoroughly, dried and weighed, then sorted into four fractions, using 6, 16 and 25 mm sieves. Each size fraction was then separated into twelve lithological types by hand, using a lens, acid and other routine tests to aid identification of rock types. Tables 30&31 show the results of these analyses.

The stone content of the Drab Till at Dimlington (sample DT 18) differs from that of the overlying Purple and "Hessle" Tills, in particular containing fewer shale fragments. A sample of the "Hessle" Till from the Yorkshire Wolds (HT 56 from Eppleworth) contained more chalk and flint in its stone fractions than the Drab, but if allowance was made for this difference (which probably results from incorporation of subjacent chalk material in the till at Eppleworth), the two were otherwise similar in stone contents. However, the stones in the "Hessle" at Dimlington are different from those in the "Hessle" at Eppleworth.

The total percentage weights of stones, and their distribution between the four size fractions in HT 59 and PT 9 (equivalent to Tunstall samples HT 1/5 and PT 1 respectively), are almost identical, indicating no significant breakdown of the stones to smaller size fractions at the depth of HT 59, i.e. 1.5 m. Limestones, shales and siltstones are more abundant in the Purple Till (PT 9) than in the overlying "Hessle" (HT 59). This could be due to weathering out of some of these stones in the upper sample, although removal of the limestone by weathering seems unlikely, as HT 59 came from below the decalcified horizons. An original vertical variation in relative proportions of erratic types seems to be more likely. Obviously a number of samples of each till need to be analysed before firm conclusions can be drawn about detailed variation in erratic stone content, but the work involved in this is too large to complete in a study of this type.

The decalcified horizons of the soil profile at Dimlington (HT 57 and 58) have very different stone contents from the underlying calcareous "Hessle" (HT 59). The total amounts of stones in these horizons are much less than in the calcareous till; also, some rock types are unrepresented or greatly reduced in relative amount in the upper horizons, whereas others are correspondingly increased. Limestone and chalk are absent from the upper horizons, except for a small amount of chalk in the topsoil, which has probably been added as fertiliser. Amounts of shale and siltstone are also greatly reduced, but sandstones are increased. The most important feature of sample HT 57 is the abundance of iron oxide concretions in the 2-6 mm fraction; similar concretions are present, but in smaller amount, in HT 58. They are common also in the coarser sand fractions of samples HT 1/2 and HT 1/3, and again predominate in horizon 2. They are pedogenic in origin, because they are completely absent from the calcareous till.

Because of the obvious disturbance of the topsoil at Dimlington, a bulk sample of this horizon was not taken. However, 30 g of stones (>2 mm) were separated from the Tunstall topsoil (HT 1/1), and these were separated into rock types. The total percentage of stones in this horizon is greater than in the subjacent decalcified horizons, but less than in the calcareous till, although this determination may not be reliable as the sample analysed was comparatively small. Secondary iron concretions, similar to those in horizon 2, are present, but in considerably smaller proportion. Shales and siltstones, and also sandstones, are much rarer than in lower horizons, but flint and quartz are much more abundant. If the secondary iron concretions are excluded, the recalculated proportion of igneous rocks is also significantly smaller in horizon 1 than in deeper horizons. One stone type, "clinker", which occurs in horizon 1 but no other, provides further evidence of human influence on the topsoil.

Table 32 estimates the overall changes in stone content of the soil horizons; the total amount and proportions of different types in HT 59 are taken as representative of unaltered till, and it is assumed that the only change involved is physical breakdown of coarser fragments, with no removal from or addition to any of the upper horizons. The figures indicate progressive breakdown of nearly all rock types in samples HT 57 and 58; sandstones are increased relative to other rock types in HT 57 and 58, but in overall amount these too have decreased, probably adding material to the sand fractions. Amounts of secondary iron concretions increase up the profile; as they are absent from HT 59, those found in other horizons must have formed pedogenically. The figures for HT1/1 do not follow the trends shown by HT 57 and 58; absolute amounts of all rock types except shales, siltstones and iron concretions are larger than in HT 57 (Table 32), and the most resistant rock types (flint, chert and vein-quartz) are present in greater abundance than in the parent till. This indicates that processes other than just mechanical disaggregation of shales and sandstones and chemical dissolution of limestones were involved in the genesis of this horizon. This is also apparent from the much smaller contents of all fractions finer than 20 μm in horizon 1 compared with the parent till. Much of the fine material in this horizon must have been either translocated vertically to deeper horizons or removed laterally from the profile by preferential erosion.

To summarise, the results of the stone analyses show the following features:

1. Complete dissolution of chalk and limestone fragments in the three upper horizons of the soil.
2. Almost complete disaggregation of shale and siltstone fragments in these decalcified horizons, thereby probably increasing the amounts of clay and silt particles in the profile.
3. Considerable disaggregation of sandstone fragments in the decalcified horizons, probably increasing the sand content of the soil.
4. Disintegration of many of the igneous erratic stones in the upper horizons.
5. Growth of secondary iron oxide concretions, especially in horizon 2, restoring the stone content of some upper horizons.

6. Growth of secondary carbonate concretions in the uppermost part of the calcareous horizons (see section 6.2.3).

The disaggregation of sandstones in the uppermost horizons is responsible for their increased sand content (Table 25). Similarly, the increase of clay in horizons 2 and 3 of the Tunstall profile (Table 25) could result, at least partly, from the disaggregation of shale particles. However, the medium and fine silt grades decrease proportionately in these horizons, despite disaggregation of siltstone fragments. This could be due to further breakdown of the silt particles to clay, or merely to the masking effect of larger increments in the sand and clay grades, so that on a percentage basis the final proportion of silt is less than in the parent material.

A major feature of the profile is the increase in clay percentage in horizon 3 compared with the parent material. Disaggregation of shale fragments >2 mm undoubtedly contributes to this, but can only account for < 1 % of the total clay in this horizon. However, much of the extra clay could be derived from smaller shale and siltstone particles, which are common in the coarser sand fractions of the calcareous till.

6.3.6 Composition of coarse sand fractions (250 - 2000 µm)

The coarse sands were subdivided at 500 µm and 1000 µm by dry sieving; each fraction was examined in reflected and transmitted light with a stereoscopic magnifier, and counts were made of the different types of grains present. These analyses (Tables 33a-c) show that in the calcareous till shale and siltstone fragments decline in relative abundance with decreasing grain size. A more marked decline in abundance occurs up the profile in each size fraction, shales and siltstones being virtually absent from the topsoil. There is a corresponding increase in quartz and sandstone grains, though the ratio of these two constituents is not constant through the profile. In its coarser fractions (>500 μm), the calcareous till (HT 1/6) contains only twice as many single quartz grains as sandstone particles. However, in the decalcified horizons, single quartz grains greatly predominate over sandstone fragments, and many of the latter have evidently been disaggregated. This, and the destruction of shale and siltstone particles, would account for the relative increase of fine sand and depletion of coarse sand up the profile, as shown by the detailed sieving analyses (Table 29, Figure 76).

6.3.7 Mineralogical composition of fine sand and coarse silt fractions

The fine sand (53-250 μm) and coarse silt (20-53 μm) fractions show many changes in mineralogical composition through the Tunstall profile (Tables 34-41). The light fractions contain more quartz in horizons 1 and 2 than lower in the profile, but the amounts of muscovite decrease upwards to zero in the topsoil, and although felspar is constant through most of the profile, it is slightly less abundant in the topsoil. Small amounts of opaline silica occur in the calcareous subsoil, but not in decalcified horizons. Calcite and dolomite occur in horizons 4-6 and in PT1, but were excluded from the counts.

The percentage of heavy minerals in these two size fractions decreases gradually up the profile, but increases again slightly in the topsoil (Table 34). The unoxidised Purple Till (PT 1) contains more than twice the weight percentage heavy minerals present in HT 1/6. This upward decrease seems to result from the removal by weathering of pyrites, siderite and other heavy minerals. Pyrites and siderite are both abundant in PT 1, but absent higher in the profile. As the minerals of the heavy fractions have varying densities, shapes and sizes, it is unreliable to convert the counts to weight percentages, and it is consequently impossible to say if the amounts of pyrites and siderite fully account for the difference in weight percent heavy minerals between PT 1 and HT 1/6. Nevertheless, inspection of the grain counts (Tables 35,37) shows that the difference is of about the order expected if such losses by weathering have occurred. The till samples collected in Holderness allow a comparison to be drawn at several localities between the reddish brown oxidised "Hessle" Till at 1-2 m depth, and the unoxidised till, either Purple or Drab, at greater depth (5-10 m). The unoxidised till of each pair contains a considerably greater weight of heavy minerals than the overlying oxidised till, usually about twice as much, and the only significant differences between the heavy mineral assemblages of each pair are the proportions of siderite and pyrites. This supports the suggestion that these minerals have been oxidised in the upper few metres of the till. The oxidation products do not occur in the fine sand or coarse silt fractions, either because they are finer than 20μm, or because they have been removed completely by dissolution during gleying.

However, this does not explain why the topsoil (HT 1/1) has an increased content of heavy minerals in both fine sand and coarse silt fractions. One explanation of this may be that the softening and weathering of the metamorphic and igneous erratics in horizon 1 has contributed extra amounts of heavy minerals to the fine sand and coarse silt fractions. As the original heavy mineral assemblages of the till were probably derived at least partly from the same rock types as many of the erratics, there would be no significant change in the heavy mineral assemblage of horizon 1 if this replacement had occurred. An alternative explanation of the increase is that rain-washing of the surface soil formed a lag deposit rich in coarser and denser grains, which has subsequently been incorporated into a homogeneous plough layer.

The oxidative weathering of both siderite and pyrites has been widely reported and fairly extensively studied. Schaller and Vlisidis (1959) reported the spontaneous oxidation of a ground sample of siderite kept in a stoppered bottle. When collected in 1915, this sample contained 59 % FeO ($FeCO_3$ contains a theoretical 62 % FeO); by 1944 the FeO content had decreased to 6 %, and by 1958 to 0.7 %, because of spontaneous oxidation to Fe_2O_3. X-ray patterns taken in 1955 showed that the sample was "hematite with small to moderate amounts of goethite and siderite". Thus in 43 years almost complete oxidation of the siderite had occurred. As specimens of siderite in collections remain unoxidised for a much longer time, they thought there was "a latent after-reaction due to the mechanical and thermal effects produced by the grinding of the sample". The siderite in the till is fine-grained, and was of course subject to glacial grinding, which might have made it more susceptible to oxidation. Nevertheless, the length of time available for oxidation to have occurred since deposition of the till is two orders of magnitude greater than that involved in the laboratory sample.

Discussing the weathering of the Northampton Sand Ironstone formation, Taylor (1949) stated that "weathering and oxidation take place wherever the bed is brought into the zone of circulating atmospheric waters. Undoubtedly the greatest part of the weathering is related to the present or pre-glacial land surface. This is shown by the widespread oxidation at outcrop, under shallow cover, or beneath boulder clay. Siderite is oxidised to geothite with removal of the carbon dioxide in solution. Redistribution of the iron into limonitic crusts occurs progressively, and at outcrop where the bed has suffered the greatest amount of weathering the topmost layer may consist entirely of a curly cavernous mass of limonite."

Discussing iron carbonates in the northern Pennine orefield (from which some of the siderite in the Devensian tills could well be derived), Smythe and Dunham (1947) suggested that "within the 'oxidation zone' above the groundwater table, waters of surface origin carrying dissolved oxygen and carbon dioxide act upon the carbonates. In the orefield the depth of this zone varies from zero adjacent to the valley bottoms (where the permanent water-table is virtually at the surface) to a maximum of about 300 feet beneath the hills. The product of oxidation of both ankerite and chalybite is a mixture of hydrous ferric and manganese oxides; crystalline goethite is rare. Chalybite is more responsive to oxidation than ankerite". This suggests that the level in the Holderness tills above which siderite has disappeared is the upper surface of the permanent water table.

The pyrites present in the Purple Till is probably oxidised to sulphate and eventually to iron hydroxides, and the iron then mobilised in a similar fashion to that derived from siderite. Bloomfield (1972a) discussed the weathering of pyrites in soils, and concluded that it starts by chemical oxidation yielding SO_4^{2-} and Fe^{2+}, and that Thiobacillus ferro-oxidans converts the ferrous iron in solution to an ochreous deposit of ferric hydroxide. This bacterium flourishes in the very acid conditions (pH less than 3.5), which develope through formation of sulphuric acid, and can then attack pyrites directly, decomposing it faster than the original chemical oxidation. However, the pyrites in the Holderness tills seems to have been oxidised in the presence of free calcium carbonate, because the oxidised zone extends down to 5-6 m below the surface, whereas the decalcified horizons are usually less than a metre in depth. The pyrites-containing till can therefore never have approached the acidity in which T. ferro-oxidans flourishes, and it is unlikely that iron bacteria were responsible for much of the weathering of the pyrites.

Chamosite was identified by X-ray powder diffraction in each horizon of the Tunstall profile, but as it is difficult to distinguish optically between fresh green chamosite and chlorite, a combined count for these minerals is given. In the upper horizons very few chlorite or chamosite grains were found, and those present are brown and almost opaque, probably with a coating of limonite. Similar brown grains predominate over green grains in horizons 3 and 4; at greater depths the green material becomes more common, although brown chamosite is still abundant. If allowance is made for the diluting effect of the presence of siderite on the proportions of other minerals in sample PT 1, it is seen that the Purple Till contains more chamosite than the overlying "Hessle", though it has similar proportions of the brown and green forms. The Jurassic bedded iron-ore formations, from which the chamosite is probably derived, contain some brownish chamosite ooliths even in the unweathered state (Taylor, 1949); they contain alternating concentric shells of green chamosite and brown limonite, which probably reflect fluctuations between oxidising and reducing conditions in the depositional environment. Youell (1958) stated that " a stable oxidised chamosite has been identified as a common constituent of weathered ironstones. Its appearance resembles goethite, and much material formerly classed as goethite or limonite must now be regarded as oxidised chamosite. The first stage of alteration of siderite-chamosite ores is the breakdown of the siderite to a fine state of subdivision, followed by conversion to goethite. The second stage, which may to some extent overlap the first, is the conversion of chamosite to the ferric form; in some specimens chamosite and oxidised chamosite occur in equal amounts. The final stage is the breakdown of the oxidised chamosite to goethite and a residue which is usually amorphous and consists of the silicate sheets . . . leached of all octohedral ions." Youell concluded that this residue has similar X-ray diffraction spacings to kaolinite.

Thus some of the brown grains in the Purple Till could be derived from unweathered source rocks, others from the weathered portion of these rocks. However, further weathering of the chamosite has occurred in the uppermost part of the till, so that the green-coloured grains have been further oxidised to limonite, and it has been almost completely removed from the top 30 cm of the profile.

After siderite, the commonest non-opaque heavy minerals in sample PT 1 are biotite and chlorite. Allowing for the absence of siderite, the proportion of these micaceous minerals in sample HT 1/6 is slightly less than in PT 1. However, other samples of Purple and "Hessle" Till from the south-east Holderness coast show little difference in the relative amounts of these minerals, which suggests that weathering has not appreciably affected them at 2m depth. Similar amounts occur in horizons 5 and 6 of the Tunstall profile, but above 1.4 m they decrease progressively towards the surface. As the proportions of resistant minerals are virtually unchanged through the profile (see section 6.4.1), the upward decrease in these micaceous minerals may reasonably be ascribed to weathering. Walker (1949) found that biotite weathers to vermiculite in some Scottish soils, hydrated Mg^{2+} replacing K^{+}, and Fe^{2+} being oxidised to goethite. Gilkes and Little (1972) found similar changes in the weathering of chlorite; iron and magnesium are lost, and ferrous iron oxidised. However, these weathering products are not found in the fine sand and coarse silt fractions of the Tunstall profile, and have probably been incorporated in finer fractions. Further consideration is given to the weathering of micaceous minerals in section 6.3.8.

Significant amounts of apatite and collophane occur in all horizons except the two uppermost, where these minerals are entirely absent from the sand fraction and rare in the coarse silt. Apatite is normally regarded as a relatively insoluble form of phosphate by plant nutritionists (e.g. Parker, F.W., 1953), but Johnston and Olsen (1972) have shown that the presence of plant roots accelerates its dissolution. In the Tunstall profile over 90 % of the roots occur in the two uppermost horizons, and may account for the loss of apatite and collophane.

Other fine sand and coarse silt minerals seem to have been little affected by weathering. Amounts of augite are significantly reduced relative to the resistant minerals in the two uppermost horizons (Fig. 82), but amphiboles, which are present in smaller quantities than pyroxenes, seem to be unaffected by weathering. The remaining heavy minerals also seem to be resistant to weathering.

The Holkham profile is poorer than the Tunstall soil in weatherable sand and silt minerals (Tables 68-74), and shows smaller changes in mineralogy with depth. In addition, the lowest horizon (HT 2/5) is probably partly decalcified and thus more weathered than horizon 6 of the Tunstall profile. Micas may already have been partly weathered from this horizon. Nevertheless, some weathering trends similar to those in the Tunstall profile are evident; for example, apatite, chlorite, chamosite and biotite are all much decreased in amount in the upper horizons. In contrast, the amounts of augite seem not to be affected by weathering.

6.3.8 Composition of clay, and fine and medium silt fractions

Detailed determinations of the layer silicate mineralogy of the fine and coarse clay, and fine and medium silt fractions are given in Tables 42-45. Although the figures quoted in these are to the nearest 1 %, the absolute values should be interpreted with care, as there are many possible sources of error in the method used (Gibbs, 1965; Harward and Theisen, 1962). Nevertheless, samples HT 1/5 and HT 1/6, which are similar in particle size distribution and in the mineralogical composition of their coarse silt and fine sand fractions, gave similar X-ray diffraction patterns for each fraction analysed; it was therefore felt that the quantitative results derived from the diffractograms would give fairly reproducible estimates of the relative amounts of the various minerals in the different horizons. X-ray diffractometry was supplemented by chemical determinations of mica, felspar, quartz, "free" iron oxides, and amorphous silica and alumina. Two sets of figures were obtained for mica content, one from the diffractograms by the method given in Chapter 4, and the other from the non-exchangeable potassium content. The X-ray determination seemed to over-estimate the amount of mica in the coarser fractions, but slightly under-estimate it in the fine clay. This may be partly explained by the presence of K-containing mica layers in interstratified expanding minerals. All K-containing layers contribute to the mica content as determined chemically, but where such interstratified minerals collapse to a 10 Å spacing on heating, they are counted as expanding minerals by the X-ray method used here. Thus an increase in interstratified minerals in the fine clay fraction could account for the observed effect. In Tables 44-46 the mica percentages quoted are those based on the chemical determinations.

X-ray diffractograms of the ethylene glycol treated clays from the deeper horizons of the Tunstall profile (HT 1/4, 5 and 6) showed relatively well defined peaks at about 14.5 and 17 Å, indicating the presence of both vermiculite and smectite components in the expandable layer silicates. At higher levels in the profile, the 17 Å peak became more diffuse, and in the topsoil formed merely a "shoulder" on the high angle side of the 14 Å peak. The smectite component is thus less well defined in these horizons, and complicated interlayering is indicated. The 14 Å peak of all the air dried samples has a "shoulder" on its low angle side, at about 12 Å, which usually disappears after glycol solvation. On heating to 335°C, a small peak at 14 Å invariably results, though most of the material contributing to the 14/17 Å peaks seems to collapse to 10 Å. This indicates the presence of a small amount of discrete chlorite, along with greater numbers of vermiculite and smectite layers. The 12 Å "shoulder" suggests interstratification of one or more of these components with mica layers. Because of the almost complete collapse of this intermediate spacing to 10 Å on heating, and its expansion on glycol solvation to 14 Å +, it may represent interstratified mica-vermiculite/montmorillonite. In horizons 1 and 2, however, the heated samples give peaks and "shoulders" between 10 and 14 Å, showing incomplete collapse, while small "shoulders" remain on glycollation; in these, interstratification involving chloritic interlayers is therefore suspected.

Kaolinite occurs in all fractions of all horizons. Goethite also occurs in all horizons, and the clay fractions of horizons 1 and 2 and the silt fractions of horizon 2 contain lepidocrocite. Quartz and felspar are absent from the fine clays, but progressively increase in amount in coarser fractions.

The layer silicates in the fine and medium silt fractions give sharper X-ray reflections than those of the clays; the minerals are thus in silt grade particles, and not aggregated forms of the minerals in the clay fractions. Traces of the specimens in air at 20°C show strong peaks for mica and kaolinite. A small peak at about 12.5 Å is present in the deeper horizons, though it is only a "shoulder" in horizons 1 and 2. It disappears on glycol solvation, the spacing having presumably expanded to 14 Å +. A peak at about 14 Å, due to vermiculite and chlorite, remains, though it is much less intense than in the air dried samples. Two further peaks appear, at about 15-15.5 Å and 16-16.5 Å, though these are poorly defined in samples from horizons 1 and 2; they probably represent three or more component random interstratifications of mica, chlorite, vermiculite and montmorillonite. In no case was a well defined 17 A peak produced, so no true montmorillonite or randomly interstratified mica-montmorillonite occurs in these fractions.

The diffractograms of the medium silt fractions show a poorly resolved reflection at 25-30 Å, which shifts to higher spacing on glycol solvation. This represents partial ordering, possibly of mica-montmorillonite (Reynolds and Hower, 1970). Whittig and Jackson (1955) detected a spacing of about 29 Å in the glycerol solvated fine silt from the A_1 horizon of a brown forest soil in Wisconsin. The peak disappeared on heating, so they suggested it was due to a pedogenic, regularly interstratified montmorillonite-illite (18 Å +

10Å = 28 Å). A similar material may be present in the medium silt of the Tunstall soil, but as the spacing is most apparent in samples from the calcareous horizons, it seems it is a primary mineral in the till rather than one formed pedogenically. Gilkes and Hodson (1971) described a similar mineral from the Middle Coal Measures of N. Staffordshire and from a bentonite seam in the Woolhope Limestone in Herefordshire.

The diffraction patterns for spacings greater than 10 Å indicate a complicated mixture of expanding and non-expanding layer silicates in the finer fractions of the Tunstall soil. In Tables 42,44,45 this mixture has been subdivided into mica/illite, vermiculite, smectite and chlorite components. The recognition of vermiculite and montmorillonite rests on the occurrence of the 14 Å and 17 Å reflections from ethylene glycol solvated specimens. More generally, Mg-saturated glycerol-solvated specimens are used, but there is no widespread agreement concerning the validity of either test. Both probably show a difference in expanding properties that relates to the interlayer charge density of the minerals concerned, and either may legitimately be applied to show the changes in expanding properties of minerals within a set of related samples. The overall estimation of the proportions of mica, chlorite and expanding interlayers is sound, but the quantitative allocation of these interlayer types to regular and interstratified phases in complex mineral mixtures is not possible at present.

Weaver (1956) estimated that over 70 % of 6000 sedimentary rock samples he examined contained some variety of binary, tertiary or even quaternary mixed-layer clay. Interstratification is common also in soil clays (Jackson <u>et al</u>., 1954), and as a further complication intergrades of montmorillonite/vermiculite/chlorite may occur (Jackson, 1964). Artificial intergrade minerals have been produced by precipitation of hydroxy-aluminium, hydroxy-iron, and magnesium hydroxide in the interlayer spaces of montmorillonite and vermiculite (e.g. Carstea <u>et al</u>., 1970a, 1970b). A 14 Å diffraction spacing is the most common for natural clay intergrades (Jackson, 1964), and the terms "dioctahedral vermiculite" (Brown, 1953a), "vermiculite" (Loughnan et al., 1962), "chlorite-like" (Klages and White, 1957) and "chlorite" (Bradley, 1955) have been used to describe them. Despite these complications, it is possible to quote an "end-member" composition by the scheme outlined in Chapter 4 and discussed above, and weathering changes in the Tunstall profile can be discussed quantitatively in terms of these end-members.

6.3.9 Bulk mineral composition of finer soil fractions

Tables 44-46 give the bulk mineral composition of the finer soil fractions, derived from the combined results of the X-ray and chemical analyses.

Quartz. The proportion of quartz decreases with decreasing grain size. As it originally formed mainly sand-sized crystals in igneous and metamorphic rocks, it is usually most abundant in the sand fractions of sediments. However, it is the coarse and medium silt fractions of the till that contain most quartz; Kuenen (1960) and Smalley (1966) have ascribed the unusually large proportion of silt-sized quartz in tills to the crushing and grinding of sand by glacial ice.

Quartz is resistant to temperate weathering (Barshad, 1964), and any increase in its proportion relative to other minerals in a given size fraction is likely to result from weathering of these minerals. The proportion of quartz within each size fraction in horizons 3-6 is essentially constant, but it increases substantially in horizons 1 and 2, indicating that weathering of the other minerals is most intense in these uppermost horizons.

Felspar. Chemical determinations indicated roughly equal proportions of potassic and sodic end-member felspars in all fractions analysed; the amounts of calcic felspar are much smaller. The largest amounts of total felspar occur in the coarse silt fraction, which according to Dreimanis and Vagners

(1971) is the "terminal grade" for felspar, i.e. the final product of glacial comminution. Amounts of total felspar are similar for each size fraction in horizons 3-6, then increase in horizons 1 and 2, though to a slightly lesser extent than does quartz. This could indicate very slight weathering of the felspars in the uppermost horizons, but may be only experimental error, as there are no significant changes in the ratios of the three end-members throughout the profile.

Layer silicates. Relative amounts of total layer silicate minerals increase with decreasing grain size, and consequently comprise most of the clay and fine silt fractions. Nevertheless, they occur in small quantities even in the fine sand fraction. Mica, as determined chemically, is the most common layer silicate in all fractions of the deepest horizons, with the exception of the fine clay, in which expanding layer silicates (mainly vermiculite) predominate. In all fractions, mica decreases in proportion up the profile, the change being apparent in the clay fractions as deep as horizon 4, which is calcareous. However, in the topsoil this trend is halted or even reversed. Several workers (e.g. Nettleton et al.,1973) have also noted an apparent increase of mica in surface soil horizons, and have attributed it to the action of plants, which draw their supplies of potassium partly from below the surface layer, but when they die return it only to the surface. Weathered layer silicate clays in the topsoil then fix this potassium in expanding layers, which consequently collapse to 10 Å spacings. Some potassium from fertilisers may also be fixed in the topsoil clay, enhancing the 10 Å diffraction peak (Beckett, 1970). Both processes could have operated in the Tunstall profile.

Only in the clay fractions is the apparent loss of mica from upper horizons balanced by an increased proportion of other layer silicates in the same horizon. In the silt fractions kaolinite is also depleted in amount in the upper horizons, but these horizons contain an increased proportion of clay-sized kaolinite. Proportions of vermiculite in the clay and silt fractions of horizons 1 and 2 are similar to those in horizons 5 and 6, but are significantly increased in horizon 3. In contrast, smectite tends to decrease in proportion up the profile. Chlorite in the silt fractions decreases upwards, but in the fine clay it is more abundant in horizons 1 and 2 than beneath. The simplest weathering sequence suggested by these results is the leaching of potassium from mica by acid ground water to produce expanding minerals of the vermiculite type, and the decrease in size of kaolinite particles by physical weathering. However, the relative amounts of different fractions in each horizon must also be taken into account, as must the possible translocation of clay, and in some instances the changes in bulk composition resulting from complete removal of some components (e.g. calcium carbonate). The changes in layer silicates through the Tunstall profile are discussed quantitatively in section 6.4.2.

Amorphous silica and alumina. Amounts of both of these, as determined chemically (Table 43), are small in all fractions of all horizons, but increase two-fold in the fine clay fraction between the calcareous parent material (HT 1/6) and the topsoil (HT 1/1), suggesting that weathering has caused slight desilication of some minerals and mobilised some alumina. Mobilisation and redeposition of alumina in the profile is also indicated by the hindered expansion and collapse of the clays in the upper soil horizons, as this probably results from deposition of aluminium hydroxide interlayers in the expandable minerals.

Iron oxides. Both crystalline and amorphous iron oxides are present in the clay and silt fractions. The X-ray diffractograms of horizons 1 and 2 are the only ones showing prominent lepidocrocite peaks, and although goethite is present throughout the profile, the upper horizons again give the strongest peaks. However, lepidocrocite has a platy morphology, and orients better than goethite on the glass slips used for diffractometry, so that its reflections are enhanced compared with goethite (Brown, 1953 b)). The relative amounts of these crystalline components cannot therefore be estimated from the diffractograms with any certainty, and an asterisk scale is used in Tables 44-45 to show the relative order of magnitude of the respective reflections.

The amounts of "free iron", as determined chemically (Table 43), are largest in the fine clays; they increase towards the surface in this fraction, but in coarser fractions they increase downwards. However, these trends are not reflected in the rough estimates of crystalline iron oxides made from the diffractograms, even though both lepidocrocite and goethite dissolve in dithionite-citrate and are therefore included in the "free iron" figures. Much less crystalline material is apparent in the calcareous horizons than in decalcified ones, yet the total "free iron" contents are not very different. Much of the "free" iron oxide is therefore amorphous to X-rays, and the ratio of this amorphous material to crystalline iron oxides must decrease up the profile.

As lepidocrocite reflections appear only in the diffractograms of fractions from the two uppermost soil horizons, this mineral is probably pedogenic. Brown (1953b) thought the lepidocrocite he found in boulder clay soils in Lancashire was also pedogenic; in this and other soils the mineral is associated with orange mottling (the pure mineral is itself orange in colour), and is an oxidation product of ferrous compounds, possibly forming in the presence of organic matter (Schwertmann and Taylor, 1972c). In the Tunstall profile, the most distinct brown mottling occurs in horizon 2, in which lepidocrocite seems to be most abundant; no mottling was detected in horizon 1, although lepidocrocite is present, but here the mottling could have been destroyed by cultivation and mixing of the surface soil.

Although goethite occurs throughout the profile, it was not detected in the clay from sample PT 1 (unoxidised Purple Till), and may therefore be derived from the oxidation of pyrites and siderite. The strongest

4.18 Å peaks are in diffractograms of clays from the uppermost horizons, where the goethite was possibly derived from some of the lepidocrocite, which is the less stable polymorph of FeO(OH). Summarising a series of papers on sesquioxide formation and transformation, Van Schuylenborgh (1972) considered the presence of lepidocrocite in soil horizons depends on the relative rates of on the one hand, reduction and oxidation reactions producing soluble ferrous ions and subsequently precipitating them as γ-FeO(OH) (lepidocrocite) or amorphous $Fe(OH)_3$, and on the other hand, ageing reactions whereby these minerals change to α-FeO(OH) (goethite). Ćirić and Škorić (1972) showed that ageing reactions proceed slowly in soils, whereas oxidation-reduction reactions are faster, thus explaining why lepidocrocite and amorphous iron hydroxides predominate over goethite in actively hydromorphic soils.

6.3.10 Micromorphology

Thin sections of horizons 2-6 were examined with a petrographic microscope, mainly to search for evidence of clay translocation. Translocated clay is oriented, as clay particles are mainly of a platy habit. Because the particles are small, unoriented clay appears optically isotropic, but oriented clay is anisotropic and can readily be recognised under the microscope by its birefringence.

In the thin sections of all the horizons examined there was considerable evidence of orientation of clay particles in the soil matrix. However, as this oriented clay is distributed throughout the soil matrix, it is probably an original feature of the till itself, having developed in response to shearing stresses in the parent ice sheet. Some thin layers of oriented clay also lined pores and small fissures in many of the horizons, but these could have resulted from pressures exerted by growing roots in the case of pores, and from pressures due to expansion and contraction during wetting and drying cycles in the case of fissures. That is, they are probably stress cutans.

True illuviation cutans, that is clay separations clearly associated with pores, and showing strong continuous orientation, well developed banding, and with no inclusions of coarse material, are rare. There is therefore very little evidence of clay translocation in the Tunstall profile.

6.4 Pedogenic Significance of Results

6.4.1 Uniformity of Parent Material

The main aim of the soil profile study was the quantitative estimation of pedogenic changes, but before this can be attempted it is important to establish satisfactorily the uniformity of parent material throughout the profile. Brewer (1964) gave this as the first requirement of a soil parent material in this type of study. His second was that the rock or deposit analysed as parent material should be unaltered in any way by the soil-forming processes that one is trying to evaluate. He emphasised the difficulties in attaining these two requirements, and also pointed out the need to distinguish between pedologic weathering and so-called "geologic weathering" (Jenny, 1941). "Geologic weathering" includes processes taking place at depth under the influence of such agents as deep ground water. However, the internal variability of many rocks or unconsolidated deposits is such that the exact composition of the original, unaltered parent material of many soil profiles can never be determined.

Unfortunately, it was only after much of the study had been completed that many of the implications of the changes in texture and mineralogy of the so-called Hessle Till, and their relationships to the properties of the underlying Purple and Drab Tills, were fully realised. Thus, in Chapter 5 it was suggested that the Hessle Till originally contained similar proportions of siderite and pyrites to those in the underlying tills, and that oxidation of these minerals was to a large extent responsible for the reddish brown colours typical of the surface tills throughout the area. Over most of the area occupied by the Devensian tills, the Hessle Till is probably the oxidised upper part or thin extension of the Drab, but in south-east Holderness it is the oxidised surface layer of the Purple Till. In the latter area, samples of the oxidised but undecalcified till (Hessle of Zone A) are similar in texture and clay mineralogy to the underlying Purple, and differences in stone content and in sand and silt mineralogy (apart from the complete or partial lack of obviously weatherable materials in the Hessle) are very small. Accordingly, sample PT 1 (unoxidised Purple Till from 8m below the top of Tunstall cliff) and sample HT 1/6 are regarded as the best approximation to the true parent material of the profile studied there.

In north Norfolk, no grey boulder clay was seen below the reddish brown Hunstanton Till, although on the foreshore at Brancaster Whitaker and Jukes Browne (1899) recorded brown clay "like that of Hunstanton" passing "both laterally and vertically into lead-coloured, very chalky boulder clay", which may be unoxidised Drab Till. As no sample of this unaltered parent material of the Holkham profile was available, horizon 2/5 is used in this study as the closest approximation to it.

Barshad (in Bear, 1964) gave six methods for establishing uniformity of parent material in a soil profile:

1. Total mineralogical analysis, with particular attention to the heavy mineral suite.

2. Particle size distribution of the resistant minerals, heavy or light, of the non-clay fractions.
3. The ratio of two resistant minerals in any one fraction coarser than clay, preferably the fine sand or coarse silt.
4. Particle size distribution of the whole non-clay fraction.
5. Nature of clay distribution with depth.
6. Nature of the change in chemical composition of the non-clay fraction.

In the present study, use was made of methods 1, 2, 3, 4 and 5.

6.4.1.1 Particle size distribution as evidence of homogeneity

Particle size analyses of the Tunstall and Holkham profiles are given in Tables 24-29, 62-67 and Figures 70-71. In both the clay content is greatest in the deepest decalcified horizon, and decreases above and below. In the Holkham brickpit a lithological discontinuity (a seam of clayey gravel) prevented sampling of all but the uppermost calcareous horizon. At Tunstall, the clay content decreases through horizon 4, the zone of secondary carbonate accumulation, but does not further decrease below this.

Because of the preponderance of quartz and felspars in the non-clay fractions of most sedimentary parent materials, and the relative resistance of these minerals to weathering, Barshad (1964) considered that the particle size distribution of the whole non-clay fraction can be used as an indicator of parent material uniformity. Tables 28+64 and Figures 74-75 present the results for the Tunstall profile and the Holkham profile on this basis.
In the Tunstall profile, these indicate a progressive upward depletion in the finer silt fractions, with a corresponding increase in the sand and coarse silt contents. If such a change appeared suddenly at one point in the profile, or if discrete segregations of sandy or coarse silty material were present in the upper part of the profile (as for example in profiles on the Lowestoft Till), then contamination of the upper part of the profile with coversand or loess

might be suspected; however, the change is gradual, and no sudden increases in any particular particle size grade are apparent (see Figure 12). The mineralogical data show that this gradual upward increase in the sand and coarse silt relative to fine silt results from weathering. The fine silt fractions of the lowest horizons contain only about 30 % quartz + felspar, but the upper horizons contain 45-50 % ; the coarser fractions show a similar change, but total amounts increase progressively, so that the fine sand fraction contains over 90 % of these minerals in the deepest horizon. As minerals which are relatively susceptible to weathering make up the remainder of these fractions, those with largest amounts of weatherable minerals (i.e. the finer fractions) are most likely to diminish in total amount up the profile.

Tables 29 & 65 and Figures 76-77 give the results of the detailed sieve analyses of sand fractions from the Tunstall and Holkham profiles. Quartz and felspar together comprise the bulk of these size grades, so that their particle size distribution is essentially that of resistant minerals. In the Tunstall profile some grades of sand are better represented than others (Fig. 76), these forming a series of peaks in the diagram, which occupy the same positions and are of comparable height for samples HT 1/2 to HT 1/6 inclusive and PT 1, thereby indicating that these horizons were derived from the same parent material. However, there is a progressive depletion in amounts of the coarser sands and a corresponding increase in the finer sand fractions towards the surface. The coarse sand fractions of lower horizons contain many fragments of shale, siltstone and sandstone (Tables 33 a-c), which are easily disaggregated into their constituent grains by weathering; this process has affected the upper horizons, as their coarser grades contain far fewer fragments, and is probably responsible for the gradual change in relative amounts of coarser and finer sand grades through the profile.

The Tunstall topsoil (HT 1/1) has approximately the same distribution of sand as the lower horizons, but is slightly enriched in medium grades, 250-500 μm. This could have been derived from the modern beach, as cliffs of similar height in East Anglia have at times been covered by blown sand from nearby beaches (Green et al., 1953; Banham, 1971), and this sand is mainly of medium grade. Alternatively, physical disaggregation of sandstone fragments in the topsoil could have increased the proportion of medium sand; such fragments are certainly more abundant in horizons HT 1/2 and below than in HT 1/1. The slightly different particle size distribution of the sand in the topsoil may therefore result simply from weathering of material similar in composition to the till at depth, and there is no need to resort to the suggestion of contamination with blown sand.

In the Holkham profile, the parent material was probably less uniform than at Tunstall, because there are considerable differences in the particle size distribution of the sand fractions between successive horizons (Figure 77). The upper horizons (HT 2/1 and 2/2) are similar to the calcareous till (HT 2/5) in this respect, but the intervening decalcified horizons (2/3 and 2/4) are significantly different, and the differences cannot be explained by weathering of the till.

6.4.1.2 Mineralogical composition as evidence of uniformity

The detailed analyses of heavy and light fractions of the fine sand (53-250 μm) and coarse silt (20-53 μm) fractions from all horizons of the Tunstall and Holkham profiles (Tables 34-41; 68-74) were used in a further test of homogeneity of the parent materials. In this the heavy minerals are the more useful, as they contain more mineral species. However, weathering has partly removed biotite, chlorite, augite and apatite from the higher horizons, so these weatherable minerals were excluded from the calculations.

Various classifications of mineral stability have been suggested, some based on persistence in soils, others on persistence in sediments (e.g. Goldich, 1938; Pettijohn, 1941; Dryden and Dryden, 1946; Weyl, 1952; Jackson and Sherman, 1953; Fieldes and Swindale, 1954). The specific environment of weathering is probably the most important aspect to be considered, as the stability sequence in tropical soils, for example, is different from that in podzol profiles (Brewer, 1964). Nevertheless, most workers agree that the main minerals used in the homogeneity test (rutile, anatase, brookite, zircon, tourmaline, garnet, epidote, kyanite and staurolite) are all relatively stable under most conditions.

Tables 40-41; 73-74 and Figures 79, 81-83 show that the relative proportions of these stable minerals are fairly constant throughout both the Tunstall and Holkham profiles, thus indicating the uniformity of the respective parent materials. At Tunstall the uniformity established on this basis extends down to samples HT 1/6 and PT 1, and the vertical variability of the whole profile is no greater than the lateral variability of the same till over a kilometre at Dimlington (Figures 81+82).

6.4.1.3 Homogeneity of parent materials - conclusions

The evidence presented above shows that the Tunstall soil profile developed from a parent material uniform enough to allow reliable quantitative calculations to be made of the pedogenic changes that have occurred in it. The Holkham profile is reasonably uniform mineralogically, but less so texturally. Quantitative calculations of pedogenic changes were not therefore attempted on data from this profile, though a qualitative comparison with the Tunstall profile was made.

6.4.2 Quantitative Evaluation of Soil Profile Development and Mineralogical Changes

6.4.2.1 Choice of an Index Mineral

"Soil development can be evaluated . . . . as long as the initial state can be determined" (Barshad, 1964). The initial state of the material in which the Tunstall soil developed was established in section 6.4.1, and in the present section an attempt will be made to determine the degree of development of the soil profile, mainly on the basis of mineralogical changes. Barshad outlined methods by which these changes may be measured quantitatively, using mineralogical and chemical data. The method adopted here is a modification of the mineralogical technique, in which gains and losses within the profile are measured against an index mineral. This term was proposed by Marshall (1940) to describe a mineral that is resistant to weathering, and immobile. He recommended zircon, tourmaline, garnet, anatase or rutile; quartz, albite and microcline are additionally recommended by Barshad. Zircon has been used frequently (Haseman and Marshall, 1945; Adams and Matelski, 1955), but as with some of the other recommended index minerals, the weight percentage is difficult to determine from heavy mineral counts. As the element zirconium occurs predominantly in zircon, chemical determination of Zr has been used in place of the more tedious mineralogical determination of zircon (e.g. Alexander <u>et al.</u>, 1962; Beavers <u>et al.</u>, 1963; Chapman and Horn, 1968; Sudom and St. Arnaud, 1971). However, FitzPatrick (1971) regarded the chemical method as less reliable than the mineralogical determination.

Chemical determination of titanium has similarly been used as an alternative to mineralogical determination of anatase and rutile, but this suffers from even more drawbacks as a weathering index than zirconium, as it is subject to mobilisation in all size fractions (Sudom and St. Arnaud, 1971). The use of silt and sand sized zircons is regarded as fairly reliable, because of their relatively large size and consequent stability (FitzPatrick, 1971). However, as this mineral is present only in relatively small amounts, uneven distribution in the parent material and experimental errors in determination could lead to inaccuracies in the calculation of mineralogical changes in the profile. For this reason, a resistant mineral present in larger amounts is preferable as an index mineral.

Quartz is such a mineral, widely regarded as extremely resistant to weathering in temperate regions, occurring preferentially in the silt and sand grades of sediments, and forming a large proportion of many soil-forming materials. Its stability and use as an index mineral has been discussed by several authors. Raeside (1959) stressed the possibility of physical breakdown of quartz particles; however, Sudom and St. Arnaud (1971) used quartz in the total non-clay fraction, thereby eliminating the effect of physical breakdown within the sand and coarser silt fractions. Raeside also discussed the solubility of quartz in soils, and concluded that on old land surfaces in tropical high rainfall areas sufficient time may have elapsed for significant leaching of quartz from the soils to have occurred. However, the present study is concerned with soil development on a comparatively young land surface and in an area with a moderate rainfall and cool temperate climate, so the possibility of significant dissolution of quartz can be ignored. However, to overcome the difficulties caused by possible physical disintegration of quartz particles, it was decided to use as an index the amounts of quartz in a fairly wide particle size range.

Barshad (1964) advocated the use of Na- and K-felspars in addition to quartz as an index. The felspar analysed in the Tunstall profile is overwhelmingly of the sodic and potassic varieties, and there is little evidence to suggest that it has been significantly weathered. Combined quartz and felspar analyses were therefore used. Clay-sized particles of quartz and felspar may be subject to weathering and/or translocation in the soil, so to safeguard against this possibility quartz and felspar in the size fractions greater than 5 μm only were used in the index mineral calculations. However, the physical breakdown of stones (>2 mm) has probably increased the amount of sand-sized quartz and felspar in the upper soil horizons. It was not possible to allow for this in a very accurate way, because of the difficulties involved in dealing with samples large enough for accurate estimation of stone types, but the large samples obtained from Dimlington for this allowed a semi-quantitative assessment to be made of the effect of the physical breakdown of stones on profile development. At the opposite end of the scale, the breakdown of quartz and felspar particles into fragments <5 μm across is thought to be an unlikely process in the Tunstall soil. The quartz and felspar particles <5 μm in size that are present in the soil are probably derived directly from the parent till, having been formed by glacial comminution. Therefore, the quantitative calculations were based on the relative content of quartz and felspar in the 5-2000 μm fractions. These calculations are given in Tables 47-60.

6.4.2.2 Quantitative Calculations - Particle Size Analyses

Table 47 gives the basic calculations of changes in composition of the various horizons of the Tunstall profile, in terms of a column of soil one square centimetre in cross-sectional area. Line 6, the weight percentage of index mineral in each horizon, shows that the amounts of quartz and felspar are significantly increased in the two uppermost horizons, and in horizons 3 and 4 they are slightly depleted compared with horizons 5 and 6. In line 8 these index mineral contents are used to calculate the original weight of 1g of the present soil material from each horizon, and in lines 10-12 these weights are adjusted to allow for the volume changes that seem to have taken place. Although the percentage changes in horizons 1 and 2 seem large, figure 84 puts these changes into perspective, showing that a total volume reduction of only 4.4 cc per square cm column of soil (i.e. about 3 %) has taken place down to the top of horizon 5.

Table 50 gives the changes in amounts of each size fraction that have occurred within each horizon, and Table 51 the same changes as percentages of the original amounts. Horizon 5 shows no overall change with respect to horizon 6 (which was taken as the parent material for the purposes of these calculations), but does show detailed differences in particle size, some fractions varying by as much as 9 % from the amounts in horizon 6. Percentage change of this order are probably due to small random variations in the composition of the parent material, and it is unwise to attach further significance to them in any of the soil horizons. However, there are many percentage changes much larger than this figure, in particular the depletion of fractions finer than 20 μm in horizons 1 and 2, the increase of fine clay in horizons 3 and 4, the increase of fine sand and coarse silt in horizon 3, and the depletion of coarse sand in horizons 2-4. Figure 85 summarises these changes.

The depletion of coarse sand is readily explicable in terms of the disaggregation of the abundant rock fragments in this size fraction. However, the fine material released by this disaggregation is insufficient to account for the increase in finer fractions in horizons 3 and 4, and the contribution to finer fractions made by disintegration of stones (> 2 mm) must also be taken into account. Rough estimates of this contribution (Table 54) show that in horizons 3 and 4 there has been a loss of 3.1g of stones from a centimetre square column of soil. This is much less than the net gain of 17.4g of <2 mm soil material, so that disintegration of stones in situ cannot account for the whole increment in the <2 mm fractions of horizons 3 and 4. In contrast, there has been a loss of 16.2g of <2 mm material and 1.6g of stones from a centimetre square column of horizons 1 and 2. If all these figures for horizons 1-4 are summed, an overall net loss of 3.5g of soil is apparent.

This amounts to 1.4 % of the original total weight of carbonate-free soil in these horizons. As there has been an overall loss of 11.2g of carbonate per centimetre square column from the profile (section 6.2.3), the loss of carbonate from the profile is much more important quantitatively than the loss of other minerals.

As there seems to have been little overall change in the total content of non-carbonate minerals in the profile as a whole, the most reasonable explanation of the relatively large loss of material from horizons 1 and 2 and the almost equal gain in horizons 3 and 4 is translocation of material from upper to lower horizons. This apparently contradicts the micromorphological evidence (section 6.3.10), which indicates little or no translocation in the Tunstall profile. However, Khalifa and Buol (1968) suggested that cutans of translocated clay in the B horizon of a North Carolina soil were eventually incorporated into the ped matrix by alternate wetting and drying and by bioturbation. The microscopic estimation of illuviation cutans in clay-rich soils therefore may not be a reliable method of quantitatively estimating translocated clay.

On the basis of the quantitative data presented in Tables the following changes in the Tunstall profile are proposed:

1. Disintegration of rock fragments in the coarse sand and stone fractions in the upper 140 cm of the profile, to provide an increment of sand, silt and clay particles.

2. Physical and chemical weathering of the less resistant minerals (mainly layer silicates) in the finer soil fractions, giving an increase especially of fine clay.

3. Translocation of fine clay downwards into horizons 3 and 4.

6.4.2.3 Quantitative Calculations - Mineralogical Analyses

Tables 55-56 show the quantitative changes in mineralogical composition of the various size fractions, calculated on the basis of uniform distribution of the quartz + felspar index; these changes are most easily visualised in graphic form in Figures 86-89. An important change is the gain of fine clay sized expanding minerals, mainly vermiculite, in horizons 2-4. On a total soil basis for horizons 1-4 (Table 59), there seems to have been significant production of vermiculite above the amount already present in the parent material. In contrast, mica shows a significant overall decrease in the same horizons. This indicates that mica has in part been weathered to vermiculite throughout the soil profile. Although mica of all size fractions is depleted in amount relative to the parent material, the gain in vermiculite is mainly in the fine clay and, to a lesser extent, in the coarse clay. Further, although the main loss of mica is from the two uppermost horizons, vermiculite production is apparently concentrated in somewhat lower horizons, especially horizon 3. According to Jackson (1965), mica weathering proceeds by release of potassium ions from their interlayer positions at flake edges in the presence of exchangeable Ca or Mg; in the Tunstall profile, Ca and probably also some Mg were available through weathering of calcite and dolomite. Raman and Jackson (1964) showed by electron microscope studies that the mica flakes curl into scrolls at their edges as ionic replacement occurs. Complete ionic replacement within large mica flakes probably did not occur extensively in the Tunstall profile, but small fragments of vermiculite must have broken off the mica flakes as weathering progressed. In this way mica of all particle sizes was reduced to predominantly fine clay sized vermiculite. However, this did not remain at the site of formation, but was translocated down the profile, so that, although weathering of mica was most pronounced in the uppermost horizons, the weathered material is now concentrated lower in the profile.

Kaolinite also seems to have undergone significant weathering changes within the profile, though total amounts of it are virtually unaltered compared with the parent material (Table 60). Figure 87 shows that there is much more fine clay sized kaolinite in horizons 1-4 than initially, and that there has been a gain of coarse clay sized kaolinite in horizons 2-4. In contrast, the silt fractions are depleted in kaolinite compared with the parent material. This suggests that weathering has reduced the particle size of the kaolinite, and that some fine clay sized kaolinite has been translocated down the profile.

Chlorite occurs in only small amounts, but from figure 87 it seems also to have suffered reduction in particle size, as a depletion in the silt grades is accompanied by increments in the fine clay of upper horizons. Total amounts of amorphous silica and alumina are also small (Table 59), but in the upper horizons there are significant increments of both in the fine clay fraction. There has been a small overall production of "free" iron oxides in the profile, most of which is in horizon 3, the horizon of maximum gleying; there has also been a reduction in grain size of the iron oxides.

Table 60 shows there has been an overall addition of quartz and felspar to the < 2mm fraction of the soil, amounting to about 5 % of that originally present. This presumably does not indicate pedogenic formation of these minerals, especially as the increment is confined to the fine sand and coarse silt fractions (Figures 88, 89), but results from the disaggregation of > 2 mm stones, mainly sandstone fragments, which were not included in the calculations. Some doubt must therefore be cast on the validity of using quartz and felspar as the index minerals in this study. However, the increment of quartz and felspar is fairly evenly spread throughout horizons 1-4 (Table 57), so the internal errors in the calculations are not greater than about 5 %. The mineralogical and textural changes discussed above are much greater in magnitude than this (e.g. 74 % loss of mica from horizon 1; 74 % gain of vermiculite and 59 % gain of fine clay in horizon 3), so the validity of the main conclusions is not affected.

6.5 Soil Classification and Horizon Designations

6.5.1 Tunstall Profile

This profile has a "distinct topsoil", that is an appreciably darkened Ap horizon (the plough layer, HT 1/1), containing at least 0.6 % organic carbon in the upper 15 cm (Avery, 1973). In the terminology of the Seventh Approximation (Soil Survey Staff, 1960), this horizon is classified as an Ochric Epipedon because of its colour value of 4.

The subjacent decalcified horizons (HT 1/2 and HT 1/3) have appreciably more clay than the topsoil, in the ratios 1.6:1 and 1.8:1 respectively. They are also richer in clay than the presumed parent material (HT 1/6), the ratio for HT 1/3 being 1.2:1. For soil horizons with 15-40 % clay in their fine earth (<2 mm) fraction, one criterion for the presence of an argillic horizon is that the ratio of the clay in the argillic horizon to that in the eluvial horizon must be 1.2 or more (Avery, 1973). Horizon 2 (HT 1/2) cannot be regarded as the eluvial horizon, as it contains more clay than the parent material, and any eluvial horizon originally present must now be incorporated in the plough layer. If the whole of HT 1/1 is considered to represent the eluvial horizon, then the clay ratios quoted above would qualify the subjacent horizons as illuvial or argillic horizons. However, two other qualifying criteria are necessary for such a designation, that the ratio of fine clay to total clay in the argillic horizon is greater than in the eluvial horizon by at least 50 %, and that clay skins are present in the argillic horizon. The first criterion is not met, as the ratio decreases steadily down the profile (Table 26), and thin sections of HT 1/2 and HT 1/3 showed no true cutans of translocated clay. These horizons cannot therefore be regarded as argillic, and do not qualify for a subscript "t" in their horizon designations. They may be regarded as weathered B horizons (Bw).

Gleying phenomena are apparent in all horizons from HT 1/2 to HT 1/6, and a subscript "g" is added to their designations. In HT 1/2 the gleying is less well developed than in other horizons, so in accordance with the practice of the Soil Survey of England and Wales (e.g. Crompton and Matthews, 1970), the subscript "g" is bracketed. Apart from this minor difference, the horizon nomenclature adopted is in accord with the recommendations of the International Society of Soil Science (1967).

The uppermost calcareous horizon (HT 1/4) contains secondary carbonate as concretions, coatings on ped faces, and linings of pores, and is therefore designated a C_{ca} horizon.

The profile possesses some of the vertic features of the Pelosol group (Avery, 1973). Horizons 2 and 3 have well developed prismatic peds, which are especially noticeable on dry vertical profile faces (Figure 69). In the dry state, wide cracks (>5mm wide in many instances) extend from just below the plough layer to the base of the decalcified horizons, and sometimes to even greater depths. The "clay skins" recorded in the field probably result from differential movement of the peds during wetting and drying cycles. Potential linear extensibility was not measured, so the profile cannot be assessed against this criterion. However, the criterion of >35 % clay for a depth of at least 30 cm, starting at less than 25 cm depth, is not quite met, as horizon 2 (20-33 cm) contains only 31.6 % clay, though horizon 3 (33-69 cm) contains 36.2 %. Thus the soil cannot be classified in the Pelosol group or Pelo-subgroups.

The gleyed horizons, which have greyish mottles and ped faces with chromas of 1 and 2 occurring within 40 cm of the surface, are regarded as diagnostic of the Gley soils group. The non-alluvial nature of the soil material, the presence of a distinct topsoil, and the relatively impervious Bg and C horizons are diagnostic of the Stagnogley (Surface-Water Gley) group.

As the soil has no argillic horizon, has insufficiently developed vertic features to be classified in the pelo-subgroups, and is not sandy, it must belong to the Cambic Stagnogley subgroup (Avery, 1973).

6.5.2 Holkham Profile

The Holkham profile is similar in many respects to the Tunstall profile, possessing a distinct topsoil, weathered B horizons, a C horizon enriched in secondary carbonate (HT 2/5), and gleying features in horizons below the topsoil. The most important difference between the two profiles is the degree of gleying shown in the decalcified horizons. Only in horizon HT 2/5, at a depth of nearly a metre, are ped faces with chromas lower than 2 apparent. Thus the soil cannot be classified in the Stagnogley group, but belongs instead to the Brown Earth group. The presence of gleying at depth, and minor evidence of it higher in the solum, places the soil in the Stagnogleyic Brown Earth subgroup (Avery, 1973).

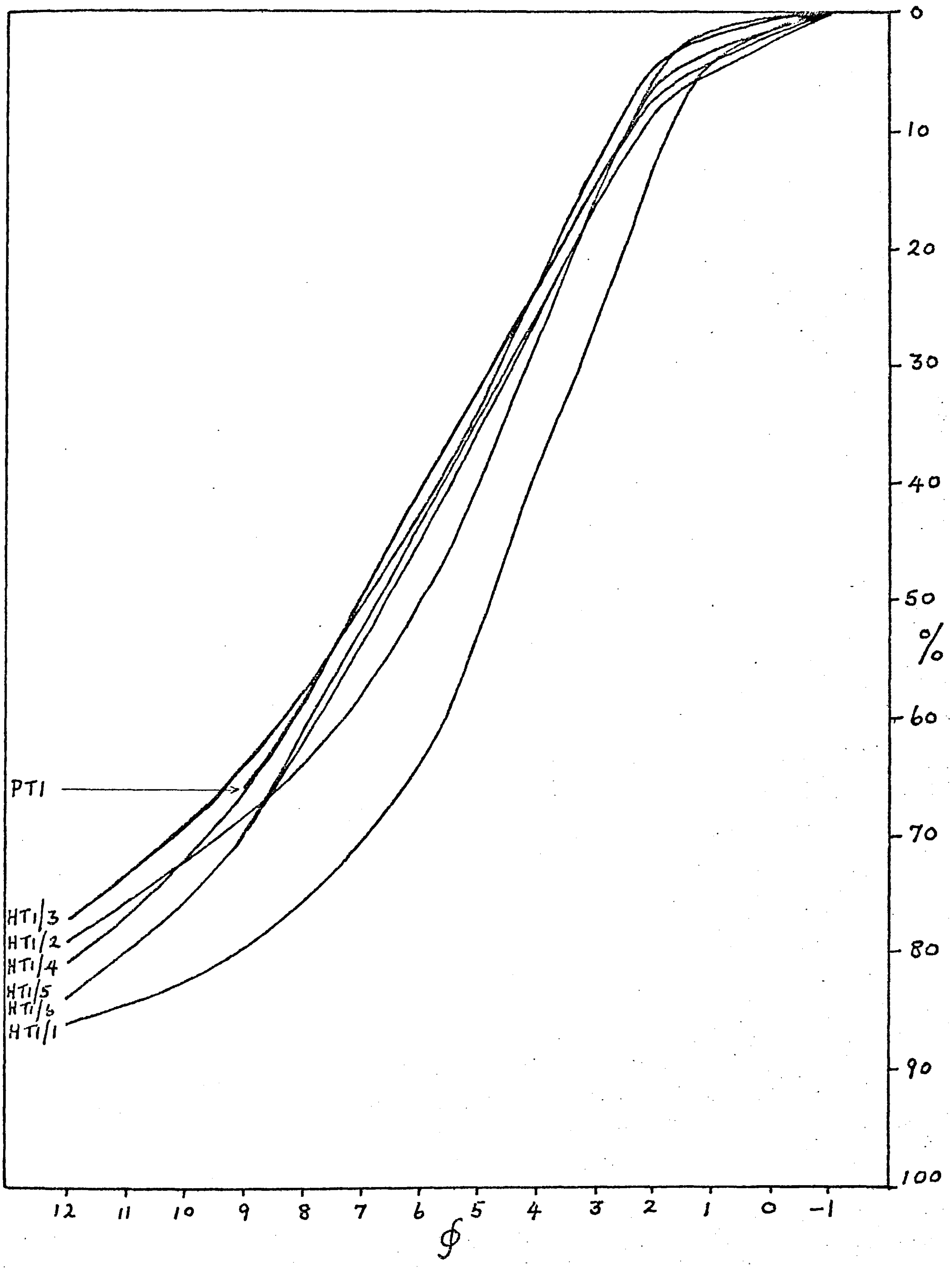


FIGURE 70 TUNSTALL PROFILE, HT1

CUMULATIVE PARTICLE SIZE ANALYSES

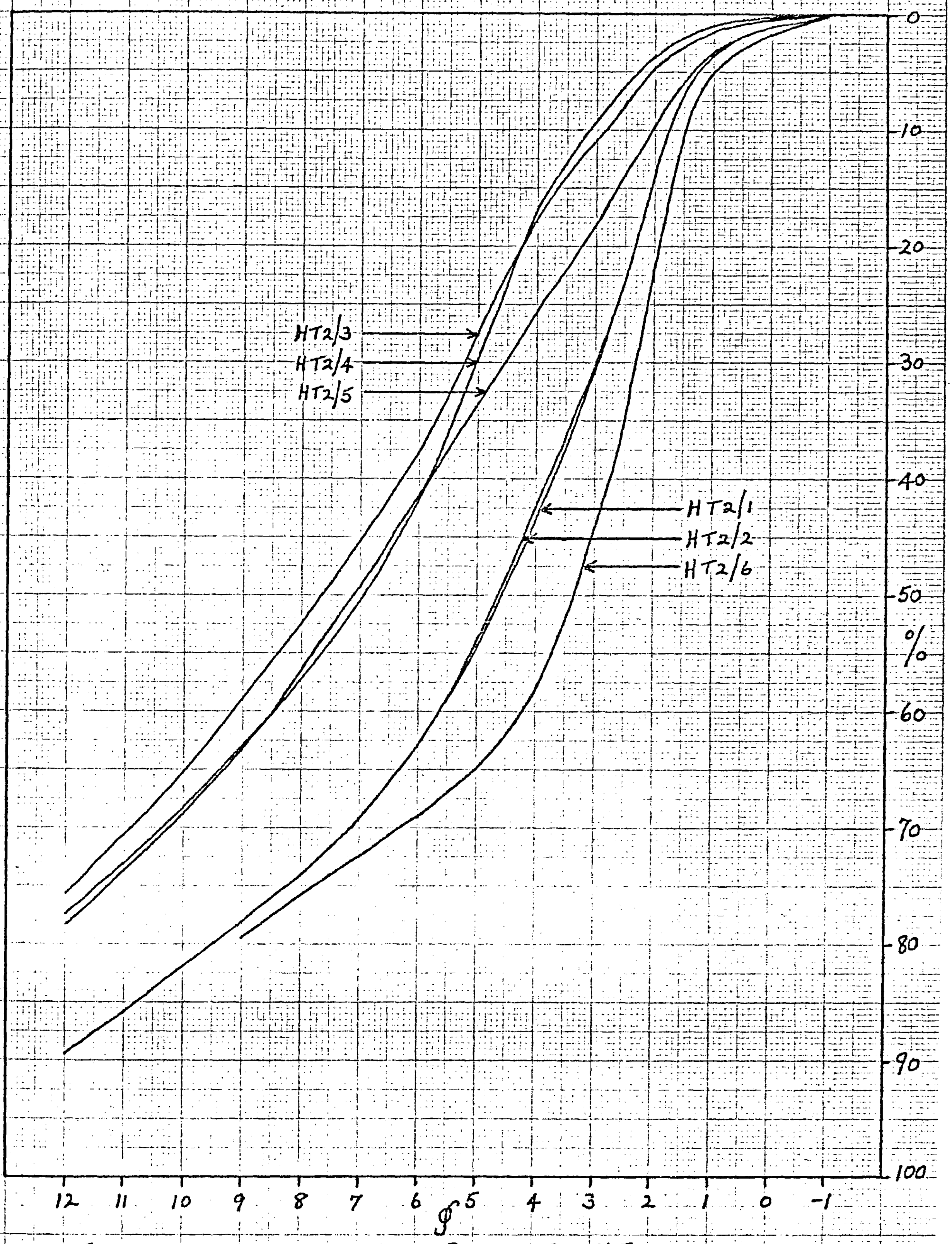


FIGURE 71 HOLKHAM PROFILE, HT2

CUMULATIVE PARTICLE SIZE ANALYSES

FIGURE 72

TUNSTALL PROFILE, HT1

TEXTURAL CLASSIFICATION

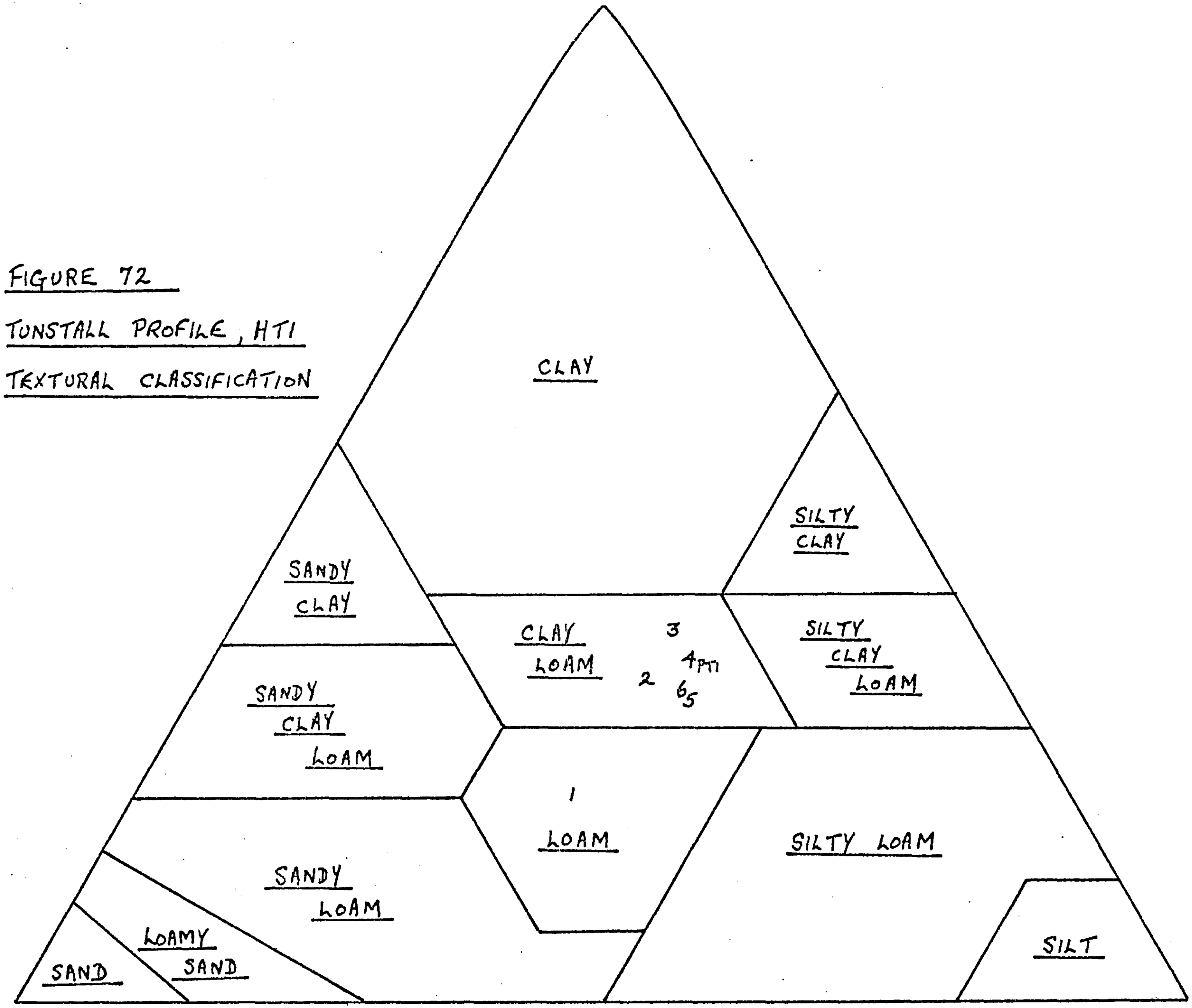
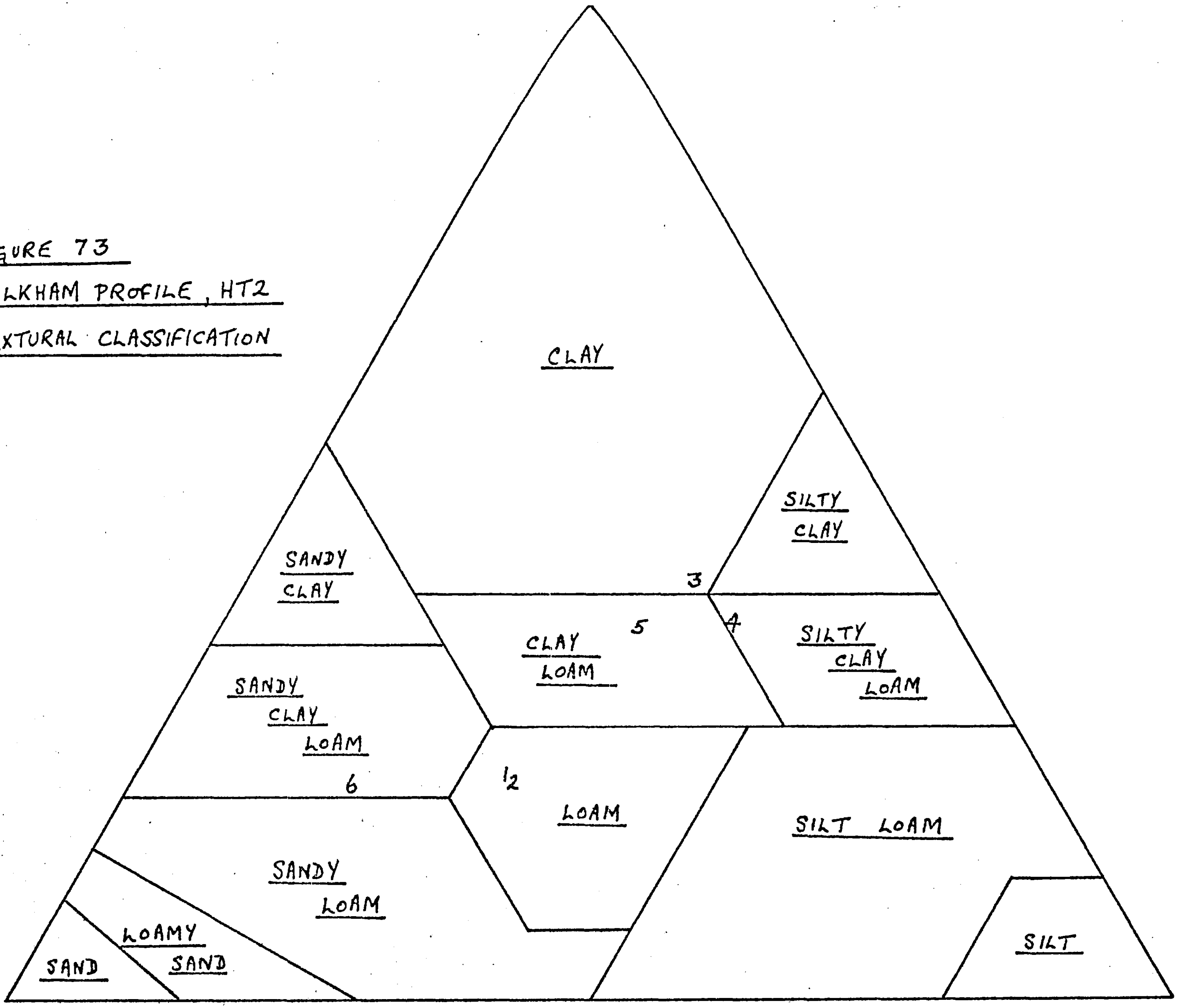


FIGURE 73

HOLKHAM PROFILE, HT2

TEXTURAL CLASSIFICATION



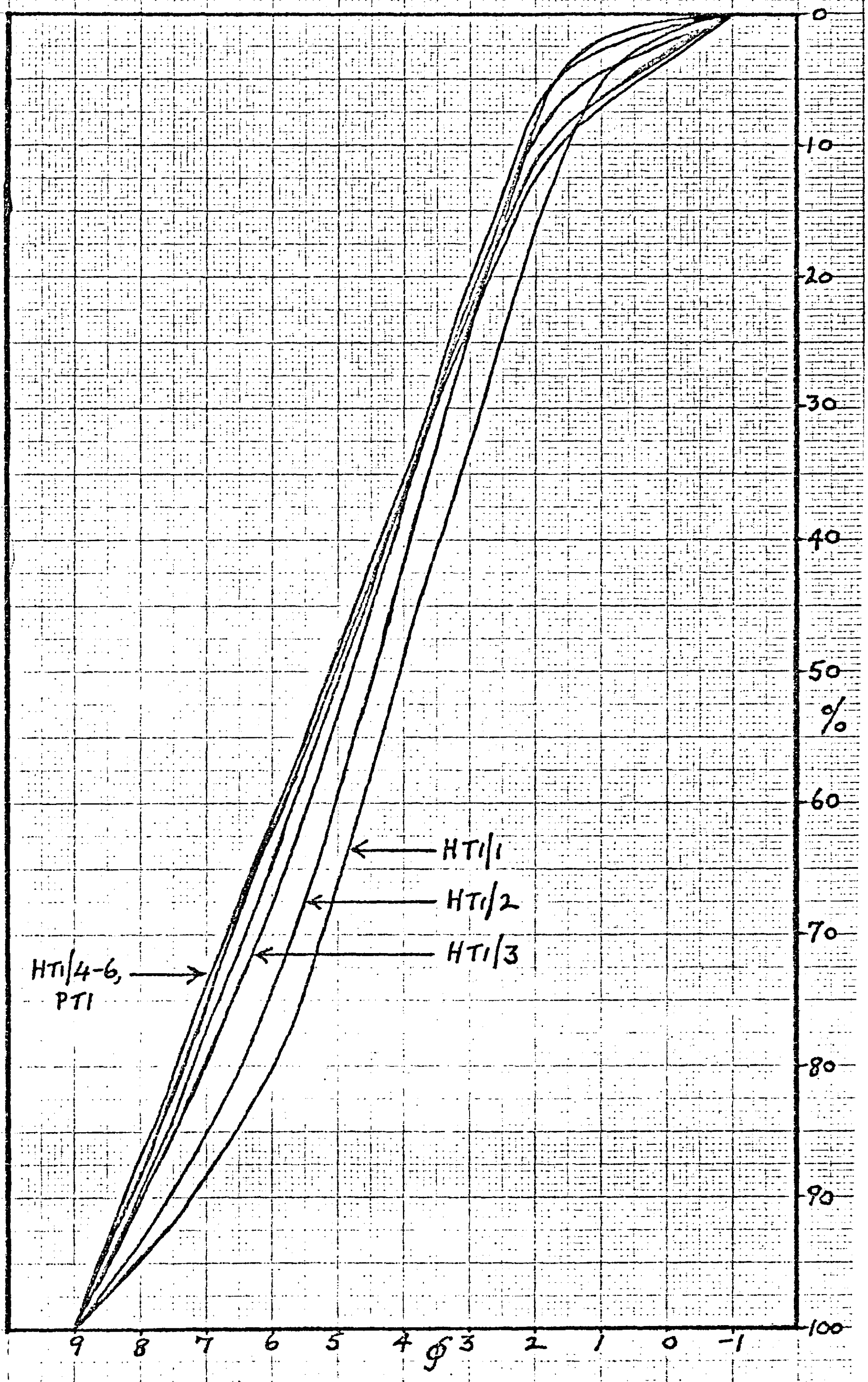


FIGURE 74 TUNSTALL PROFILE, HT1
CUMULATIVE PARTICLE SIZE ANALYSES
ON CLAY-FREE BASIS

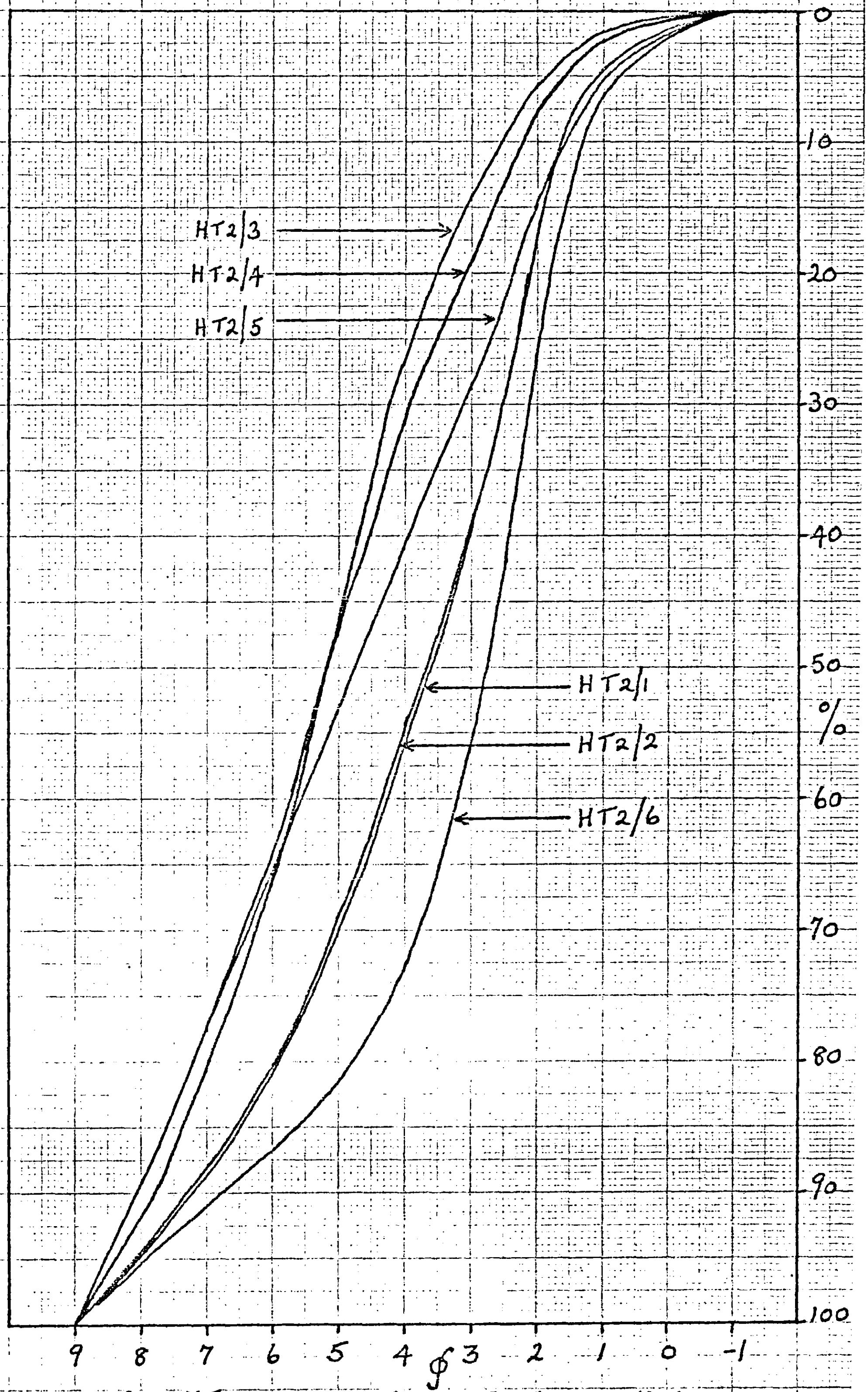


FIGURE 75 HOLKHAM PROFILE, HT2

CUMULATIVE PARTICLE SIZE ANALYSES ON CLAY-FREE BASIS

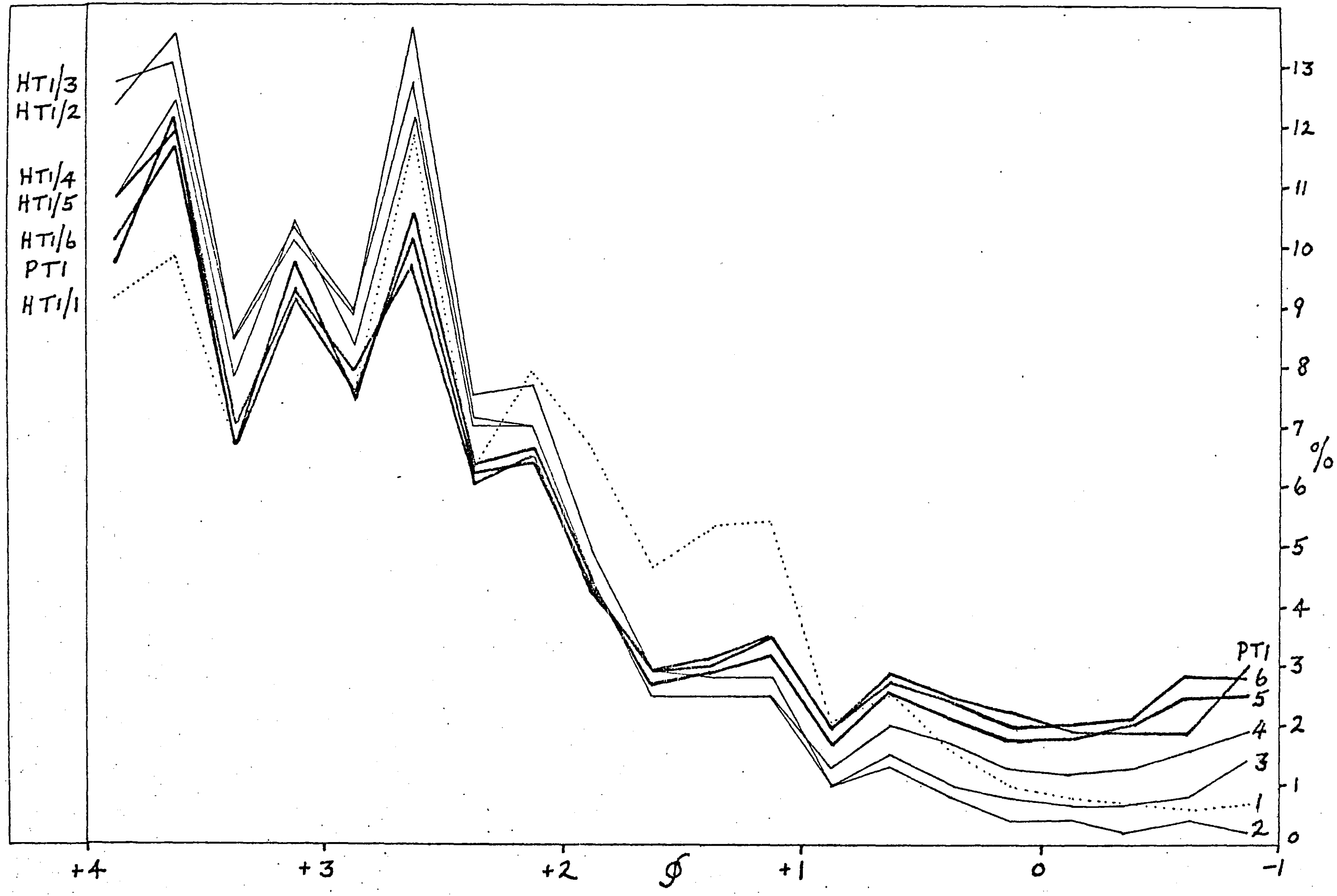


FIGURE 76 TUNSTALL PROFILE, HT1: DETAILED SAND-SIEVING ANALYSES

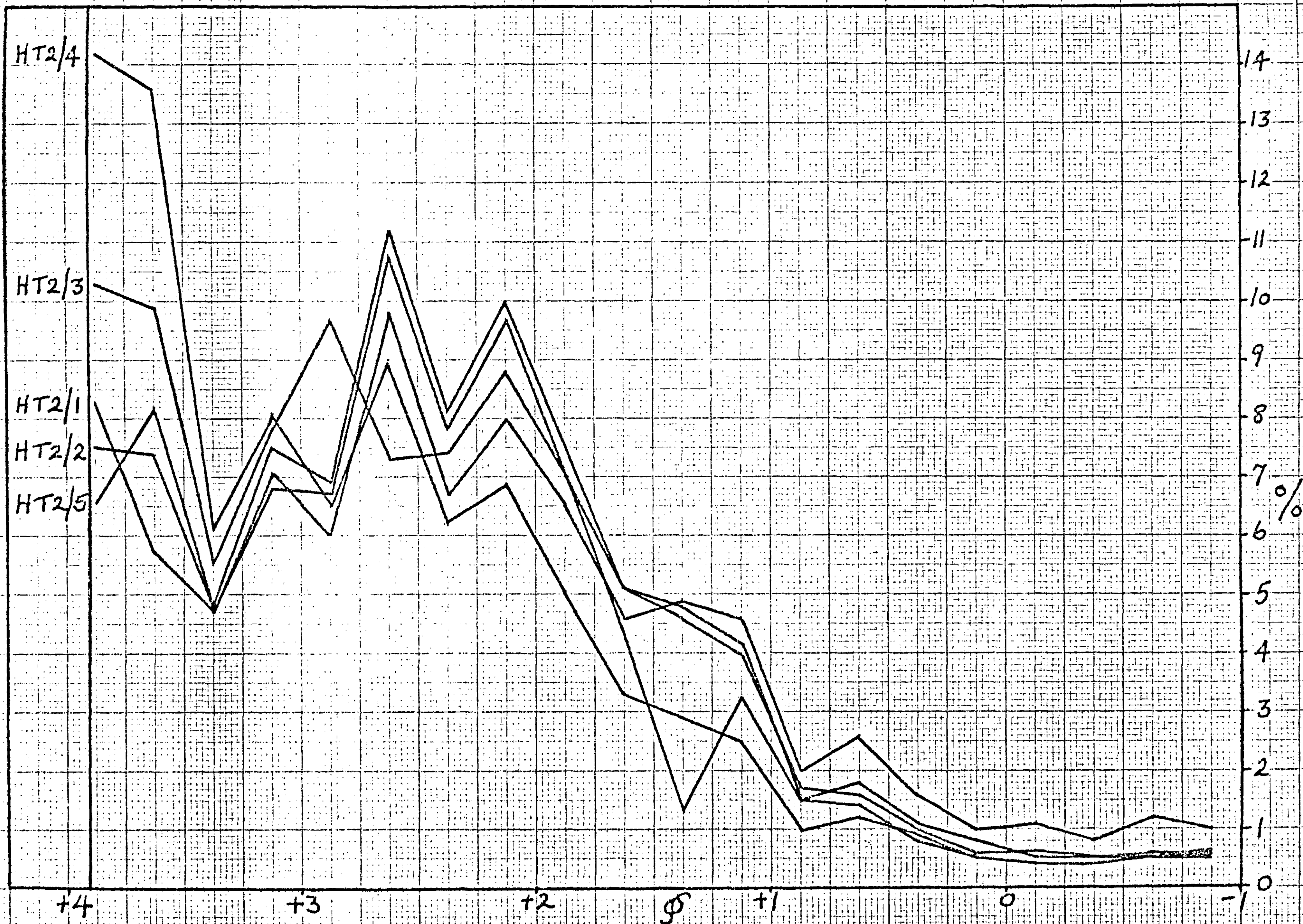


FIGURE 77 HOLKHAM PROFILE, HT2: DETAILED SAND-SIEVING ANALYSES

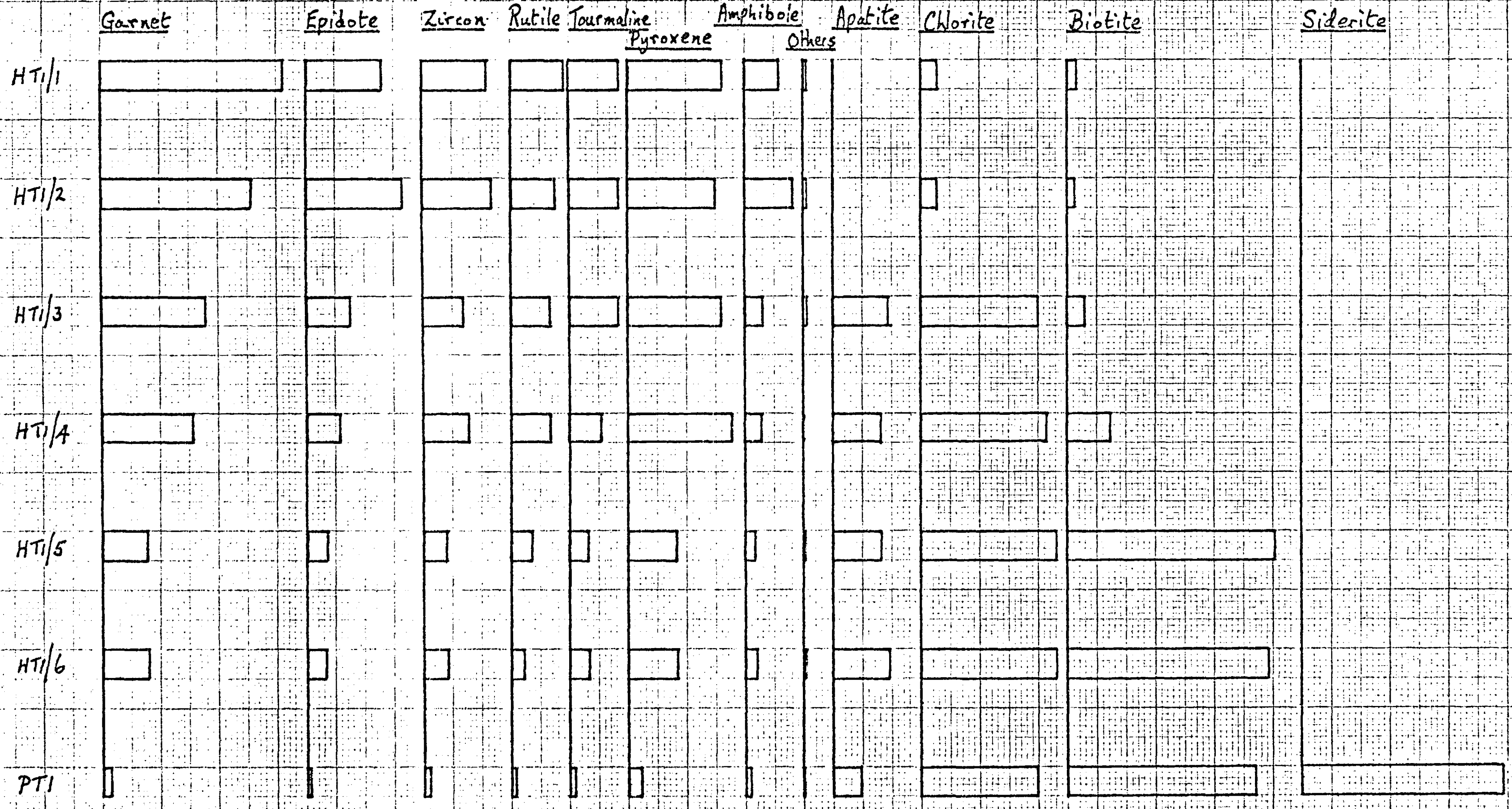


FIGURE 78 TUNSTALL PROFILE: 53-250µm HEAVY FRACTION

Non-Opaque Minerals

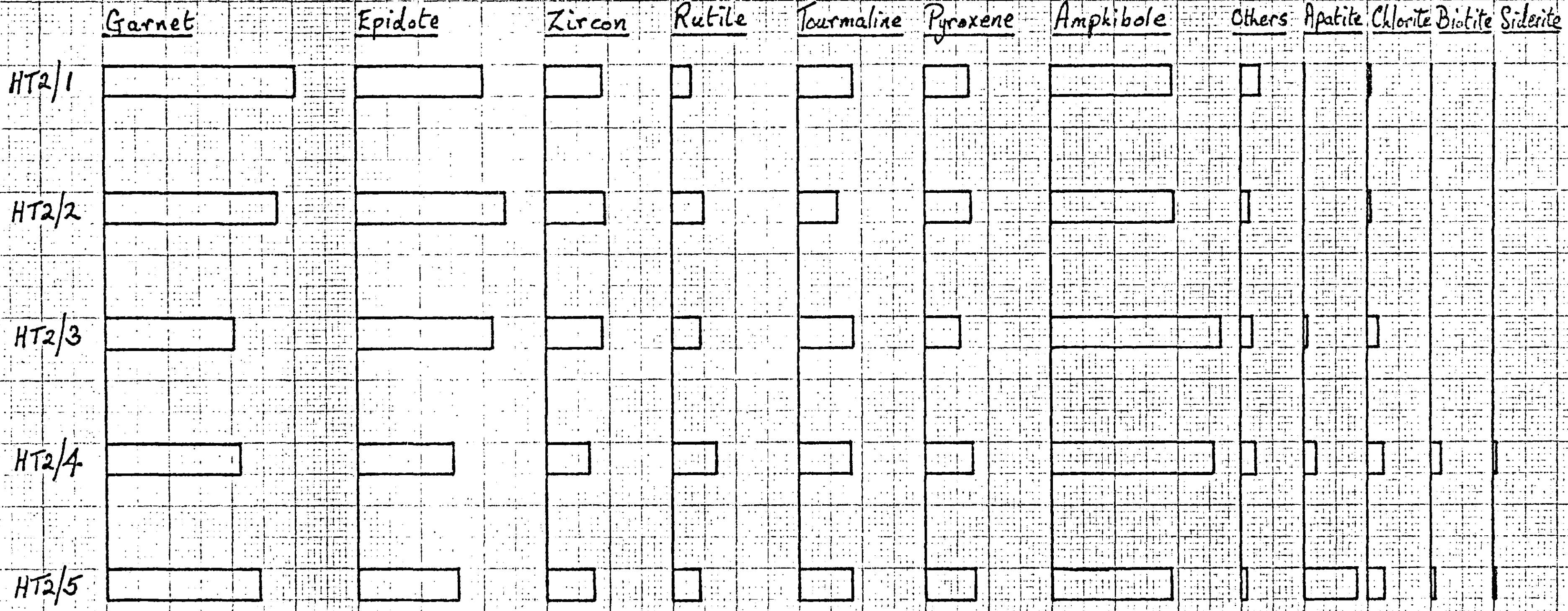


FIGURE 79 HOLKHAM PROFILE: 53-250µm HEAVY FRACTION

Non-Opaque Minerals

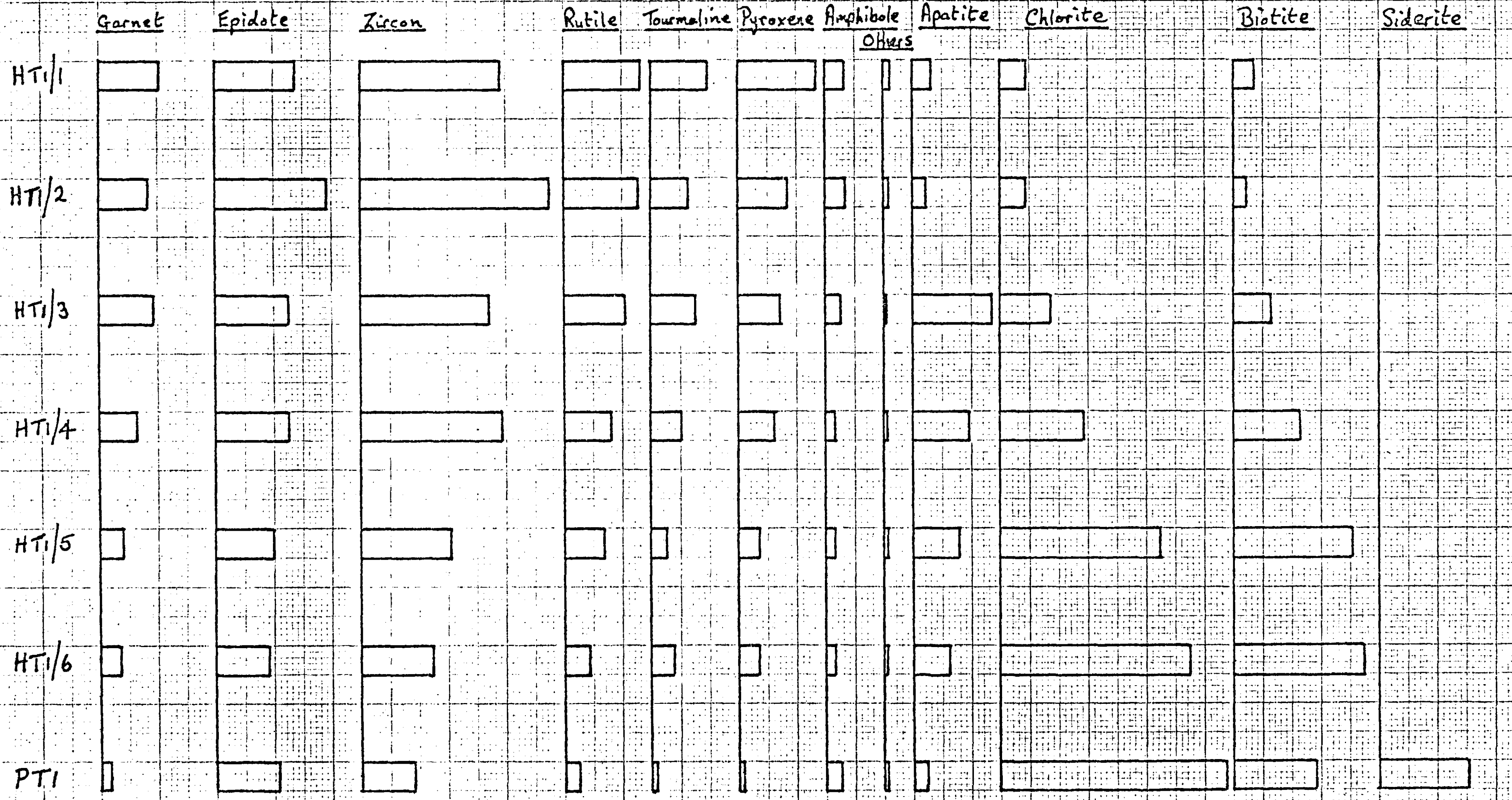


FIGURE 80 TUNSTALL PROFILE : 20-53μm FRACTION

Non-Opaque Heavy Minerals

20– 53 µm FRACTION

NON-OPAQUE HEAVY MINERALS

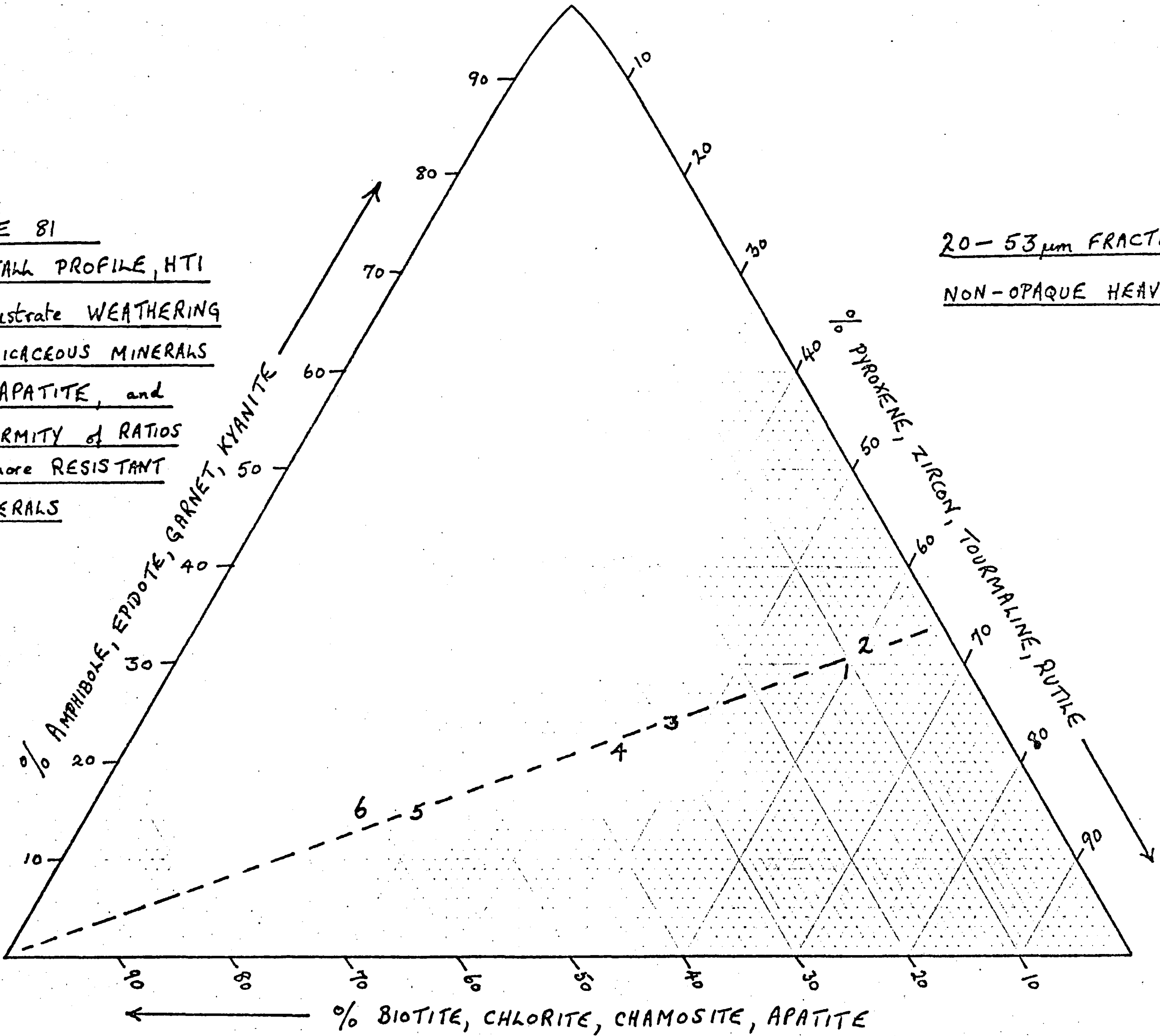


FIGURE 81

TUNSTALL PROFILE, HT1

To illustrate WEATHERING of MICACEOUS MINERALS and APATITE, and UNIFORMITY of RATIOS of more RESISTANT MINERALS

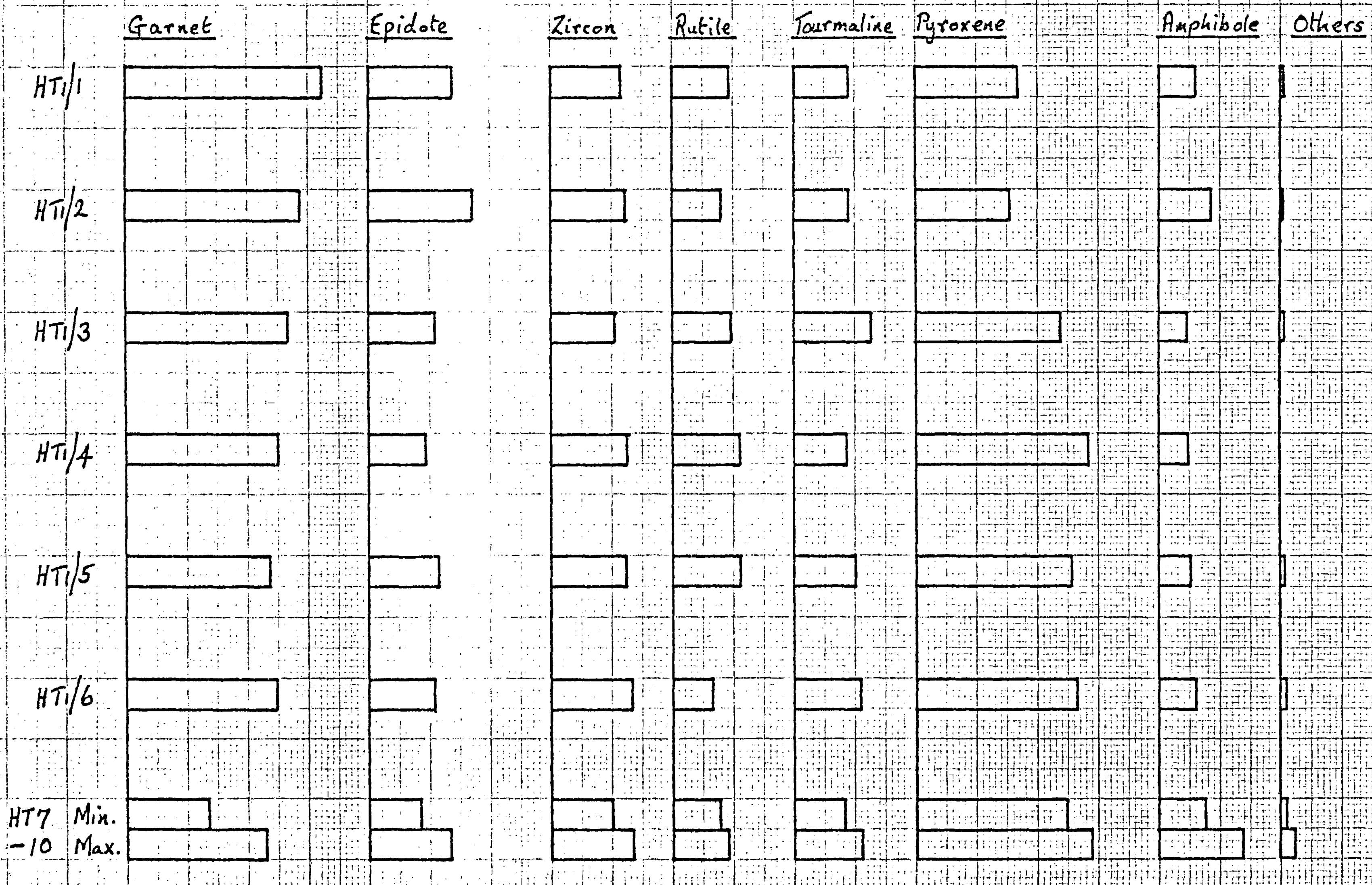


FIGURE 82 TUNSTALL PROFILE: 53-250μm HEAVY FRACTION
"Resistant" Non-opaque Minerals

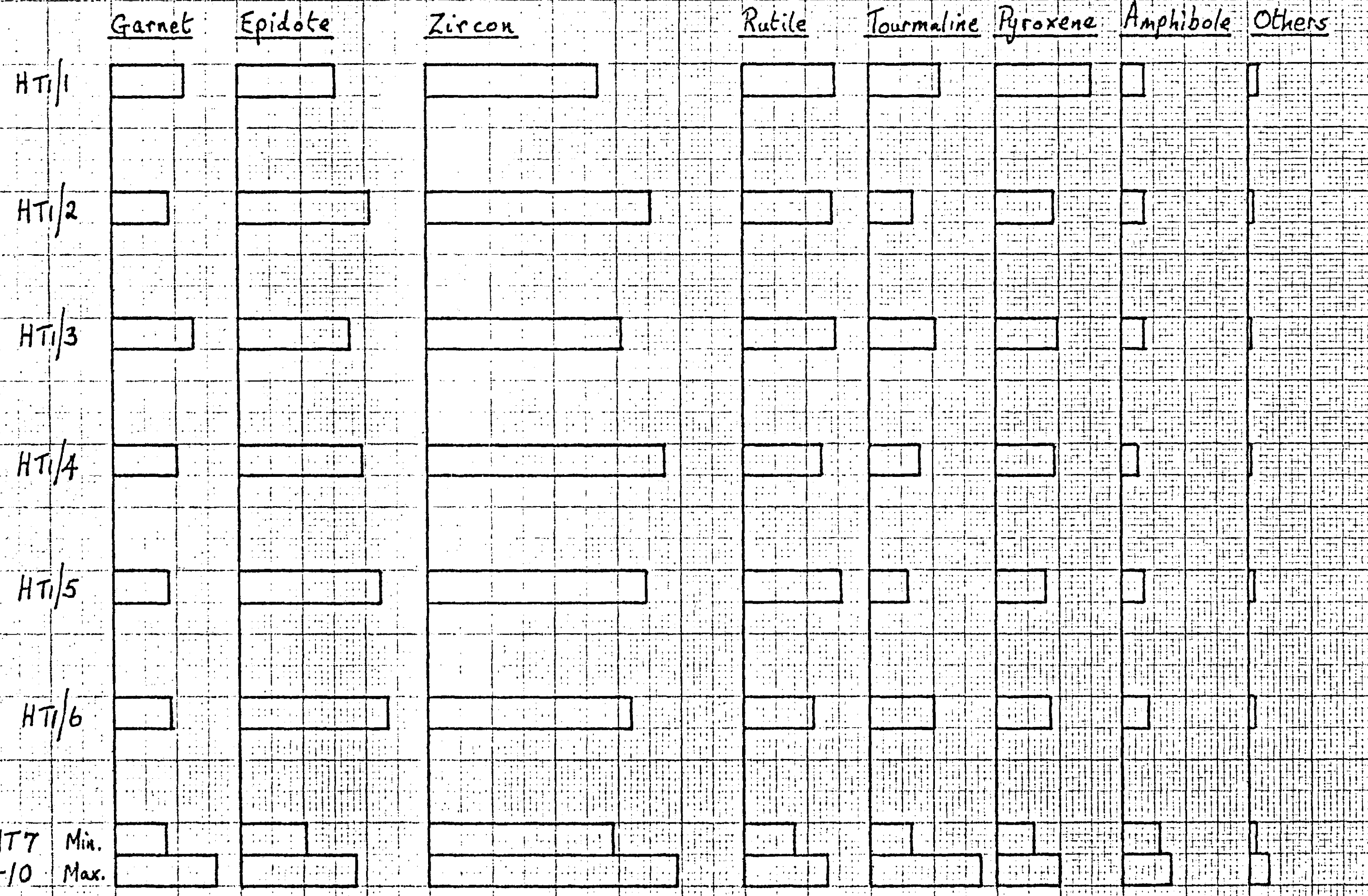


FIGURE 83 TUNSTALL PROFILE: 20-53µm HEAVY FRACTION
"Resistant" Non-Opaque Minerals

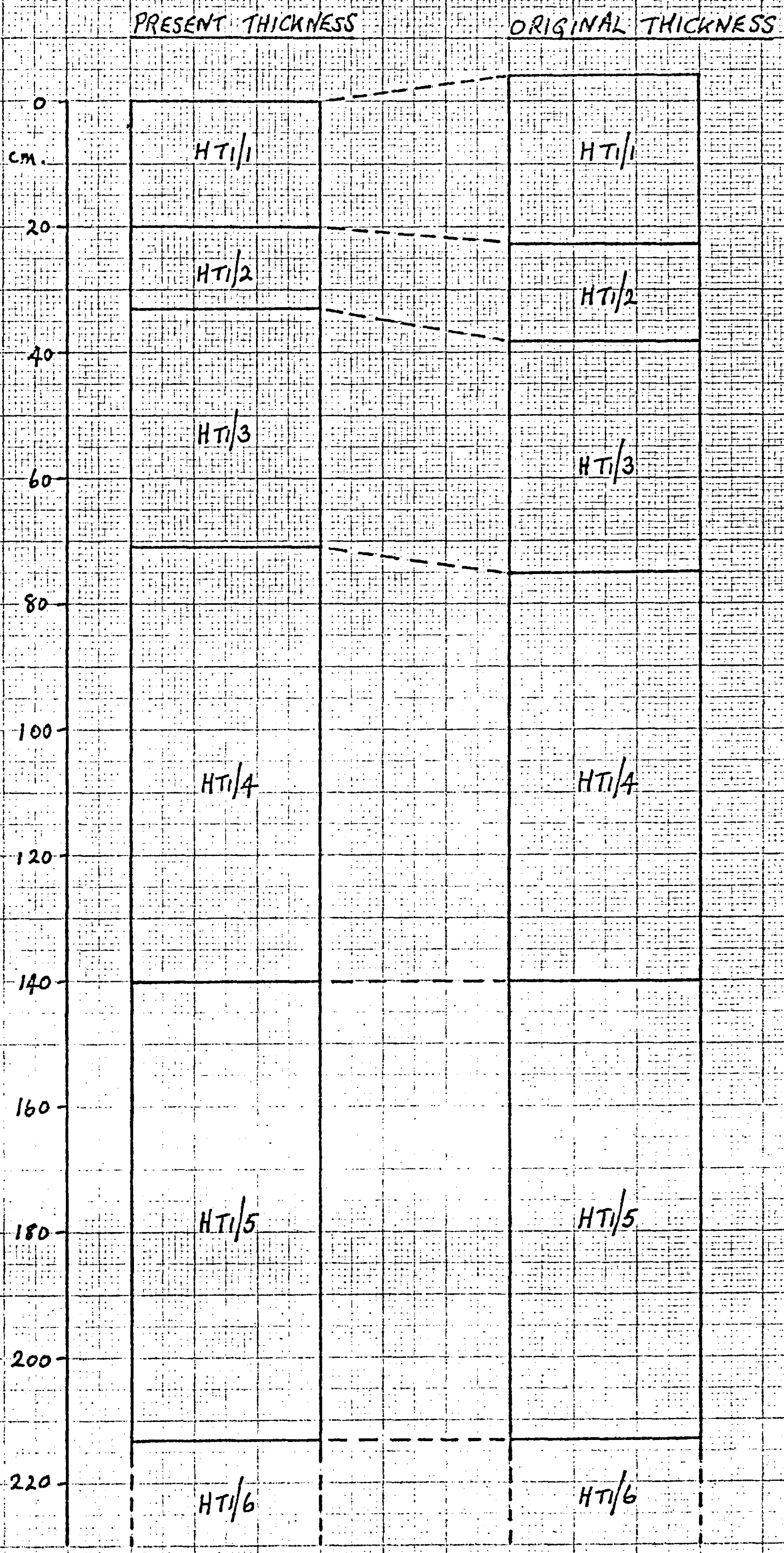


FIGURE 84 TUNSTALL PROFILE: VOLUME CHANGES

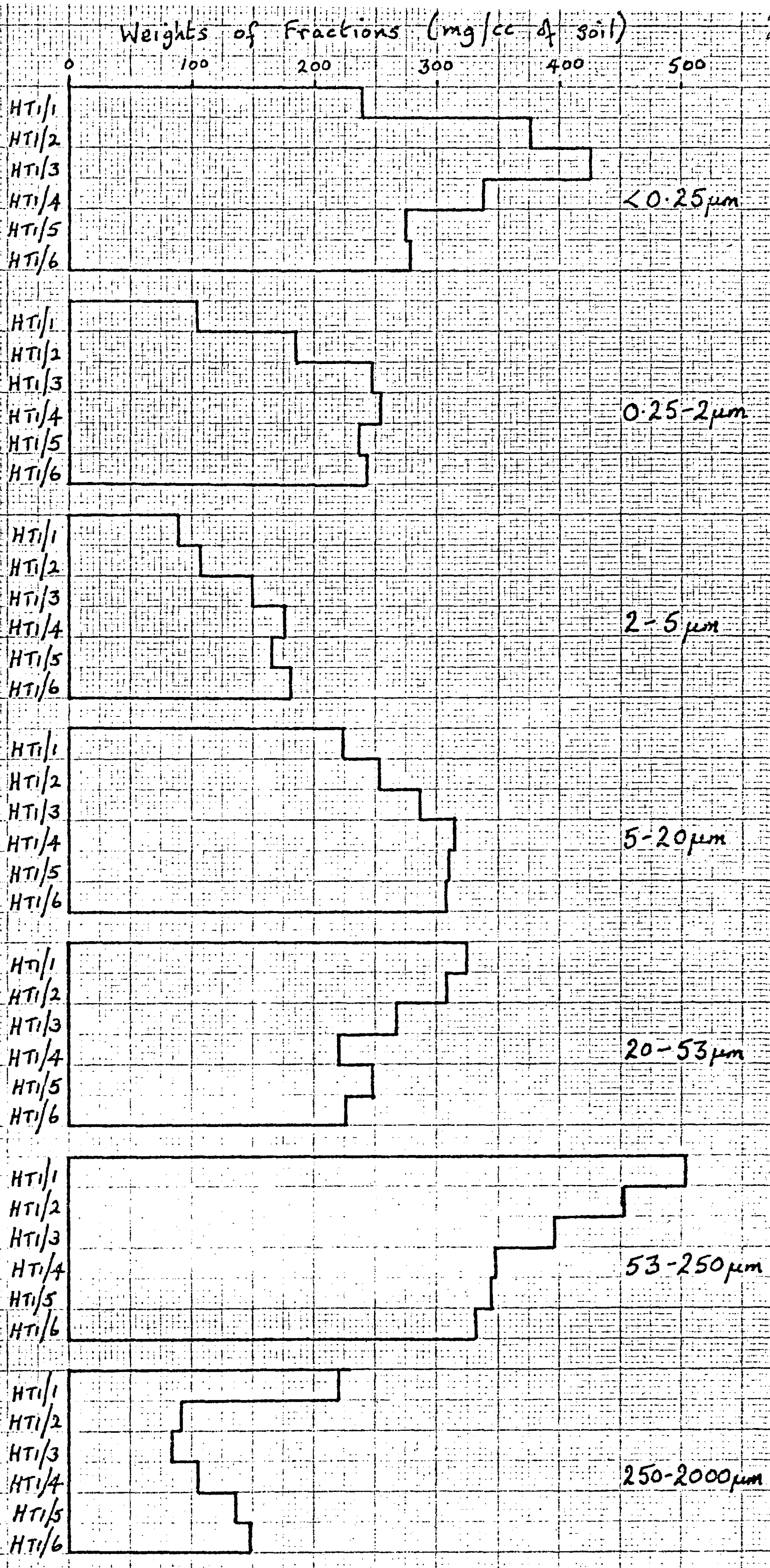


FIGURE 85 TUNSTALL PROFILE: To illustrate changes in absolute amounts of size fractions in different horizons.

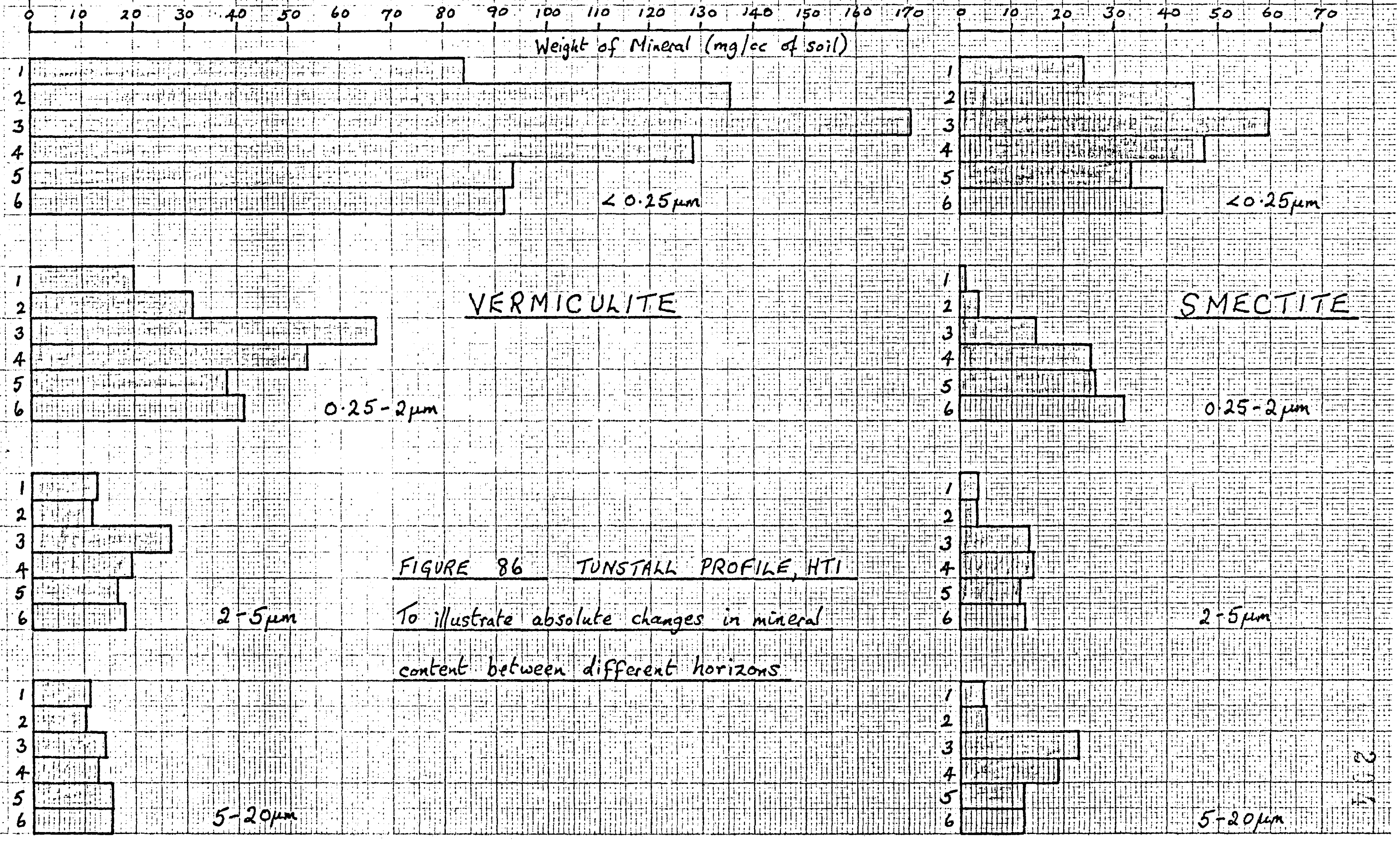


FIGURE 86 TUNSTALL PROFILE, HT1

To illustrate absolute changes in mineral content between different horizons

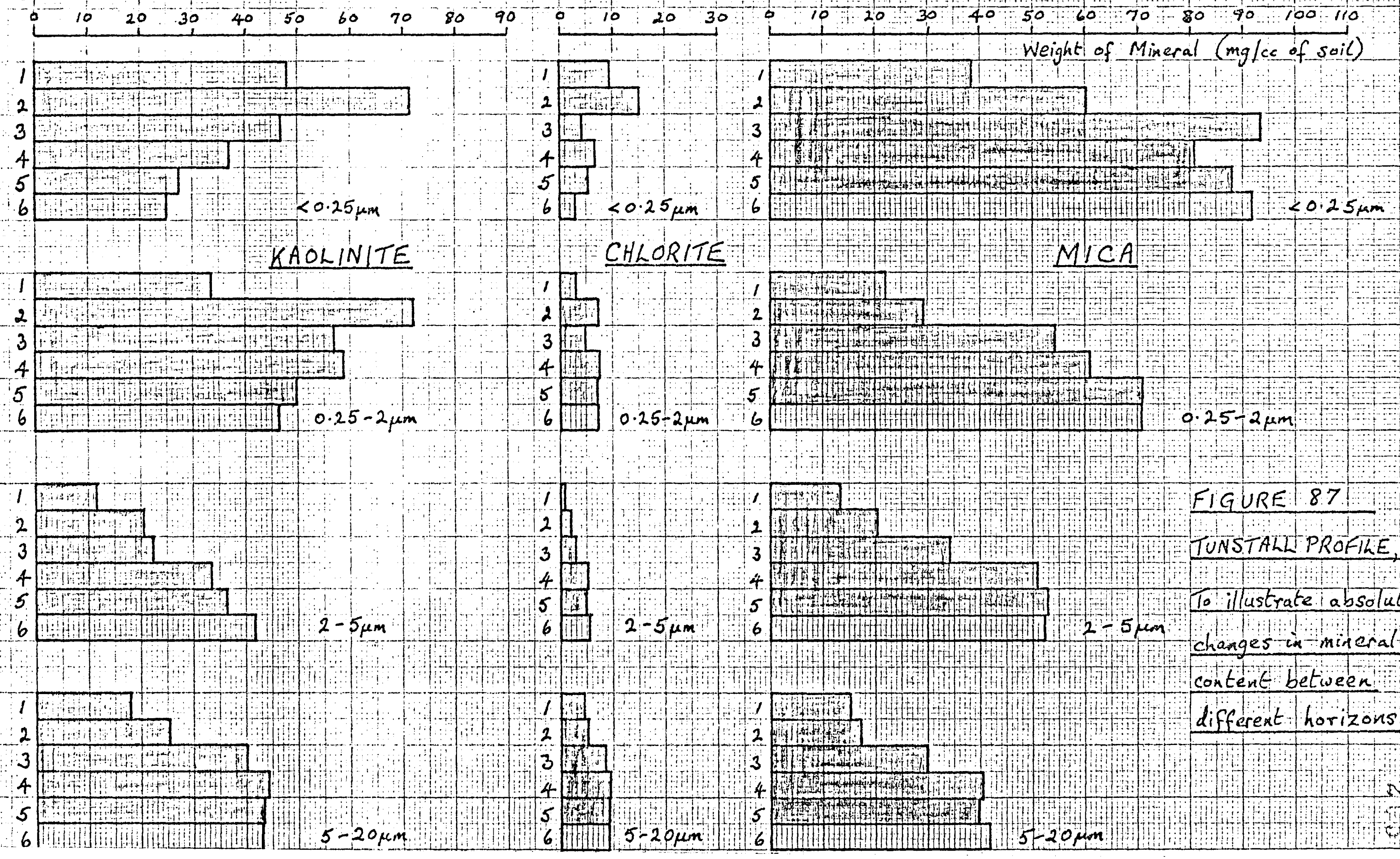


FIGURE 87

TUNSTALL PROFILE, HT1

To illustrate absolute changes in mineral content between different horizons

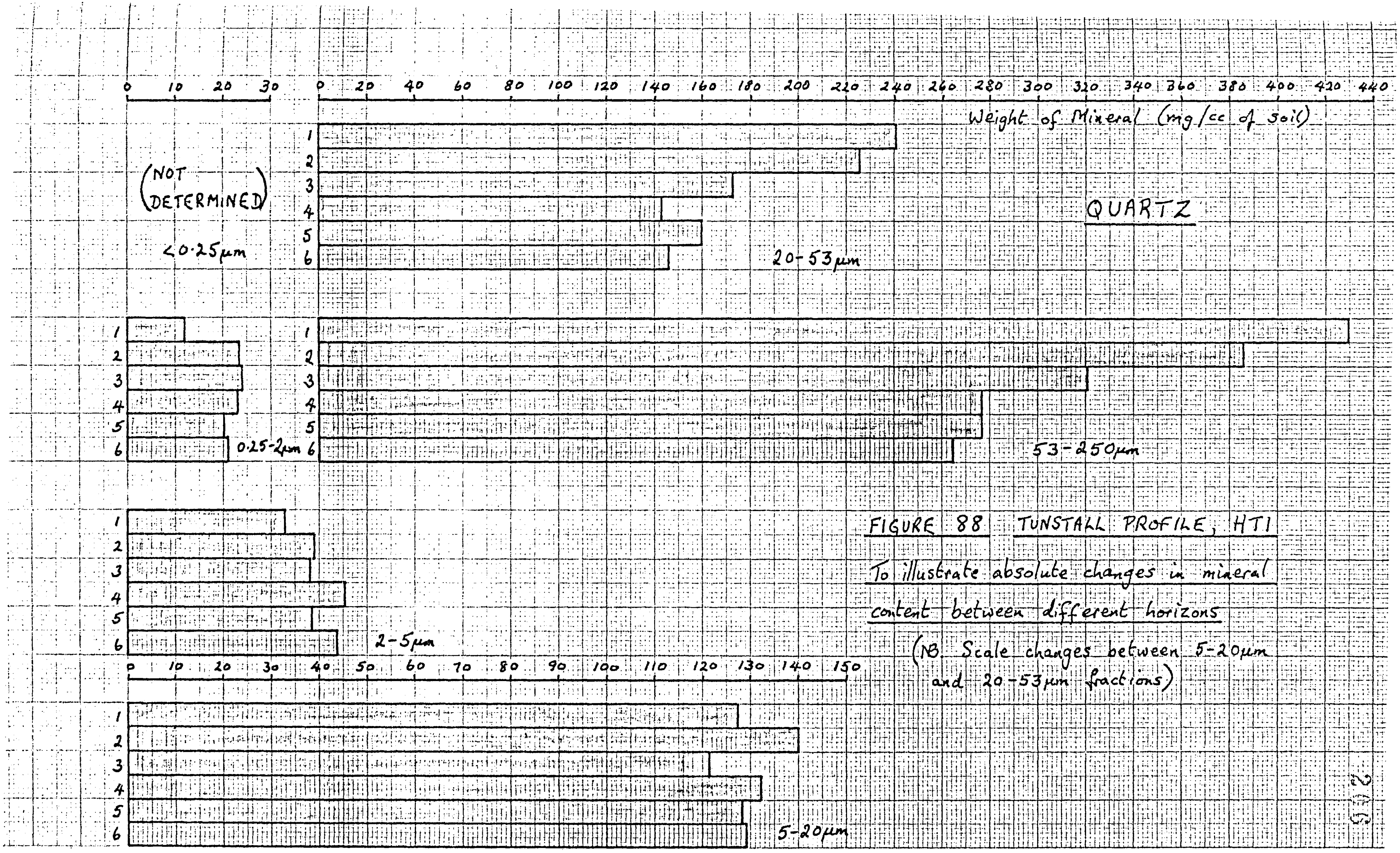


FIGURE 88 TUNSTALL PROFILE, HT1

To illustrate absolute changes in mineral content between different horizons

(NB Scale changes between 5-20μm and 20-53μm fractions)

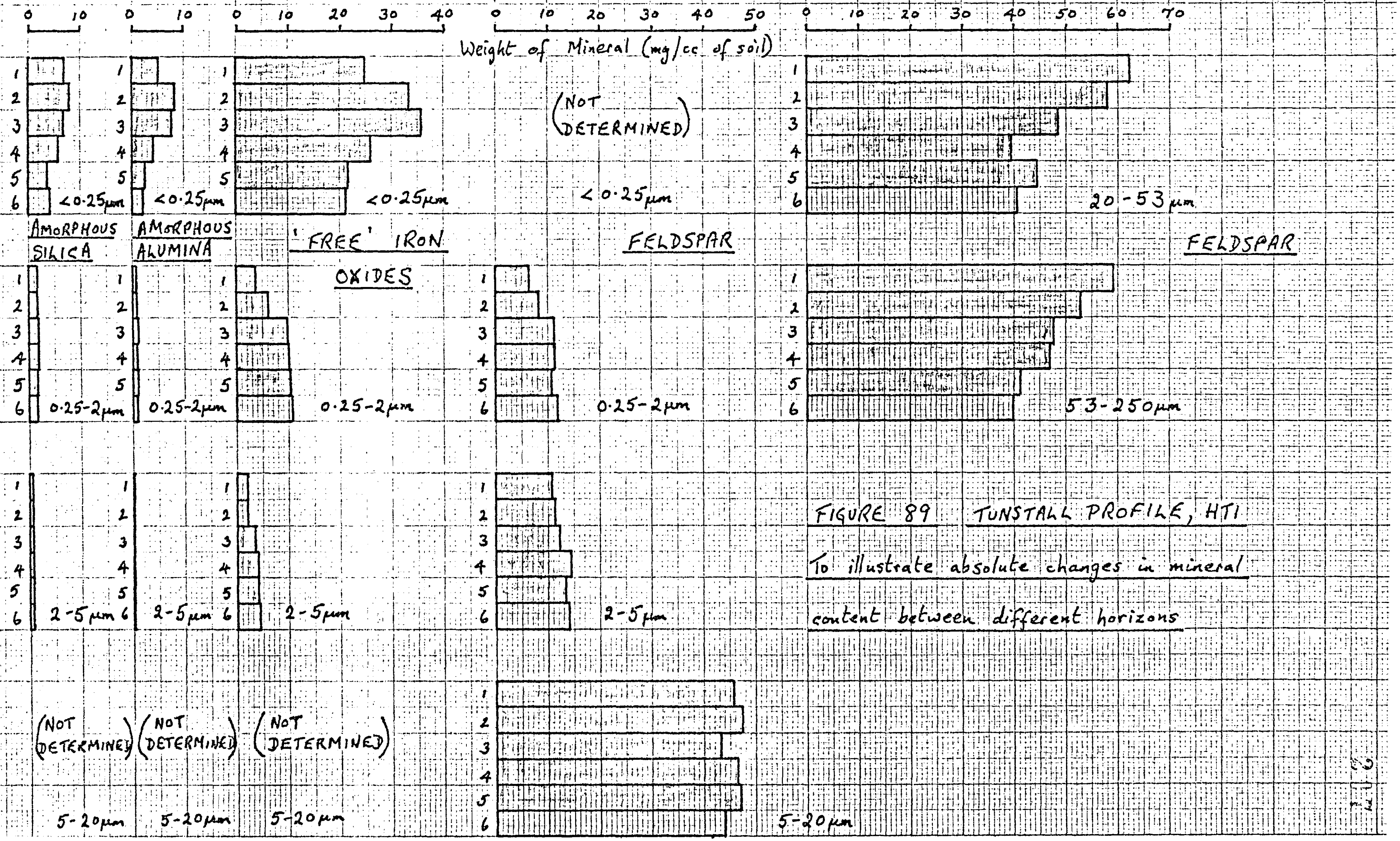


FIGURE 89 TUNSTALL PROFILE, HT1

To illustrate absolute changes in mineral content between different horizons

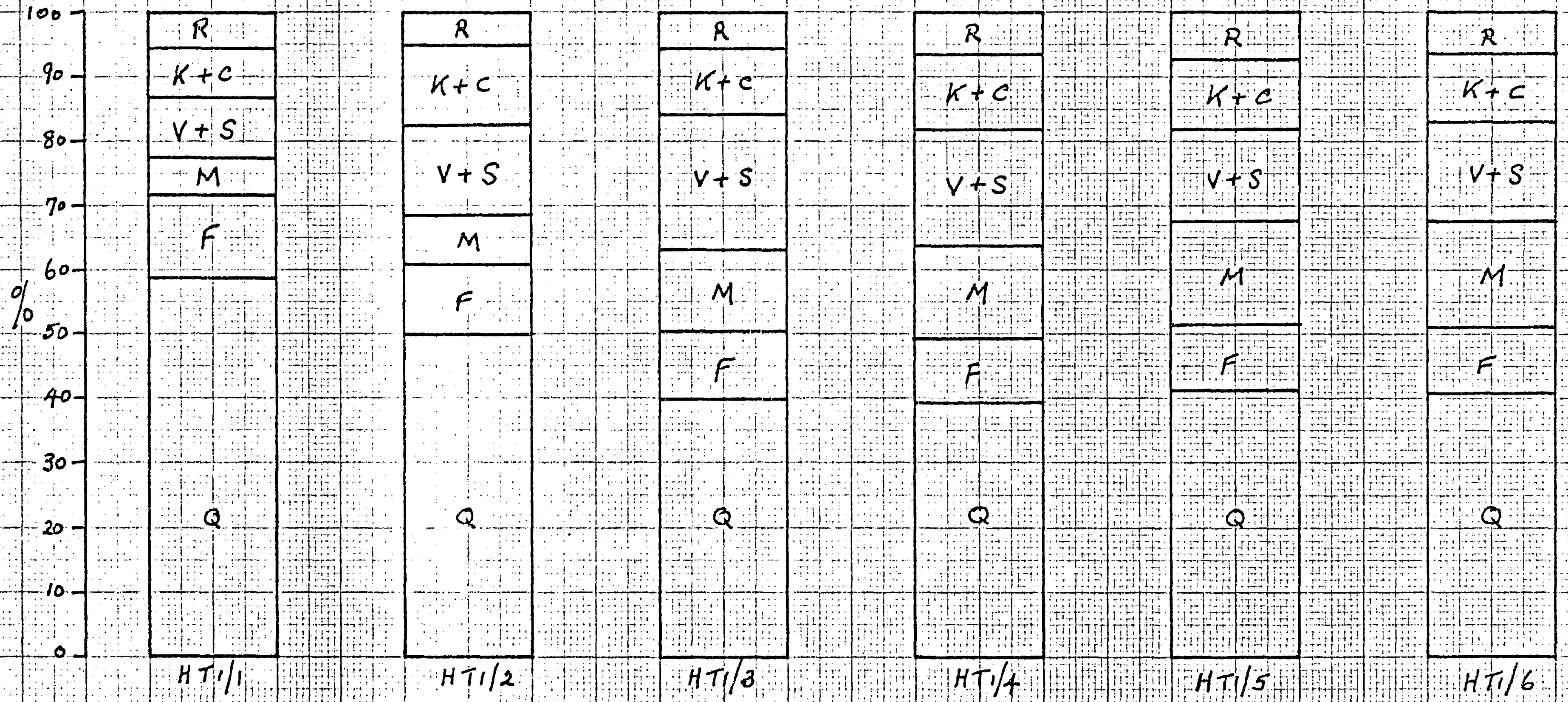


FIGURE 90 TUNSTALL PROFILE : BULK MINERALOGICAL COMPOSITION, <2mm.

Q = Quartz ; F = Feldspar ; M = Mica ; V+S = Vermiculite + Smectite ; K+C = Kaolinite + Chlorite ; R = Remainder

CHAPTER 7 CONCLUSIONS

7.1 Till Stratigraphy

The combined field and laboratory work reported and discussed in this thesis shows that the Devensian glacial sequence deposited in Yorkshire soon after 18,500 years B.P. consists of two main tills, and not three as Catt and Penny (1966) suggested. Elimination of the Hessle Till as a stratigraphic unit enables a clearer distinction to be drawn on lithological grounds between the two remaining tills. The upper (Purple) till occupies an arcuate area in south-eastern Holderness, and is also exposed in Filey Bay and other coastal regions of north-east Yorkshire, but does not occur in Lincolnshire or Norfolk. The lower (Drab) till is much more extensive, and is the only Devensian till over much of western Holderness, on the eastern slopes of the Yorkshire Wolds, and in Lincolnshire and north-west Norfolk.

The third till recognised by Catt and Penny as well as by almost all previous workers (the Hessle) is merely a deep Flandrian weathering profile on whichever of these two tills occurs at the surface; in the field the most obvious effect of this weathering is a reddening of the till. In Lincolnshire, this weathered mantle was previously also referred to as the Hessle Till; Straw (1972) recognised its true nature at South Ferriby, but there are no results of the present work to support the distinction he drew on morphological grounds between his Upper and Lower Marsh Tills in Lincolnshire. Near the presumed ice margin (e.g. on the eastern slopes of the Yorkshire and Lincolnshire Wolds), the Drab Till is thin and weathered throughout. In the north-west Norfolk coastal strip this material has previously been called the Hunstanton Till.

It is not clear whether the Drab and Purple Tills were deposited from one composite ice sheet, as Carruthers (1953) originally suggested for all the Holderness tills. Nor is it clear whether the present extent of the Purple Till is the same or less than that at the time of deposition. If subsequent erosion had removed the Purple from much of East Yorkshire and Lincolnshire, some outlying remnants might perhaps be expected, but none have been found during the present work. However, in this connection it has been interesting to examine the detailed notes on Holderness geology made by Dr.W.S.Bisat, which the Yorkshire Museum have kindly made available through Dr. L.F.Penny since Dr. Bisat's death. His descriptions and drawings of the deposits exposed on the Yorkshire coast show that he clearly understood the limited extent of the Purple Till in the section south of Hornsea, but he also recognised a small isolated mass over the Drab Till at Atwick. This must have been removed by coast erosion since he saw it, because no Purple is visible there today. Its presence suggests that some erosion has occurred between Hornsea and Atwick, possibly along the east-west valley now occupied by Hornsea Mere, and that the Purple may have originally extended a few km beyond its present limit, but probably no further.

Also among Bisat's notes were letters from Dr.J.D.Solomon, who had assembled mineralogical evidence, regrettably never published, supporting Bisat's correlation of the inland Hessle with part of the Drab of the coast section. Bisat seems to have based this correlation originally on indicator erratics, such as rhomb porphyry, and it has been confirmed in the present work by the detailed particle size analyses, the mineralogical composition of the fine sand and coarse silt fractions, and by the overall composition of fractions >2mm in the large samples taken from Dimlington and Eppleworth. Other sketches among Bisat's notes, possibly early drafts of figures intended to accompany a paper criticising Carruthers (1948), which was also never published, show that he believed the Lincolnshire Hessle and the Hunstanton Till of Norfolk to be equivalent to the Drab, and also that the Purple Till extended inland from the Holderness coast as a "basin" covering almost the same area as that of Hessle Zones A and B in Figure 61 .

The Basement Till, which is exposed on the Yorkshire coast in Filey Bay, on Flamborough Head, and at Sewerby, Bridlington and Dimlington (Catt and Penny, 1966), probably extends beneath the Drab into Lincolnshire, as a till resembling it in colour, texture, and sand and silt mineralogy, occurs at Welton-le-Wold. Its correlation with the North Sea Drift, which has been suggested by Reid (1885) and others, seems to be ruled out by the Wolstonian age indicated at Welton-le-Wold by Hoxnian mammals and Acheulian implements in the subjacent gravels. Unless convincing evidence of Wolstonian glacial deposits is found in East Anglia, the limit of the Wolstonian glaciation in eastern England should therefore be drawn somewhere in south Lincolnshire.

The relationship of the Calcethorpe, Wragby, Belmont and Heath Tills of Lincolnshire (Straw, 1969b) to the Basement Till and the East Anglian glacial succession is still uncertain. At present, it is only possible to state that they are local facies of a glacial cover, which may be either similar in age to the Basement of Holderness and Welton-le-Wold (i.e. probably Wolstonian), or equivalent to the Lovestoft Till (i.e. Anglian). An Anglian age is perhaps favoured slightly by the general lithological similarity of the Wragby Till to the Lowestoft Till, and by its extension southwards to the R. Witham, where it passes beneath the Fenland and could emerge beyond as part of the Lowestoft Till. Also, outlying masses of Wragby Till ~~ase~~ are mapped as far north as Brigg (Straw, 1969b, Fig. 3), only 3-4 km west of Kirmington, and may be represented in the Kirmington borehole (Stather, 1905c) by the lead-coloured clay beneath the Hoxnian Interglacial beds.

7.2 History of Soil Development

Soil development on the Devensian tills cannot have started until approximately 14,000 years B.P. at the earliest, and probably occurred mainly during the Flandrian period. The prismatic structure of the soils, particularly evident down to about 1m depth, was probably the first soil feature to develope, as a consequence of the drying out of the till after retreat of the ice. This has subsequently allowed oxidation to occur, at least to the depth of the permanent water table in the till. Pyrites and siderite have both been completely oxidised, and there has been a colour change from the 7.5YR 3/2 of the Purple and 10YR 3/2 of the Drab Till to the 5YR 3/4 or 5YR 4/4 typical of the uppermost few metres of whichever till occurs at the surface. Such reddening is regarded by some workers as evidence of soil development during a warm period before the Devensian, but as this is clearly not so in eastern England the criterion must be unreliable.

Leaching of the soil has promoted decalcification, typically to a depth of about 0.7m where the till is thick, but to greater depths in better drained situations, where thin till overlies Chalk or gravels. Dissolution of chalk and limestone erratics together with the lime in the soil matrix has occurred in upper horizons of the soils, and calculations made on the Tunstall profile show that 97 % of the carbonate is lost in the ground water, and only 3% has been redeposited lower in the profile to form small pink secondary concretions.

Grey (5GY 5/1) ped faces developed, most prominently between 0.3 and 2.0m depth, by reduction and leaching of iron, and also by redeposition of a little secondary carbonate. The impeded drainage in the soil has also led to development of the pronounced mottling in sub-surface horizons, and redeposition of some of the mobilised iron has resulted in secondary ferruginous concretions in similar parts of the profile.

Decalcification would have originally lowered the bulk density of the soil, but in the upper parts of the profile the present bulk density of <2mm carbonate-free soil is greater than that of the parent till. Therefore the voids left by removal of carbonate have either been closed by compaction of the soil or filled with clay translocated from higher horizons.

The detailed particle size distribution of non-clay fractions and the mineralogical composition of heavy separates from the fine sand and coarse silt fractions showed that the profile at Tunstall developed in almost uniform till, so that all the textural and mineralogical differences between horizons can be attributed to weathering and other pedological changes <u>in situ</u>, and not to admixture of other materials deposited over the till. Prominent among the effects of weathering was the breakdown of stones in the upper 1.4m. Chalk and limestone fragments were dissolved from the highest 71cm; shale and sandstone were disaggregated in the same horizons and to a lesser extent in horizon 4 (71-140 cm), thereby increasing the the clay and sand contents of these horizons; many of the igneous and metamorphic erratics were also weathered and disaggregated in the upper horizons. The greatest alteration of stones occurred in the surface soil (0-20cm depth).

Weathering of rock fragments <u>in situ</u> does not, however, account for all the textural differences between the various horizons of the Tunstall profile and the parent till. In particular, there has been an overall loss of 16.2g of <2mm carbonate-free soil per cm^2 column of the highest 33cm (amounting to 22 % of that originally present), and a gain of 17.4 g of the same sized material in a similar column through the much greater thickness of horizons 3 and 4 (33-140cm), which amounts to a 10 % increase. Translocation of clay, especially fine clay, must have occurred from the upper 33cm to these lower horizons, even though there is little micromorphological evidence for redeposition of clay. Much of this clay was produced in the upper horizons by disaggregation of shale fragments and other weathering processes. However, production of fine clay in the upper horizons must have outpaced its removal by eluviation, as ratios of fine clay to total clay increase continuously up the profile, and no argillic horizon as defined by Avery (1973) can be recognised.

Weathering changes affecting the mineralogy of fractions finer than 2mm include the complete oxidation of pyrites and siderite down to depths of approximately 5m, the removal of biotite, chlorite and chamosite mainly from the highest 33cm but also to some extent down to 140cm, and the almost complete dissolution of apatite and collophane and the partial weathering of pyroxenes in the highest 33cm. Layer silicates have undergone both physical and chemical weathering mainly in the highest 33cm, contributing thereby to the fine clay which was partly translocated to subjacent horizons. Kaolinite seems to have undergone simple physical degradation and has been translocated. However, mica has in addition been chemically weathered, mainly to fine clay vermiculite, and much of this was translocated. About 50 % of the original content of layer silicates has been removed from the highest 33cm of the profile. Horizons 3 and 4 (33-140cm depth) have increased their layer silicate content by 14 %, which corresponds to a little less than the amount removed from the highest 33cm, and is almost the same as the gain of fine clay in horizons 3 and 4; this reinforces the evidence for translocation of fine clay down the profile.

APPENDIX (TABLES 3-77)

TABLE 3 LOCATIONS OF SAMPLES

HT1 TUNSTALL TA 314318

Soil profile in Hessle Till. See Chapter for full details.

HT2 HOLKHAM TF 863428

Soil profile in Hunstanton Till. See Chapter for full details.

HT3 STIFFKEY TF 987441

Small bank exposure of Hunstanton Till at west side of R. Stiffkey.

0-45cm. Flinty colluvial material.

45-90cm. Reddish brown Hunstanton Till, decalcified.

90cm + (seen to 135cm) Well-rounded flint gravel (raised beach of Solomon, 1932a, p.257; Baden-Powell & West, 1960, p.78).

Till sampled at 45-90cm below surface.

HT4 BACTON TG 333350

Pocket of silty drift infilling hollow in Bacton Valley Gravels at top of cliff at Gas Terminal Site.

"Hessle Till" of Baden-Powell (1944).

HT5 KEYINGHAM TA 235255

Lens of reddish brown Hessle Till exposed above the Kelsey Hill Gravels, on the south face of the gravel pit.

HT6 KIRKBURN SE 975566

Shallow soil profile pit dug in centre of harvested barley field on Kirkburn Manor Farm, at the feather edge of the till outcrop.

0-15cm. Plough layer; silty, with many chalk, flint, and erratic pebbles. (KMF1)

15-23/35cm. Variable thickness of reddish brown decalcified Hessle Till. (KMF2; HT6).

23/35cm + Silty chalky head, possibly containing loess. (KMF3).

Till sampled at 15-35cm below surface.

HT7 DIMLINGTON TA 397408

Cliff exposure, 350m north of Dimlington Road Ends.

Dimlington cliffs expose Hessle Till over Purple, Drab and Basement Tills.

Hessle Till sampled at 180-210cm below the surface, below the zone of secondary carbonate, and just above a gravel layer.

HT8 DIMLINGTON TA 393216

Cliff exposure, 350m south of Dimlington High Land.

Hessle Till sampled at 210cm below the surface, in the zone of secondary carbonate.

HT9 DIMLINGTON TA 394215

Cliff exposure, 400m south of Dimlington High Land.

Hessle Till sampled at 210-240cm below the surface, just below the zone of secondary carbonate.

HT10 DIMLINGTON TA 392217

Cliff exposure, 200m south of Dimlington High Land.

Hessle Till sampled at 270cm below the surface, 90cm below the zone of secondary carbonate.

HT11 WALKINGTON SE 997385

Abandoned chalk quarry at the cross-roads, 1 mile north of the village.

0-170cm Reddish-brown decalcified Hessle Till.

170cm + Chalk.

Till sampled at 80-85cm.

HT12 EPPLEWORTH TA 021324

Abandoned chalk quarry half a mile north-east of the village, on the southern side of a dry valley.

Succession at southern end of east face:-

0-25cm Dark grey loamy flinty hill wash

25-55cm Reddish-brown decalcified Hessle Till

55-145cm Reddish-brown calcareous Hessle Till

145-280cm Reddish-brown calcareous Hessle Till, with gleyed fissures

280-300cm obscured by talus.

300cm + Chalk.

Till sampled at 160-170cm.

The till decreases in thickness towards the northern end of the east face, where the till is only 15-30cm thick, and overlies a thinly bedded silty deposit containing much comminuted chalk, which itself overlies silty chalky head (sample EP1) over solid chalk.

HT13 and HT14 WOODMANSEY TA 023383

Working chalk quarry half a mile north of Victoria Barracks.

Succession at southern end of east face:-

0-25cm	Plough layer
25-95cm	Strong brown sandy loam
95-140cm	Reddish-brown decalcified Hessle Till
140-320cm	Reddish-brown calcareous Hessle Till
320cm +	Chalk

Till sampled at 190-200cm (HT13)

Sandy loam sampled at 35-45cm (HT14)

HT15 LOCKINGTON SE 973464

Abandoned chalk quarry at junction of unclassified road from Lockington with B1248 Beverley to Malton road.

0-150cm	Reddish-brown decalcified Hessle Till
150cm +	Chalk

Till sampled at 80-85cm at south-east end of quarry.

HT16 KILNWICK SE 974499

"Superfine Chalks" Hornhill Works chalk quarry.

Succession at north-east end of quarry:-

0-25cm	Plough layer
25-90cm	Reddish-brown decalcified Hessle Till
90-300cm	Reddish-brown calcareous Hessle Till
300cm +	Chalk

Till sampled at 140-150cm.

HT17 RUSTON PARVA TA 070618

Ruston Limeworks chalk quarry, on north-east side of NW-SE dry valley.

Succession at north-east end of quarry:-

0-25cm	Plough layer
25-200cm	Reddish-brown decalcified Hessle Till
200-350cm	Silty chalky head
350cm +	Chalk

Till sampled at 110-130cm

On the north-west face of the quarry exposures showed the till grading progressively, in a north-east to south-west direction (i.e. towards the dry valley) into sandy and gravelly beds overlying the chalky head.

HT18 FOSTON TA 103571

Roadside trench, Gembling Lane End, cut in Hessle Till.

Trench already infilled, sample taken from loose blocks of yellowish brown calcareous till lying on the surface, original depth unknown.

HT19 BEEFORD TA 122540

Foundation trench for new house, west end of village, cut in Hessle Till.

Trench already filled in, sample taken from loose blocks of yellowish red decalcified till lying on the surface, original depth unknown.

HT20 HUTTON CRANSWICK TA 025529

Abandoned chalk quarry at south end of Hutton village.

Succession exposed on east face of quarry:-

0-180cm	Reddish-brown decalcified Hessle Till
180cm +	Chalk

Till sampled at 120cm below surface.

HT21 NAFFERTON TA 060584

Bank exposure 5m from confluence of small west bank tributary with Nafferton Beck, south of village.

About 2m of brown (Hessle?) till overlying dark brown (Drab) till.

Sampled at 150cm below surface, in calcareous till.

HT22 HARPHAM TA 082624

Drainage ditch on verge in north-east corner of cross-roads.

Brown calcareous (Hessle?) till sampled 180cm below surface at bottom of ditch.

HT23 BRIDLINGTON TA 163670

Abandoned chalk quarry at east end of town.

50-100cm of chalky hill wash overlying 0-30cm of reddish brown decalcified Hessle Till, on chalk. Till sampled at its thickest development.

HT24 ULROME TA 177570

Cliff exposure, 100m south of road ending.

200cm of reddish brown Hessle Till overlying Drab Till.

Decalcified till sampled at 100cm from surface.

HT25 SKIPSEA TA 182553

Cliff exposure 20m north of road ending.

60cm of "made ground" overlying reddish brown Hessle Till, over Drab Till.

Calcareous till sampled at 190cm below surface.

HT26 HORNSEA TA 212472

Cliff exposure 20m south of end of sea wall.

"Made ground" overlying reddish brown Hessle Till, over Drab Till.

Calcareous till sampled at 130cm below base of "made ground".

HT27 ALDBROUGH TA 257396

Cliff exposure 20m south of road ending.

Reddish brown Hessle Till overlying Purple Till over Drab Till.

Calcareous till sampled at 130cm from surface.

HT28 FLINTON TA 230362

Drainage ditch on south side of B1238, exposing reddish-brown Hessle Till.

Calcareous till sampled at 170cm below surface.

HT29 SPROATLEY TA 203350

Drainage ditch on north side of B1238, exposing reddish-brown Hessle Till.

Calcareous till sampled at 180cm below surface.

HT30 BILTON TA 156343

South bank of small stream, at east side of road, exposing brown (Hessle?) till.

Calcareous till sampled at 190cm below surface.

HT31 LONG RISTON TA 118428

Drainage ditch at east side of A165, exposing about 300cm reddish brown Hessle Till over Drab Till.

Calcareous till sampled at 250cm below surface.

HT32 WAWNE TA 096364

Dutch auger sample, taken from the middle of ploughed field, midway down slope between farm and stream. Sandy soil at top of slope, Drab Till exposed in bank of stream. Reddish brown Hessle Till outcrops along steepest sections of slopes.

Calcareous till sampled at 60-100cm (HT 32)

HT33 SOUTH SKIRLAUGH TA 139393

Drainage trench on new housing estate, south side of Meaux road, east of village, exposing reddish brown Hessle Till.

Decalcified till sampled at 105cm from surface.

HT34 SEATON TA 167476

Bank of roadside stream, half a mile north-east of village, exposing brown (Hessle?) Till.

Calcareous till sampled at 150cm below surface.

HT35 MARTON TA 179392

Bank of stream, north side of road, exposing reddish brown Hessle Till.

Calcareous till sampled at 150cm below surface.

HT36 FITLING TA 249349

Bank of drainage ditch on west side of road exposing reddish brown Hessle Till.

Calcareous till sampled at 180cm below surface.

HT37 HOLME- NEXT-THE-SEA TF 706430

Foundation trench on housing development exposing reddish brown decalcified Hunstanton Till.

Till sampled at 105cm below surface.

HT38 EASINGTON TA 408188

Cliff exposure at road ending, showing brown (Hessle?) till over Drab Till.

Calcareous till sampled at 150cm below surface.

HT 39 GRIMSTON HALL TA 288352

Cliff exposure at northern end of Late-glacial deposit and land-slipped area. Dark reddish brown Hessle Till exposed at cliff top; underlying strata obscured by talus. Calcareous till sampled at 120 cm below surface.

HT 40 HESSLE TA 013261

Abandoned chalk quarry; type-site of "Hessle Till". Succession is :

	Made Ground
0-115 cm	Reddish brown decalcified till
115-160 cm	Angular chalky gravel
160-190 cm	Fractured chalk
190 cm +	Chalk

Decalcified till sampled at 90-100 cm below "made ground".

HT 41 DIMLINGTON TA 401204

Cliff exposure at southern end of Dimlington Road Ends.

Reddish brown calcareous till sampled at 100 cm below cliff top.

HT 42 DIMLINGTON TA 402203

Cliff exposure south of Dimlington Road Ends.

Reddish brown calcareous till sampled at 100 cm below cliff top.

HT 43 DIMLINGTON TA 403200

Cliff exposure south of Dimlington Road Ends.

Dark reddish brown calcareous till sampled at 100 cm below cliff top.

HT 44 DIMLINGTON TA 403199

Cliff exposure 50 m north of boundary fence to Gas Terminal.

Dark reddish brown calcareous till sampled at 100 cm below cliff top.

HT 45 EASINGTON TA 404196

Cliff exposure south of Gas Terminal.

Dark reddish brown calcareous till sampled at 100 cm below cliff top. 30 cm sand layer below this upper till, underlain by brown till (oxidised Drab Till ?) passing down into unoxidised, very dark greyish brown Drab Till occupying the remainder of the cliff. Upper reddish brown till possibly represents the oxidised feather edge of the Purple Till.

HT 46 EASINGTON TA 407191

Cliff exposure close to Coastguard Lookout. Reddish brown till seems to grade down into unoxidised very dark greyish brown Drab Till. Between this and HT 45 the Drab Till is overlain by a complex of gravels and reddish brown till.

Reddish brown calcareous till sampled at 100 cm below cliff top. Probably represents oxidised Drab Till.

HT 47 GREAT COWDEN TA 236427

Cliff exposure:

0-25 cm	Plough layer
25-130 cm	Lacustrine clays
130-450 cm	Dark reddish brown till
450-500 cm	Sandy seams in till
500 cm +	Purple Till
Base of cliff	Drab Till

Dark reddish brown calcareous till sampled at 170-180 cm below cliff top

HT 48 PATRINGTON TA 307217

Auger sample of mottled reddish brown calcareous till at 70-90 cm below surface.

HT 49 BOREAS HILL TA 182250

Abandoned gravel pit. Reddish brown calcareous till exposed on west face, sampled at 100 cm depth.

HT 50 WELWICK TA 342200

Auger sample of mottled yellowish red calcareous till at 65-80 cm below surface.

HT 51 WELWICK TA 348217

Drainage ditch exposure, 400 m south of North Farm. Dark reddish brown calcareous till sampled at 2m below surface.

HT 52 ATWICK TA 197510

Cliff exposure; slipped block (still with turf cover) utilised for sampling.

0-120 cm	Dark reddish brown till
120 cm +	Reddish brown clayey sand, 2-3 m thick in localised pockets
c. 2m +	Dark brown unoxidised Drab Till

Dark reddish brown calcareous till samples at 80-90 cm below surface.

HT 53 ELSTRONWICK TA 233313

Stream exposure. Drab Till exposed in bed of stream, 3-5 m below land surface. Mottled brown calcareous till sampled at depth of 2m in bank of stream.

HT 54 MAPPLETON (WITHERNWICK ROAD) TA 222417

Auger sample of yellowish red calcareous till at 80-105 cm below surface.

HT 55 HOLLYM TA 344245

Drainage ditch exposure. Dark reddish brown calcareous till sampled at 150 cm depth.

HT 56 EPPLEWORTH TA 021324

See HT 12 for stratigraphical details. Bulk sample of brown calcareous till at 250 cm depth for stone analysis.

HT 57 DIMLINGTON TA 398207

Cliff exposure between Dimlington Road Ends and Dimlington Farm. Bulk sample of mottled yellowish brown decalcified till at 30-50 cm depth for stone analysis.

HT 58 DIMLINGTON TA 398207

As for HT 57; reddish brown mottled, decalcified till sampled at 50-80 cm depth

HT 59 DIMLINGTON TA 398207

As for HT 57; reddish brown calcareous till sampled at 130-170 cm depth.

PT 1 TUNSTALL TA 314318

Cliff exposure, showing Hessle, Purple and Drab Tills.

Purple Till sampled at 8m below surface.

PT 2 DIMLINGTON TA 396211

Cliff exposure, showing Hessle, Purple, Drab and Basement Tills.

Purple Till sampled from slipped mass 600 m north of Dimlington Road Ends.

PT 3 DIMLINGTON TA 392217

Cliff exposure, near Dimlington High Land.

Purple Till sampled from slipped mass

PT 4 DIMLINGTON TA 392217

Cliff exposure, near Dimlington High Land

Purple Till sampled 8m below surface, near boundary between Hessle and Purple Tills.

PT 5 DIMLINGTON TA 396211

Cliff exposure, 570m north of Dimlington Road Ends

Purple Till sampled 120 cm above junction with Drab Till.

PT 6 GRIMSTON HALL TA 289352

Cliff exposure. Purple Till sampled 50 cm below Zone II peat, from slipped mass.

PT 7 GREAT COWDEN TA 236427

See HT 47 for details of stratigraphy.

Purple Till sampled at 7m below surface.

PT 8 KEIGHTON TA 149756

Cliff exposure on New Closes Cliff; at cliff top above extensive landslipped area. Purple Till sampled at 8m depth below top of cliff.

PT 9 DIMLINGTON TA 401204

Cliff exposure at south end of Dimlington Road Ends.

Bulk sample of Purple Till at 8m depth, for stone analysis.

DT 1 DIMLINGTON TA 397210

Cliff exposure, north of Dimlington Farm.

Drab Till sampled 200 cm above junction with Basement Till.

DT 2 KEYINGHAM TA 236254

Deep drainage trench in base of gravel pit, exposing Drab Till below Kelsey Hill Gravels.

DT 3 DIMLINGTON TA 397210

Cliff exposure, 500m north of Dimlington Road Ends.

Drab Till sampled 6m below junction with Purple Till.

DT 4 DIMLINGTON TA 396211

Cliff exposure, 540 m north of Dimlington Road Ends.

Drab Till sampled 150 cm above junction with Basement Till.

DT 5 DIMLINGTON TA 396211

Cliff exposure, 570m north of Dimlington Road Ends.

Drab Till sampled 150 cm above junction with Basement Till.

DT 6 DIMLINGTON TA 396211

Cliff exposure, 600 m north of Dimlington Road Ends.

Drab Till sampled 250 cm above junction with Basement Till.

DT 7 DIMLINGTON TA 395212

Cliff exposure, 630 m north of Dimlington Road Ends.

Drab Till sampled 120 cm above junction with Basement Till.

DT 8 DIMLINGTON TA 392217

Cliff exposure, near Dimlington High Land.

Drab Till sampled 180 cm above junction with Basement Till.

DT 9 GRIMSTON HALL TA 289352

Cliff exposure at Zone II locality.

Drab Till sampled 350 cm below junction with Purple Till.

DT 10 NAFFERTON TA 060584

Bank exposure at confluence of small west bank tributary with Nafferton Beck, south of village.

2m of ?Hessle Till over Drab Till. Drab Till sampled at stream level, 3m below surface.

DT 11 FRAISTHORPE TA 170625

Cliff exposure, 300m south of Auburn House "Picnic Place".

Gravels over Drab Till. Till sampled at base of cliff.

DT 12 LONG RISTON TA 118428

Drainage ditch on east side of A 165. 3m of Hessle Till over Drab Till.

Drab Till sampled at 350 cm below surface.

DT 13 MEAUX TA 095390

South bank of Holderness Drain between old and new road bridges.

Drab Till sampled 350 cm below surface.

DT 14 SPEETON TA 145760

Cliff exposure; Drab Till overlying Speeton Shell Bed.

DT 15 SEWERBY TA 198683

Foreshore exposure, 100m west of pillbox, 400m east of Bridlington promenade. Drab Till overlying chalk rubble.

DT 16 SEWERBY TA 198685

Cliff exposure. Drab Till sampled at 6.5m below cliff top, 1.5m below contact with overlying outwash gravels. Directly above the notch of the buried cliff where exposed in present cliff.

DT 17 ATWICK TA 197510

See HT 52 for details of stratigraphy.

Drab Till sampled at 8m below surface.

DT 18 DIMLINGTON TA 401204

Cliff exposure, at southern end of Dimlington Road Ends.

Bulk sample of Drab Till from base of cliff, for stone analysis.

D1 - D7 DIMLINGTON TA 398207

Cliff exposure. Successive samples of "Hessle Till" soil profile at 1m depth intervals (D1 - D5); gradational boundary between oxidised and unoxidised till at about 5m depth. D6 and D7 are unoxidised Purple Till samples at 5.5 and 6m depth respectively.

D8 - D16 DIMLINGTON TA 393215

Cliff exposure, Dimlington High Land, base of cliffs.

D8 Purple Till, 0-10cm above bedded clayey fine sands, over Drab Till.

D9 Drab Till, 40-50cm below base of Purple Till; Drab Till merges gradually upwards into bedded silts and sands below Purple Till.

D10 - D14 Drab Till sampled at 1m intervals below junction with Purple Till (D10, 1m below; D11, 2m; D12, 3m; D13, 4m; D14, 5m).

D15 Drab Till 9m below junction with Purple Till (laminated silty beds and slipped material 5-9m below Purple Till).

D16 Drab Till 10m below Purple Till, 1m above beach level.

S1 - S7 SKIPSEA TA 186541

Cliff exposure. Successive samples of "Hessle Till" soil profile at 0.5m depth intervals. At 3.5m (S7), the oxidised till grades into unoxidised Drab Till.

S8 - S9 SKIPSEA TA 186541

Site as for S1 - S7. Drab Till at 6.5m and 9m depth respectively.

A1 - A4 ALDBROUGH TA 259395

Cliff exposure. Drab Till at base of cliff. A1 at 1m above beach level; A2, 2m; A3, 3m; A4, 4m.

A5 - A6 ALDBROUGH TA 259395

Site as for A1 - A4.

Purple Till at 4.4m and 5.4m respectively above beach level.

BT 1 DIMLINGTON TA 391218

Cliff exposure near Dimlington High Land.

The upper part of the Basement Till below the Drab Till is fragmented and discoloured to a depth of 69cm, the discolouration following the cracks between fragments.

Horizons:

0-12 cm Olive grey clay, uniform colouration. Chalk erratics very soft and easily crushed between the fingers. Sample BT 1/1.

12-43 cm Olive grey clay, less uniform colouration; sub-horizontal cracks between lenticular fragments of clay are slightly browner than within the lenses. Chalk erratics less soft than in BT 1/1, and small ones more common. Sample BT 1/2.

43-58 cm Olive grey clay; colour differentiation between cracks and peds more marked; chalk erratics all hard. Sample BT 1/3.

58-69 cm Olive grey clay; ped interiors grey, cracks brown. Chalk erratics all hard. Sample BT 1/4.

69 cm + Basement Till; some tendency to fragmentation and cracking, but no oxidative discolouration along cracks. Sample BT 1/5.

BT 2 DIMLINGTON TA 397212

Foreshore exposure of Basement Till.

North of Dimlington Farm

BT 3 DIMLINGTON TA 395212

Cliff exposure, north of Dimlington Farm.

Basement Till sampled 5m below junction with Drab Till.

BT5 DIMLINGTON TA 396211

Cliff exposure, 570m north of Dimlington Road Ends.

Basement Till sampled near junction with Drab Till.

BT6 DIMLINGTON TA 396211

Cliff exposure, 540m north of Dimlington Road Ends.

Basement Till sampled 45cm below junction with Drab Till.

BT7 DIMLINGTON TA 395212

Cliff exposure, 630m north of Dimlington Road Ends.

Basement Till sampled near junction with Drab Till.

BT8 DIMLINGTON TA 395212

Cliff exposure, 680m north of Dimlington Road Ends.

Basement Till sampled 60cm below junction with Drab Till.

BT9 DIMLINGTON TA 394213

Cliff exposure, 780m north of Dimlington Road Ends.

Basement Till sampled 120cm below junction with Moss Silts.

SBC1 DIMLINGTON TA 396213

Foreshore exposure midway between Dimlington Farm and Dimlington High Land.

Lens of fossiliferous Sub-Basement Clay (Bridlington Crag of Catt & Penny, 1966) within Basement Till.

BTRC DIMLINGTON TA 393217

Foreshore exposure at Dimlington High Land.

Erratic of red clay within Basement Till.

DMS1 DIMLINGTON TA 394213

Cliff exposure, 700m north of Dimlington Farm.

Dimlington Moss Silts from lower silty beds filling basin in underlying Basement Till.

DMS2 DIMLINGTON TA 394213

Cliff exposure, 700m north of Dimlington Farm.

Sample of sands overlying Moss Silts. Overlain by Drab Till.

PTE TUNSTALL TA 314318

Cliff exposure.

Very dark greyish brown clay lens within Purple Till.

MT1 and MT2 KIRMINGTON TA 105118

East face of abandoned eastern brick-pit.

0-130cm reddish brown decalcified till)
) Lower Marsh Till of Straw (1969b)
130-200cm reddish brown calcareous till)

Sampled at 120cm (MT1) and 145cm (MT2).

MT3 MELTON ROSS TA 090117

Main chalk quarry of Melton Ross Lime Co., between A160 and railway.

East face of quarry exposes up to 2m reddish brown decalcified Lower Marsh Till overlying chalk.

Sampled at 100cm below surface, at east end of southern face.

MT4 GRIMSBY TA 238082

Low roadside cutting on Laceby Acres housing estate, exposing reddish brown calcareous till (Upper Marsh Till of Straw, 1969b).

Sampled at 50cm below surface.

MT5 BARNOLDBY-LE-BECK TA 238033

Cutting on south side of road, east end of village, exposing about 2.5m of reddish brown till (Upper Marsh Till).

Calcareous till sampled 2m below surface.

MT6 and MT7 WELTON-LE-WOLD TF 282883

Welton gravel quarry of Stephen Toulson & Sons Ltd.

Succession near eastern end of northern face:-

2-3m highly chalky silts, sands and gravels.

10-12m dark greyish brown till (Lower Marsh Till of Straw, 1969b, p.92).

10m + flinty outwash sands and gravels.

Till (≡ Drab Till?) sampled at 75cm above base (MT6) and 200cm below top (MT7).

MT8 SOUTH ELKINGTON TF 285883

Elkington quarry (abandoned) of Stephen Toulson & Sons Ltd.

Succession near western end of northern face:-

2-3m reddish brown till (Lower Marsh Till, surface ablation till, Straw, 1969b, p.92).

1-2m bedded silts and sands.

5-6m dark greyish brown till (Lower Marsh Till, basal till, Straw, op.cit.)

10m + flinty and chalky sands and gravels.

Calcareous reddish brown till (≡ Hessle Till?) sampled 200cm below surface.

MT9 LOUTH TF 324876

Road cutting, north side of Wragby Road, at entrance to new housing estate.

Reddish brown decalcified till (Upper Marsh Till) sampled at 200cm below surface.

MT10 MUCKTON TF 374815

Road cutting, east side of road, in village.

Brown calcareous till (Lower Marsh Till) sampled at 160cm below surface.

MT11 NORTH RESTON TF 382840

Bank of Long Eau stream, 10m east of new road bridge.

0-50cm	"made ground"
50-150cm	alluvium
150-220cm	brown calcareous till (Upper Marsh Till).
220cm	stream level

Till sampled at 200cm below surface.

MT12 NORTH RESTON TF 382838

Abandoned gravel pit, south of A157 road.

0-50cm	"made ground"	
50-100cm	reddish brown decalcified till	Upper Marsh Till
100-120cm	reddish brown calcareous till	
120cm +	chalky gravels	

Calcareous till sampled at 100-110cm below surface.

MT13 INGOLDMELLS POINT TF 574687

North bank of river on west side of sluice. Reddish brown calcareous till (Lower Marsh Till) exposed at high tide level.

MT14 ULCEBY CROSS TF 412737

Drainage ditch on north-west side of roundabout.

Brown decalcified till (Lower Marsh Till) sampled at 40cm below surface.

MT 15 KEAL COTES TF 367616

Bank of small stream, on east side of A16 road, northern end of Stickney moraine. Brown calcareous till (Lower Marsh Till) sampled 2m below surface; overlain by 1.5m of fen alluvium.

MT 16 SOUTH FERRIBY SE 995222

Cliff exposure 200m north-east of former jetty. 5m brown till (Lower Marsh Till) overlying c. 50cm chalky shingle containing erratics (raised beach of Burchell, 1931), over Chalk. Calcareous till sampled 140cm above shingle.

MT 17 SOUTH FERRIBY SE 996223

Cliff exposure 300m north-east of former jetty. 3m of brown till over 2m very dark greyish brown till (Lower Marsh Till)(= Drab Till?). Base of till obscured by modern beach. Sampled 50 cm below junction of brown and grey tills.

MT 18 WELTON-LE-WOLD TF 282883

For stratigraphical details see MT 6 and MT 7.

Dark greyish brown till (cf. Basement Till), sampled at 9m below top of north face of quarry.

MT 19 SOUTH ELKINGTON TF 285883

For stratigraphical details see MT 8.

Dark brown till (cf. Drab Till) sampled 6m below top of north face of quarry, 1.5m below a gradational oxidation front, the overlying till (MT 8) being reddish brown.

MT 20 WELTON-LE-WOLD TF 282883

For stratigraphical details see MT 6 and MT 7.

Brown till sampled 6m below top of north face of quarry, above MT 18.

Dark greyish brown till (MT 18) seems to grade up into brown till (MT 20) with no obvious break.

Overlain by variable depth (2-3m) of chalky till (see CT 1).

CT 1 WELTON-LE-WOLD TF 282883

For stratigraphical details see MT 6 and MT 7.

Chalky till (Calcethorpe Till ?) sampled at 2m below top of north face of quarry.

LHH HIGH HUNSLEY SE 956353

Abandoned quarry, now water-filled (marked as isolated patch of "boulder clay" on Geological Survey Sheet 72 (Beverley).

Small excavation made at east side of quarry 1m below surface of adjacent field. Very fine sandy or coarse silty, non-calcareous, flinty drift sampled.

Y 185/8 ASKHAM BRYAN SE 551482

Soil profile pit in Deighton series (Crompton and Matthews, 1970, p. 112), developed on calcareous, reddish brown clayey till; sampled at 1.5m below surface.

GH 1 GATE HELMSLEY SE 694562

Railway cutting (abandoned York - Market Weighton branch) through York moraine. 50m east of railway bridge, north side of cutting. Small hand-dug exposure 3m below top of cutting. Dark brown calcareous till.

LT 1 SCRATBY TG 516152

Cliff exposure. Soil profile developed in Lowestoft Till (see p. for full description).

LT 2 CORTON TM 547967

Cliff exposure. For local succession see Banham, 1971, p. 281.

LT 5 EYE TM 147757

Natural gas pipeline trench. Soil profile developed in Lowestoft Till (see p. for full description).

Profile No.	LT1
Location	Cliff face exposure, near Cliff House, Scratby (TG 516152)
Elevation	15m O.D. Slope and Aspect Almost flat.
Land Use	Lawn grass.
Horizons cm	
0-10 (LT1/1)	Dark greyish brown (10YR4/2) sandy loam; slightly stony, angular to rounded gravel and small stones, mainly flint and quartzite; weakly developed medium sub-angular blocky structure; friable; abundant fine pores, rare fine fissures; moderate intimate humus; abundant fine grass roots; earthworms common; narrow even boundary.
10-23 (LT1/2)	Yellowish brown (10YR5/4) loam, with common distinct medium strong brown (7.5YR5/6) mottles and dark grey (N4/o) infillings of worm tubes; slightly stony; angular to rounded flint gravel and small stones; strongly developed coarse sub-angular blocky structure; very firm; abundant fine pores, few medium pores; few fine fissures, mostly vertical; intimate humus in worm tube infillings; abundant fine grass roots; earthworms common; merging even boundary.
23-56/76 (LT1/3)	Yellowish brown (10YR5/6) clay loam, with common faint fine yellowish brown (10YR5/4) mottling and yellowish brown (10YR5/4) clay skins on ped faces; slightly stony; angular to rounded flint gravel; strongly developed coarse prismatic and columner structure; very firm; abundant very fine proes; common fine fissures, mostly vertical; common fine grass roots; earthworms common; sharp irregular boundary.
56/76-81/84 (LT1/4)	Yellowish brown (10YR5/6) calcareous clay, with common distinct fine pale olive (5Y6/3) mottles and 5mm wide dark greyish brown (10YR4/2) zones of decalcification along many

	fine vertical and horizontal fissures, with clay skins; stony; mostly rounded chalk with angular to rounded flint gravel and small stones; strongly developed coarse prismatic structure; extremely firm; abundant very fine and fine pores; few medium pores; few fine fissures (mostly vertical); few fine grass roots; narrow boundary.
81/84-150 + (LT1/5)	Yellowish brown (10YR5/6) calcareous clay, with many distinct medium grey (10Y5/1) mottles; stony; mostly rounded chalk with angular to rounded flint gravel and small stones; moderately developed coarse angular blocky structure; very firm; common very fine pores; rare fine fissures; rare fine fibrous roots.
0-150 (LT1/6)	Strong brown (7.5YR5/8) sand extending as branching pipes up to 25cm wide throughout the profile; slightly stony; sub-angular to rounded flint gravel and small stones; structureless, weakly coherent; very friable; abundant fine and very fine pores; sharp irregular boundaries.
LT1/7	Brown (10YR5/3) loam with common distinct fine strong brown (7.5YR5/8) mottles; filling depression, about 20m across, up to 1.5m deep, in surface of till 20m north of LT1 profile.
Profile No.	LT5
Location	Gas pipeline trench, north of Eye (TM 147757)
Elevation	43m O.D.
Slope and Aspect	Flat
Land Use	Arable
Horizons cm	
0-25 (LT5/1)	Brown/dark brown (10YR4/3) sandy loam; slightly stony; angular to sub-angular gravel and small stones, mainly flint; weakly developed fine to medium sub-angular blocky

	structure; friable; abundant fine and very fine pores; common very fine and fine fissures; low intimate humus; abundant fine fibrous roots; earthworms common; narrow even boundary.
25-90/100 (LT5/2)	Yellowish brown (10YR5/6) clay, with yellowish brown (10YR5/4) clay skins on ped faces; slightly stony; angular to sub-angular gravel and small stones, mainly flint; strongly developed coarse prismatic structure; very firm; abundant very fine pores; few fine fibrous roots; earthworms common; narrow irregular boundary.
90/100-250 + (LT5/3)	Light olive brown (2.5Y5/4) calcareous clay, with many distinct fine olive grey (5Y4/2) and yellowish brown (10YR5/6) mottles; stony; sub-angular to rounded chalk and angular to sub-angular flint gravel and small stones; weakly developed coarse sub-angular blocky structure; very firm; abundant very fine pores; few very fine fissures.
25-200 (LT5/4)	Strong brown (7.5YR5/6) sand extending as pipes, lenses, wedges and irregular layers deep in the profile; very rare flint gravel; structureless; very friable; abundant very fine pores; sharp very irregular boundaries.

Total thickness of till is about 2.5m, underlain by:-

LT5/7	Yellow (10YR7/6) sands below till; small-scale low-angled cross-bedding; slightly stony; rounded chalk gravel and small stones, some flint and shell fragments (≡ Corton Sands?)

PGT1 CORTON TM 547967

Cliff exposure.

For local succession see Banham (1971, p.281).

Pleasure Gardens Till sampled 30cm above Oulton Beds.

CBC1 BOUGHTON TF 693025

Drainage ditch exposure of Chalky Boulder Clay below Cover Sands.

NB1 CATTON TG 235117

Road cutting; N.Circular Rd (Norwich) between Old Catton turn and Sprowston.

Norwich Brickearth, sampled 2m below surface.

NB2 BURLINGHAM TG 366109

Soil profile pit in Wickmere Series.

Thin coverloam (loessial, Catt et al, 1971) over Norwich Brickearth.

Norwich Brickearth sampled at 65-75cm below surface.

ITC1 CORTON TM 547967

Cliff exposure.

See Banham (1971, p.281) for succession.

Cromer Till (≡ First Till of N.E. Norfolk?) sampled 150cm above junction with Cromer Forest Bed Series.

ITH1 HAPPISBURGH TG 383311

Cliff exposure in North Sea Drift.

0-2m	Second Till
5-6m	Intermediate Beds.
3m	First Till

First Till sampled 1m below junction with Intermediate Beds.

2TM1 MUNDESLEY TG 308373

Cliff exposure in North Sea Drift.

Succession, from top of cliff:-

Gimingham Sands

Third Till

Mundesley Sands

Second Till

Cromer Forest Bed Series

Second Till sampled 1m below junction with Mundesley Sands.

3TM1 MUNDESLEY TG 308373

Cliff exposure in North Sea Drift

(see 2TM1 for succession)

Third Till sampled 2m above junction with Mundesley Sands.

W01 GRIME'S GRAVES TL 806902

Soil profile trench at Grime's Graves Gun Area (dug for British Society of Soil Science annual meeting, 1970).

Worlington Series, shallow phase, and Methwold Series soils alternate in a stripe pattern.

Worlington Series sampled at 50-60cm (W01/1; non-calcareous pale yellow-brown sand) and 100-110cm (W01/2; sandy chalky drift).

W02 SANTON DOWNHAM TL 822841

Soil profile trench at Downham Highlodge Warren (dug for B.S.S.S. meeting, 1970).

Worlington Series, deep phase.

Sampled at 50-60cm (W02/1; non calcareous sandy drift), and 75-80cm (W02/2; sandy chalky drift).

W03 MILDENHALL TL 741758

Soil profile trench at Highlodge Farm (dug for B.S.S.S. meeting; 1970).

Worlington Series.

Sampled at 70-75cm (W03/1; non-calcareous sandy drift) and 80-85cm (W03/2; sandy chalky drift).

BR1 BRANDON TL 770852

Soil profile trench at Brandon Park (dug for B.S.S.S. meeting, 1970).

Brandon Series.

Deep terrace sands (reworked aeolian sand?) on which a humus podzol has developed. Sampled at 150-155cm from surface.

EP1 EPPLEWORTH TA 021324

Locality as for HT12 (q.v.)

Silty chalky head underlying reddish-brown calcareous till.

RP1 RUSTON PARVA TA 070618

Locality as for HT17 (q.v.)

Silty chalky head underlying reddish-brown decalcified till.

KMF1-3 KIRKBURN MANOR FARM SE 975566

Locality as for HT6 (q.v.)

Silty chalky head (KMF3) underlying reddish-brown decalcified till (KMF2; HT6)

KMF1 sampled from plough layer above till.

HG1 HUGGATE SE 874548

Abandoned chalk quarry, west of village

Silty flinty deposit (up to 1m thick) over chalk, exposed on western face.

Sampled at 45-55cm below surface.

HCW7 HIGH CALLIS WOLD SE 828560

Profile pit in silty loam over chalk. Sampled at 25-30cm below surface.

SE1 and SE2 SEWERBY TA 198684

Oblique section of the Eemian buried cliff and its associated deposits (see Q.R.A. Field Guide, E.Yorks and N.Lincs. (1972) pp.16-17.)

SE1 - loam sampled 30cm below base of chalky head deposit, 40m north-east of pill-box at base of cliff.

SE2 - silty chalky head sampled 20m north-east of pill-box.

BK1 BINBROOK TF 178956

Profile pit dug in silty clay loam overlying chalk in deciduous plantation.

Sampled at 25-40cm below surface. Chalk at 63cm below surface.

CN1 CORTON TM 547967

Cliff section to south of village.

Silty loam underlying modern blown sand, overlying plateau gravels (see Banham, 1971, p.281 for full succession).

Silty loam sampled 20cm below junction with blown sand.

SM1 SHERINGHAM TG 160416

Profile pit dug in "Old Wood"

Silty loam, sampled at 100cm below surface, overlying glacial sands.

TABLE 4 MUNSELL COLOURS OF TILL SAMPLES

Sample	Colour, Moist		Colour, Dry	
HT1/1	10YR4/2	Dark greyish brown	10YR5/2	Greyish brown
HT1/2	10YR5/3	Brown	10YR6/3	Pale brown
HT1/3	5YR4/6	Yellowish red	7.5YR5/4	Brown
HT1/4	5YR4/6	Yellowish red	5YR5/4	Reddish brown
HT1/5	5YR3/4	Dark reddish brown	5YR5/4	Reddish brown
HT1/6	5YR3/4	Dark reddish brown	5YR5/4	Reddish brown
HT1/8	5Y4/1	Dark grey	5Y7/1	Light grey
HT1/9	5YR4/4	Reddish brown	5YR5/4	Reddish brown
HT2/1	10YR4/3	Brown/Dark brown	10YR5/4	Yellowish brown
HT2/2	10YR4/3	Brown/Dark brown	10YR5/4	Yellowish brown
HT2/3	7.5YR4/2	Brown/Dark brown	7.5YR5/6	Strong brown
HT2/4	7.5YR4/2	Brown/Dark brown	7.5YR5/6	Strong brown
HT2/5	5YR4/4	Reddish brown	7.5YR5/6	Strong brown
HT2/6	5YR4/4	Reddish brown	7.5YR5/6	Strong brown
HT3	5YR4/4	Reddish brown	5YR5/4	Reddish brown
HT4	10YR4/3	Brown/Dark brown	10YR5/3	Brown
HT5	5YR4/4	Reddish brown	5YR6/4	Light reddish brown
HT6	5YR4/4	Reddish brown	7.5YR5/4	Brown
HT7	5YR4/3	Reddish brown	5YR5/4	Reddish brown
HT8	5YR4/3	Reddish brown	5YR5/4	Reddish brown
HT9	5YR4/4	Reddish brown	5YR5/4	Reddish brown
HT10	5YR3/4	Dark reddish brown	5YR5/4	Reddish brown
HT11	5YR4/4	Reddish brown	7.5YR5/4	Brown
HT12	5YR4/4	Reddish brown	7.5YR6/4	Light brown
HT13	5YR4/4	Reddish brown	7.5YR5/4	Brown
HT14	7.5YR5/6	Strong brown	7.5YR6/4	Light brown
HT15	5YR4/4	Reddish brown	7.5YR5/4	Brown
HT16	5YR4/4	Reddish brown	7.5YR6/4	Light brown
HT17	5YR4/4	Reddish brown	7.5YR5/4	Brown
HT18	10YR4/4	Dark yellowish brown	10YR5/6	Yellowish brown
HT19	5YR4/6	Yellowish red	7.5YR5/8	Strong brown
HT20	5YR4/4	Reddish brown	5YR5/6	Yellowish red
HT21	7.5YR4/4	Brown/Dark brown	7.5YR5/6	Strong brown
HT22	7.5YR4/4	Brown/Dark brown	7.5YR6/4	Light brown
HT23	5YR4/4	Reddish brown	5YR5/4	Reddish brown
HT24	5YR4/4	Reddish brown	5YR5/4	Reddish brown
HT25	5YR4/4	Reddish brown	5YR5/6	Yellowish red
HT26	5YR4/4	Reddish brown	5YR5/4	Reddish brown

Sample	Colour, moist		Colour, dry	
HT 27	5YR 4/4	Reddish brown	5YR 4/6	Yellowish red
HT 28	5YR 4/4	Reddish brown	5YR 5/4	Reddish brown
HT 29	5YR 4/4	Reddish brown	7.5YR 6/4	Light brown
HT 30	7.5YR 4/2	Brown/Dark brown	7.5YR 5/4	Brown
HT 31	5YR 4/4	Reddish brown	7.5YR 5/4	Brown
HT 32	5YR 4/4	Reddish brown	5YR 4/6	Yellowish red
HT 33	5YR 5/4	Reddish brown	7.5 YR 5/6	Strong brown
HT 34	7.5YR 4/4	Brown/Dark brown	7.5YR 5/4	Brown
HT 35	5YR 4/4	Reddish brown	7.5YR 5/6	Strong brown
HT 36	5YR 4/4	Reddish brown	5YR 5/6	Yellowish red
HT 37	5YR 4/4	Reddish brown	5YR 5/4	Reddish brown
HT 38	7.5YR 4/2	Brown/Dark brown	7.5YR 6/4	Light brown
HT 39	5YR 3/4	Dark reddish brown	5YR 5/4	Reddish brown
HT 40	5YR 4/4	Reddish brown	7.5YR 5/4	Brown
HT 41	5YR 4/4	Reddish brown	5YR 5/4	Reddish brown
HT 42	5YR 4/4	Reddish brown	7.5YR 5/4	Brown
HT 43	5YR 3/4	Dark reddish brown	5YR 5/4	Reddish brown
HT 44	5YR 3/4	Dark reddish brown	5YR 5/4	Reddish brown
HT 45	5YR 3/4	Dark reddish brown	5YR 5/4	Reddish brown
HT 46	5YR 4/4	Reddish brown	5YR 5/4	Reddish brown
HT 47	5YR 3/4	Dark reddish brown	5YR 5/4	Reddish brown
HT 48	5YR 4/4	Reddish brown	7.5YR 5/6	Strong brown
HT 49	5YR 4/4	Reddish brown	7.5YR 5/4	Brown
HT 50	5YR 4/6	Yellowish red	7.5YR 5/6	Strong brown
HT 51	5YR 3/4	Dark reddish brown	5YR 5/4	Reddish brown
HT 52	5YR 3/4	Dark reddish brown	7.5YR 5/4	Brown
HT 53	7.5YR 4/4	Brown/Dark brown	7.5YR 5/4	Brown
HT 54	5YR 4/6	Yellowish red	5YR 5/6	Yellowish red
HT 55	5YR 3/4	Dark reddish brown	5YR 5/4	Reddish brown

Sample	Colour, moist		Colour, dry	
HT 56	7.5YR 4/4	Brown/Dark brown	7.5YR 6/4	Light brown
HT 57	10YR 5/4	Yellowish brown	10YR 6/4	Light yellowish brown
HT 58	10YR 4/4	Reddish brown	5YR 5/4	Reddish brown
HT 59	5YR 4/4	Reddish brown	5YR 5/4	Reddish brown
PT 1	7.5YR 3/2	Dark brown	7.5YR 5/4	Brown
PT 2	"	"	"	"
PT 3	"	"	"	"
PT 4	"	"	10YR 5/2	Greyish brown
PT 5	"	"	7.5YR 5/4	Brown
PT 6	"	"	"	"
PT 7	"	"	"	"
PT 8	"	"	"	"
PT 9	"	"	"	"
DT 1	10YR 3/2	Very dark greyish brown	10YR 5/2	Greyish brown
DT 2	"	"	"	"
DT 3	"	"	"	"
DT 4	"	"	"	"
DT 5	"	"	"	"
DT 6	"	"	"	"
DT 7	"	"	"	"
DT 8	"	"	"	"
DT 9	"	"	"	"
DT 10	10YR 3/3	Dark brown	10YR 5/3	Brown
DT 11	10YR 3/2	Very dark greyish brown	10YR 5/2	Greyish brown
DT 12	"	"	"	"
DT 13	"	"	"	"
DT 14	"	"	"	"
DT 15	"	"	"	"
DT 16	"	"	"	"

Sample	Colour, moist		Colour, dry	
DT 17	10YR 3/3	Dark brown	10YR 5/3	Brown
DT 18	10YR 3/2	Very dark greyish brown	10YR 5/2	Greyish brown
D 1	5YR 4/4	Reddish brown	5YR 5/4	Reddish brown
D 2	5YR 4/4	Reddish brown	5YR 5/4	Reddish brown
D 3	5YR 3/4	Dark reddish brown	5YR 5/4	Reddish brown
D 4	5YR 3/4	Dark reddish brown	5YR 5/4	Reddish brown
D 5	5YR 3/4	Dark reddish brown	5YR 5/4	Reddish brown
D 6	7.5YR 3/2	Dark brown	7.5YR 5/4	Brown
D 7	7.5YR 3/2	Dark brown	7.5YR 5/4	Brown
D 8	7.5YR 3/2	Dark brown	7.5YR 5/4	Brown
D 9	10YR 3/2	Very dark greyish brown	10YR 5/2	Greyish brown
D 10	10YR 3/2	"	10YR 5/2	"
D 11	10YR 3/2	"	10YR 5/2	"
D 12	10YR 3/2	"	10YR 5/2	"
D 13	10YR 3/2	"	10YR 5/2	"
D 14	10YR 3/2	"	10YR 5/2	"
D 15	10YR 3/2	"	10YR 5/2	"
D 16	10YR 3/2	"	10YR 5/2	"
S 1	7.5YR 5/6	Strong brown	7.5YR 6/4	Light brown
S 2	7.5YR 4/4	Brown/Dark brown	7.5YR 5/4	Brown
S 3	7.5YR 4/4	"	7.5YR 5/4	Brown
S 4	5YR 4/4	Reddish brown	7.5YR 5/4	Brown
S 5	7.5YR 4/4	Brown/dark brown	7.5YR 5/4	Brown
S 6	7.5YR 4/3	Brown/Dark brown	7.5YR 5/4	Brown
S 7	7.5YR 3/2	Dark brown	7.5YR 5/4	Brown
S 8	10YR 3/2	Very dark greyish brown	10YR 5/2	Greyish brown
S 9	10YR 3/2	"	10YR 5/2	"
A 1	10YR 3/3	Dark brown	10YR 5/3	Brown
A 2	10YR 3/3	"	10YR 5/3	Brown

Sample	Colour, moist		Colour, dry	
A 3	10YR 3/3	Dark brown	10YR 5/3	Brown
A 4	10YR 3/3	"	10YR 5/3	Brown
A 5	7.5YR 3/2	Dark brown	7.5YR 5/4	Brown
A 6	7.5YR 3/2	"	7.5YR 5/4	Brown
MT 1	5YR 4/4	Reddish brown	7.5YR 5/4	Brown
MT 2	5YR 4/4	"	7.5YR 6/4	Light brown
MT 3	5YR 4/4	"	7.5YR 5/4	Brown
MT 4	7.5YR 4/4	Brown/Dark brown	7.5YR 6/4	Light brown
MT 5	5YR 4/4	Reddish brown	7.5YR 6/4	"
MT 6	10YR 4/2	Dark greyish brown	10YR 5/4	Yellowish brown
MT 7	10YR 4/2	"	10YR 5/4	"
MT 8	5YR 4/4	Reddish brown	7.5YR 6/4	Light brown
MT 9	5YR 4/4	"	7.5YR 5/4	Brown
MT 10	7.5YR 4/4	Brown/Dark brown	7.5YR 6/4	Light brown
MT 11	7.5YR 4/2	Brown/Dark brown	7.5YR 5/4	Brown
MT 12	5YR 4/4	Reddish brown	7.5YR 5/4	Brown
MT 13	5YR 4/4	"	7.5YR 6/4	Light brown
MT 14	7.5YR 4/4	Brown/dark brown	7.5YR 5/4	Brown
MT 15	7.5YR 4/4	"	10YR 5/8	Yellowish brown
MT 16	7.5YR 4/4	"	7.5YR 6/4	Light brown
MT 17	10YR 3/2	Very dark greyish brown	10YR 5/2	Greyish brown
MT 18	2.5Y 4/2	Dark greyish brown	2.5Y 6/2	Light brownish grey
MT 19	10YR 3/3	Dark brown	10YR 5/3	Brown
MT 20	7.5YR 4/4	Brown/Dark brown	7.5YR 5/4	Brown
CT 1	10YR 6/4	Light yellowish brown	10YR 7/3	Very pale brown
BT1/1	2.5Y 4/2	Dark greyish brown	2.5Y 6/2	Light brownish grey
BT1/2	2.5Y 4/2	"	2.5Y 6/2	"
BT 1/3	2.5Y 4/2	"	2.5Y 6/2	"
BT 1/4	2.5Y 3/2	Very dark greyish brown	2.5Y 5/2	Greyish brown

Sample	Colour, moist		Colour, dry	
BT 1/5	2.5Y 3/2	Very dark greyish brown	2.5Y 5/2	Greyish brown
BT 2	2.5Y 3/2	"	2.5Y 5/2	"
BT 3	2.5Y 3/2	"	2.5Y 5/2	"
BT 5	5Y 3/1	Very dark grey	5Y 5/1	Grey
BT 6	2.5Y 3/2	Very dark greyish brown	2.5Y 5/2	Greyish brown
BT 7	5Y 3/1	Very dark grey	5Y 5/1	Grey
BT 8	5Y 3/1	"	5Y 5/1	Grey
BT 9	5Y 3/1	"	5Y 5/1	Grey
SBC 1	N 3/0	Very dark grey	N 5/0	Grey
BTRC	7.5YR 3/2	Dark brown	7.5YR 6/2	Pinkish grey
DMS 1	10YR 4/1	Dark grey	10YR 6/1	Grey/Light grey
DMS 2	10YR 4/3	Brown/Dark brown	10 YR 5/4	Yellowish brown
PTE	2.5Y 3/2	Very dark greyish	2.5Y 5/2	Greyish brown
LHH	7.5YR 4/4	Brown/Dark brown	7.5YR 5/6	Strong brown
GH 1	7.5YR 3/2	Dark brown	7.5YR 5/4	Brown

Sample	Colour, Moist		Colour, Dry	
Y185/8	5YR3/2	Dark reddish brown	5YR5/4	Reddish brown
KMF1	10YR3/4	Dark yellowish brown	10YR5/4	Yellowish brown
KMF2	5YR4/4	Reddish brown	7.5YR5/4	Brown
KMF3	7.5YR4/4	Brown/Dark brown	7.5YR6/4	Light brown
HCW7	7.5YR4/4	Brown/Dark brown	7.5YR5/6	Strong brown
HG1	7.5YR4/2	Brown/Dark brown	10YR5/3	Brown
RP1	10YR5/4	Yellowish brown	10YR7/3	Very pale brown
EP1	10YR4/4	Dark yellowish brown	10YR6/4	Light yellowish brown
BK1	7.5YR4/4	Brown/Dark brown	7.5YR5/4	Brown
CN1	10YR6/3	Pale brown	10YR8/3	Very pale brown
SM1	7.5YR4/4	Brown/Dark brown	7.5YR6/6	Reddish yellow
LT1/1	10YR4/2	Dark greyish brown	10YR5/3	Brown
LT1/2	10YR5/4	Yellowish brown	10YR5/6	Yellowish brown
LT1/3	10YR5/6	Yellowish brown	10YR5/8	Yellowish brown
LT1/4	10YR5/6	Yellowish brown	2.5YR6/4	Light yellowish brown
LT1/5	10YR5/6	Yellowish brown	2.5YR6/4	Light yellowish brown
LT1/6	7.5YR5/8	Strong brown	7.5YR5/8	Strong brown
LT1/7	10YR5/3	Brown	10YR6/3	Pale brown
LT2	5Y2/1	Black	10Y5/1	Grey
LT5/1	10YR4/3	Brown/Dark brown	10YR5/4	Yellowish brown
LT5/2	10YR5/6	Yellowish brown	10YR5/6	Yellowish brown
LT5/3	2.5Y5/4	Light olive brown	2.5Y6/4	Light yellowish brown
LT5/4	7.5YR5/6	Strong brown	7.5YR5/8	Strong brown
LT5/7	10YR7/6	Yellow	10YR8/6	Yellow
PGT1	5Y3/1	Very dark grey	5Y6/1	Grey/Light grey
CBC1	5Y2/1	Black	10Y5/1	Grey
NB1	10YR5/8	Yellowish brown	10YR6/8	Brownish yellow
NB2	10YR5/8	Yellowish brown	10YR6/6	Brownish yellow
ITC1	10YR3/2	Very dark greyish brown	10YR5/1	Grey
ITH1	10YR3/2	Very dark greyish brown	2.5Y5/2	Greyish brown
2TM1	5Y4/1	Dark grey	5Y6/1	Grey/Light grey
3TM1	5Y3/1	Very dark grey	5Y5/1	Grey
BR1	10YR5/6	Yellowish brown	10YR6/6	Brownish yellow
WO1/1	10YR4/3	Brown/Dark brown	10YR6/3	Pale brown
WO1/2	10YR5/4	Yellowish brown	10YR6/4	Light yellowish brown
WO2/1	10YR4/3	Brown/Dark brown	10YR6/3	Pale brown
WO2/2	10YR5/4	Yellowish brown	10YR6/4	Light yellowish brown
WO3/1	10YR4/3	Brown/Dark brown	10YR6/3	Pale brown
WO3/2	10YR5/4	Yellowish brown	10YR6/4	Light yellowish brown

TABLE 5 CARBONATE ANALYSES

Sample	%CaCO$_3$	Sample	%CaCO$_3$	Sample	%CaCO$_3$	Sample	%CaCO$_3$	Sample	%CaCO$_3$
HT1/6	8.2	HT27	7.3	DT8	17.6	BT5	7.0	NB1	0.0
HT2/5	4.9	HT28	14.4	DT9	21.7	BT6	6.5	NB2	0.0
HT3	0.0	HT29	17.9	DT10	6.1	BT7	7.4	1TH1	8.0
HT4	0.0	HT30	8.3	DT11	6.9	BT8	7.3	2TM1	30.8
HT5	10.2	HT31	9.8	DT12	10.6	BT9	9.8	3TN1	10.9
HT6	0.0	HT32	5.3	DT13	10.0	SBC1	7.9	BR1	0.0
HT7	8.3	HT33	0.4	DT14	6.5	BTRC	6.0	WO1/1	0.0
HT8	7.4	HT34	8.8	MT1	0.0	DMS1	8.5	WO2/1	0.0
HT9	9.1	HT35	10.8	MT2	16.4	DMS2	0.0	WO3/1	0.0
HT10	8.8	HT36	9.5	MT3	0.1	PTE	4.7	RP1	58.6
HT11	0.0	HT37	0.0	MT4	15.0	LHH	0.0	EP1	32.6
HT12	15.8	HT38	18.7	MT5	11.6	Y185/8	8.0	HG1	1.0
HT13	14.9	HT39	8.3	MT6	16.2	LT1/1	0.0	HCW7	0.0
HT14	0.2	PT1	9.5	MT7	19.7	LT1/1	0.0	BK1	0.0
HT15	0.2	PT2	10.4	MT8	15.0	LT1/3	0.0	KMF1	0.0
HT16	23.3	PT3	8.5	MT9	0.4	LT1/4	31.5	KMF2	0.0
HT17	0.2	PT4	9.0	MT10	15.3	LT1/5	37.5	KMF3	24.4
HT18	6.7	PT5	10.3	MT11	15.9	LT1/6	0.0	CN1	0.0
HT19	0.2	PT6	8.7	MT12	13.0	LT1/7	0.0	SM1	0.0
HT20	0.0	DT1	12.2	MT13	17.0	LT2	26.9	SE1	0.0
HT21	7.8	DT2	15.0	MT14	0.0	LT5/1	0.0	SE2	11.2
HT22	13.8	DT3	17.0	MT15	13.8	LT5/2	0.0	BT1/1	7.9
HT23	0.0	DT4	16.4	MT16	11.3	LT5/3	27.5	BT1/2	8.1
HT24	0.0	DT5	8.3	MT17	12.9	LT5/4	0.0	BT1/3	8.1
HT25	7.1	DT6	19.9	BT2	6.3	CBC1	20.8	BT1/4	8.5
HT26	6.2	DT7	15.5	BT3	5.9	PGT1	39.7	BT1/5	8.9

TABLE 6 PARTICLE SIZE ANALYSIS : HESSLE TILL

Ø range	-1/0	0/1	1/2	2/3	3/4	4/5	5/6	6/7	7/8	8/9	<9	Texture Class
HT1/6	2.6	2.4	3.6	8.1	8.9	8.8	8.9	8.9	9.1	8.3	30.4	CL
HT5	0.6	1.1	1.7	3.4	4.2	7.8	9.8	10.0	9.3	8.4	43.7	SiC
HT6	0.3	0.4	1.3	4.5	8.0	19.5	11.2	6.7	5.3	4.4	38.4	SiCL
HT7	1.4	1.5	2.8	8.5	11.7	11.1	9.2	8.9	7.1	7.2	30.6	CL
HT8	1.9	1.6	2.9	8.4	11.7	12.3	8.2	8.2	7.9	6.6	30.3	CL
HT9	1.7	1.8	3.1	8.5	12.0	11.4	8.2	8.5	7.5	7.3	30.0	CL
HT10	2.1	2.1	3.4	8.8	9.9	8.7	8.7	9.2	8.8	7.0	31.3	CL
HT11	0.4	1.0	2.9	8.9	11.9	10.6	8.5	6.7	6.9	6.6	35.6	CL
HT12	0.7	1.2	3.4	10.2	11.4	16.0	6.6	6.0	5.9	6.0	32.6	CL
HT13	1.1	1.8	5.0	11.2	10.3	14.8	6.3	6.6	6.1	5.3	31.5	CL
HT14	1.9	3.5	8.1	17.6	17.0	14.7	7.1	5.5	4.7	4.4	15.5	SaL
HT15	0.7	1.3	4.4	13.4	12.9	13.1	6.9	5.3	4.8	5.2	32.0	CL
HT16	0.5	0.8	2.4	7.3	10.6	16.7	6.8	7.3	7.2	6.4	34.0	CL
HT17	1.0	2.0	6.1	14.6	13.4	11.3	7.1	6.1	6.0	4.7	27.7	CL
HT18	1.3	2.1	5.5	13.5	14.0	13.0	6.8	6.0	5.8	4.9	27.1	CL
HT19	1.3	2.3	6.3	15.6	14.0	12.0	5.7	5.4	4.7	4.3	28.4	CL
HT20	1.4	1.6	7.3	15.6	14.1	13.2	7.0	5.1	5.5	4.4	24.8	L
HT21	1.3	2.1	4.9	11.6	11.4	11.6	8.0	6.9	6.7	6.5	29.0	CL
HT22	1.3	2.0	5.5	13.6	14.4	11.3	8.0	5.5	7.4	5.3	25.7	L
HT23	0.7	1.4	4.4	11.9	12.2	10.8	6.6	6.7	7.3	7.6	30.4	CL
HT24	1.3	2.1	5.8	14.8	14.4	11.7	6.3	5.7	5.2	5.5	26.6	L
HT25	1.8	2.7	5.9	13.8	12.2	12.1	7.3	6.8	5.6	5.7	26.1	L
HT26	1.6	1.7	4.4	5.9	8.3	13.8	9.1	8.4	8.3	6.8	31.7	CL
HT27	1.6	1.7	2.9	7.4	9.2	13.0	10.0	8.7	8.2	7.4	29.9	CL
HT28	1.6	1.6	3.0	6.5	9.5	14.2	10.0	8.6	7.4	6.8	30.8	CL
HT29	1.7	2.0	4.0	9.5	10.6	14.9	8.5	7.3	6.1	5.9	29.5	CL
HT30	1.7	4.6	5.6	12.1	11.7	12.0	7.2	6.3	5.5	6.1	27.2	CL
HT31	2.3	2.9	6.6	15.9	14.2	12.3	6.2	5.5	4.9	5.0	24.2	L
HT32	1.4	2.4	6.8	14.7	14.0	12.2	6.7	5.5	5.8	4.3	26.1	L
HT33	1.0	1.9	5.7	14.2	13.6	9.8	6.6	6.3	5.3	5.6	30.0	CL
HT34	1.9	2.7	5.8	12.5	11.7	9.0	7.6	7.5	6.6	5.6	29.1	CL
HT35	1.6	2.3	5.4	12.5	12.0	8.9	6.6	7.5	6.5	6.1	30.6	CL
HT36	0.8	1.0	2.0	4.6	8.0	11.6	9.4	10.1	8.7	7.8	36.0	SiCL
HT38	1.3	1.8	4.0	9.2	9.6	8.1	7.4	7.5	6.6	7.4	37.1	CL
HT39	1.6	1.7	2.8	7.0	9.1	8.7	9.4	9.9	8.7	7.8	33.3	CL

TABLE 6 (Contd..) PARTICLE SIZE ANALYSES : PURPLE TILL

Ø range	-1/0	0/1	1/2	2/3	3/4	4/5	5/6	6/7	7/8	8/9	<9	Texture Class
PT1	2.0	2.2	3.3	7.3	8.6	8.6	8.6	8.6	8.6	8.7	33.5	CL
PT2	1.5	1.5	2.3	4.9	9.3	11.5	9.7	8.9	8.5	7.5	34.4	CL
PT3	1.7	1.7	3.0	8.5	11.6	13.1	8.7	8.3	7.9	6.3	29.2	CL
PT4	0.6	0.7	1.4	4.7	7.6	11.8	7.6	8.9	8.8	8.0	39.9	SiCL
PT5	1.0	1.0	1.7	4.0	7.2	11.6	8.6	8.8	9.5	8.0	38.6	SiCL
PT6	1.2	1.5	2.8	7.1	10.2	13.7	8.9	8.9	7.9	7.5	30.3	CL
DRAB TILL												
DT1	1.5	1.9	4.9	11.5	9.5	11.2	10.4	6.1	6.2	6.8	30.0	CL
DT2	2.3	2.7	5.5	12.3	9.5	11.9	10.8	5.8	5.8	6.3	27.1	CL
DT3	1.6	2.3	5.4	13.1	12.5	17.4	5.9	5.4	5.1	4.8	26.5	L
DT4	1.9	2.3	5.5	12.9	12.2	15.9	6.8	5.5	5.1	5.0	26.9	L
DT5	1.3	1.8	4.5	11.0	10.8	12.4	7.0	6.7	6.4	6.3	31.8	CL
DT6	1.5	1.7	3.5	7.9	8.8	12.4	7.4	7.7	7.0	6.6	35.5	CL
DT7	1.8	2.3	6.0	14.2	12.6	16.1	6.2	4.8	5.0	4.6	26.4	L
DT8	2.0	2.6	5.7	14.0	12.2	14.1	5.7	5.2	4.7	4.9	28.9	CL
DT9	2.2	2.4	3.5	6.6	8.7	12.0	8.6	7.4	7.6	6.8	34.2	CL
DT10	2.4	3.3	8.3	15.8	13.5	12.0	6.9	6.0	5.7	4.6	21.5	L
DT11	2.2	3.3	7.3	14.9	12.6	8.2	7.2	7.1	5.3	5.4	26.5	L
DT12	2.1	2.7	6.4	14.2	13.6	12.3	6.8	5.6	5.7	4.9	25.7	L
DT13	2.2	2.9	6.3	13.6	12.7	10.2	6.7	6.8	5.6	5.6	27.4	CL
DT14	1.1	1.4	3.7	7.7	5.9	4.8	5.6	7.2	7.6	7.6	47.4	C
MARSH TILLS												
MT1	0.4	0.9	3.4	9.0	10.4	10.5	9.2	9.6	7.2	5.4	34.0	CL
MT2	0.3	0.4	1.5	5.2	5.3	8.5	9.3	12.4	10.0	7.7	39.4	SiCL
MT3	0.7	1.5	5.3	12.9	12.3	11.3	8.3	5.5	5.6	5.6	31.0	CL
MT4	1.3	1.6	4.2	11.9	15.6	13.2	8.4	6.4	5.2	4.9	27.3	CL
MT5	0.5	1.0	3.1	13.4	25.2	10.7	7.3	5.6	4.5	4.9	23.8	L
MT6	0.9	1.7	4.8	12.7	16.4	10.9	5.6	4.0	4.1	3.7	35.2	CL
MT7	0.6	1.2	5.4	18.8	17.9	11.4	5.1	4.2	4.9	3.8	26.7	SaCL
MT8	1.2	1.5	2.7	6.3	7.4	11.2	8.5	8.7	8.5	6.8	37.2	CL
MT9	0.3	0.5	1.6	5.2	6.2	6.4	5.6	5.3	8.0	9.0	51.9	C
MT10	1.3	1.8	4.8	12.4	12.0	9.2	6.5	5.7	6.2	6.5	33.6	CL
MT11	1.1	1.8	3.6	9.4	10.4	9.8	6.6	6.6	7.1	6.1	37.5	CL
MT12	1.7	2.4	5.8	12.3	14.0	10.9	6.8	6.4	5.0	5.1	29.6	CL
MT13	0.4	0.8	2.1	5.0	23.3	19.0	7.3	4.2	4.1	4.7	29.1	CL
MT14	0.7	1.2	3.0	6.7	8.8	18.3	11.1	6.9	4.8	4.1	34.4	CL
MT15	0.7	1.3	3.1	7.0	7.4	10.3	7.2	7.1	7.5	6.7	41.7	C
MT16	1.8	2.9	6.7	16.1	14.0	13.7	7.1	5.1	5.8	4.3	22.5	L
MT17	2.4	3.0	7.2	17.0	15.8	14.5	6.5	5.2	4.3	4.6	19.5	L

TABLE 6 (Contd..) PARTICLE SIZE ANALYSES : HUNSTANTON TILL

Ø range	-1/0	0/1	1/2	2/3	3/4	4/5	5/6	6/7	7/8	8/9	<9	Texture Class
HT2/5	1.1	2.2	6.0	8.9	7.3	7.9	8.0	7.7	7.2	6.9	36.8	CL
HT3	1.3	3.5	12.1	21.2	11.0	6.8	5.5	5.0	4.7	4.6	24.3	SaCL
HT37	0.7	1.6	4.8	13.3	12.1	9.7	5.5	5.2	5.5	6.0	35.6	CL
									BASEMENT TILL			
BT2	0.7	1.2	4.1	10.8	7.9	8.5	6.7	3.8	3.8	6.4	46.1	C
BT3	0.7	1.2	4.1	10.8	8.5	9.3	6.8	3.2	2.9	5.0	47.5	C
BT5	0.8	1.4	4.2	11.8	10.8	8.6	4.4	3.4	3.8	4.5	46.3	C
BT6	0.7	1.2	3.5	10.9	11.8	8.4	3.7	3.4	3.7	4.9	47.8	C
BT7	1.0	1.7	5.2	14.1	14.9	10.9	4.2	3.4	3.3	3.5	37.8	CL
BT8	1.2	1.6	4.4	11.2	10.5	10.1	3.4	2.7	4.3	4.3	46.3	C
BT9	1.0	1.7	4.5	12.1	11.8	11.6	3.1	3.4	3.7	4.9	42.2	C
									LOESSIAL SAMPLES			
RP1	0.1	0.1	0.0	0.1	1.9	32.1	29.0	10.0	4.5	2.2	20.0	SiL
EP1	0.1	0.2	0.3	1.2	8.4	31.2	24.6	10.2	4.8	3.0	16.0	SiL
HG1	0.3	0.1	0.1	0.7	8.1	22.6	17.1	7.4	7.0	5.3	31.3	SiCL
HCW7	1.1	0.2	0.2	0.6	10.8	25.2	18.9	10.2	5.1	3.9	23.8	SiL
BK1	0.2	0.3	0.4	0.8	8.7	25.4	16.4	8.6	4.6	4.3	30.3	SiCL
KMF1	2.3	1.6	4.0	9.2	12.7	18.8	13.3	6.7	4.6	2.4	24.4	L
KMF2	0.6	0.6	1.5	4.4	7.6	16.4	11.9	7.2	5.2	5.3	39.3	SiCL
KMF3	1.4	1.1	1.4	3.6	6.8	16.6	14.1	7.9	5.9	5.6	35.6	SiCL
SE1	0.4	0.6	3.5	15.8	5.5	11.1	10.2	6.0	4.4	3.4	39.1	CL
SE2	0.2	0.4	2.4	16.5	12.2	16.1	10.1	6.7	4.0	3.4	28.0	CL
CN1	0.4	1.7	7.8	7.2	4.4	30.3	21.7	8.5	3.7	2.6	11.7	SiL
SM1	0.6	1.7	4.2	6.4	14.1	30.1	14.5	6.3	4.2	2.8	15.1	SiL
LT1/7	0.4	1.8	10.4	14.9	10.7	30.0	14.0	3.9	2.0	1.3	10.6	L
HT4	0.3	0.6	1.9	5.7	5.3	25.1	31.4	5.7	3.4	1.7	18.9	SiL
									COVER SANDS			
WO1/1	2.8	5.2	21.8	40.2	21.3	2.2	1.5	0.8	0.7	0.5	3.0	Sa
WO2/1	2.6	4.1	19.7	44.2	17.7	3.0	2.6	1.4	1.1	0.6	3.0	Sa
WO3/1	1.9	4.0	17.1	38.3	23.8	3.2	2.1	1.5	1.3	0.9	5.9	LSa
BR1	0.0	1.6	30.4	56.0	10.3	0.2	0.0	0.0	0.0	0.0	1.5	Sa
LT1/6	1.0	5.3	25.9	40.0	15.0	4.4	1.1	0.5	0.5	0.5	5.8	Sa
LT5/4	0.0	0.7	10.6	48.4	29.8	1.8	0.2	0.2	0.1	0.3	7.9	Sa

TABLE 6 (Contd..) PARTICLE SIZE ANALYSES : EAST ANGLIAN TILLS

Ø range	-1/0	0/1	1/2	2/3	3/4	4/5	5/6	6/7	7/8	8/9	<9	Texture Class
LT1/1	0.4	1.7	24.9	30.2	8.2	8.3	4.5	3.6	2.3	3.5	12.4	SaL
LT1/2	0.5	1.8	11.5	16.1	7.7	20.4	12.0	4.3	3.3	3.1	19.3	L
LT1/3	0.4	1.9	8.3	14.0	8.3	8.6	6.5	4.3	5.2	5.4	37.1	CL
LT1/4	0.5	1.5	5.7	8.8	6.7	3.5	7.1	6.5	7.7	7.1	44.9	C
LT1/5	0.4	1.3	4.9	8.0	5.5	5.5	5.6	5.4	7.3	5.9	50.2	C
LT2	0.6	0.7	0.7	1.3	3.6	7.0	5.0	6.5	8.0	7.9	58.7	C
LT5/1	0.8	3.5	23.1	33.6	12.6	4.7	3.3	3.1	1.3	2.6	11.4	SaL
LT5/2	0.3	0.8	6.3	10.9	5.1	2.3	4.1	5.5	6.0	6.2	52.5	C
LT5/3	0.5	0.5	1.5	3.1	3.7	8.7	6.9	7.9	7.4	6.9	52.9	C
PGT1	0.6	1.8	2.8	4.8	13.2	17.8	9.8	8.0	6.4	4.3	30.5	CL
CBC1	0.8	0.8	1.8	2.0	4.9	6.1	7.6	6.1	7.2	6.4	56.3	C
1TH1	1.7	3.0	5.0	17.9	25.7	12.6	2.9	3.7	3.4	3.5	20.6	SaCL
2TM1	1.5	3.2	4.9	14.0	22.7	16.8	5.5	4.1	4.3	2.7	20.3	L
3TM1	2.4	3.2	5.0	17.5	28.0	14.6	4.2	3.6	3.3	2.6	15.6	SaL
NB1	0.4	2.9	11.2	25.6	17.3	8.6	4.7	1.4	2.3	2.0	23.6	SaCL
NB2	1.1	4.3	18.4	21.5	9.1	7.1	5.2	2.5	2.3	2.0	26.5	SaCL
									MISCELLANEOUS SAMPLES			
Y185/8	0.2	0.3	0.6	2.7	2.6	6.2	3.8	7.3	8.7	11.2	56.4	C
LHH	0.8	0.6	2.1	11.2	21.0	25.1	8.1	4.6	2.9	3.3	20.3	L
PTE	2.4	2.1	3.6	11.8	10.9	10.9	9.2	6.5	6.1	7.2	29.3	CL
SBC1	0.3	0.6	2.4	11.7	11.9	11.0	8.4	6.3	5.4	5.6	36.4	CL
BTRC	0.1	0.2	1.0	4.2	1.3	3.4	5.5	6.7	9.1	23.2	45.3	SiC
DMS1	0.4	1.3	3.6	8.6	11.9	16.2	5.6	4.8	4.3	5.0	38.3	CL
DMS2	0.0	0.5	8.5	48.9	34.3	0.5	0.3	0.2	0.3	0.3	6.2	Sa
LT5/7	0.1	1.2	11.3	54.6	19.1	9.4	0.6	0.3	0.2	0.1	3.1	Sa

TABLE 7 SAND/SAND + SILT RATIOS (x 100)

Sample	Ratio	Sample	Ratio	Sample	Ratio	Sample	Ratio	Sample	Ratio
HT1/6	40	HT27	37	DT1	45	MT1	41	BT2	50
HT2/5	43	HT28	37	DT2	48	MT2	24	BT3	53
HT3	67	HT29	44	DT3	58	MT3	52	BT5	57
HT4	20	HT30	54	DT4	57	MT4	53	BT6	58
HT5	22	HT31	60	DT5	48	MT5	61	BT7	64
HT6	31	HT32	58	DT6	43	MT6	62	BT8	58
HT7	42	HT33	56	DT7	61	MT7	65	BT9	59
HT8	43	HT34	51	DT8	58	MT8	36		
HT9	43	HT35	52	DT9	40	MT9	32		
HT10	42	HT36	30	DT10	59	MT10	53	SBC1	47
HT11	43	HT37	55	DT11	58	MT11	48	BTRC	14
HT12	50	HT38	45	DT12	58	MT12	56	DMS1	58
HT13	54	HT39	37	DT13	56	MT13	53	DMS2	99
HT14	62			DT14	40	MT14	37	PTE	48
HT15	54					MT15	38	LHH	55
HT16	44	PT1	39			MT16	59	Y185/8	18
HT17	56	PT2	35			MT17	61	KMF1	45
HT18	55	PT3	42					KMF2	31
HT19	59	PT4	30					KMF3	27
HT20	58	PT5	29					HG1	20
HT21	48	PT6	37					RP1	8
HT22	54							EP1	21
HT23	48							HCW7	26
HT24	56							BK1	23
HT25	54								
HT26	38								

TABLE 8

<2μm CLAY FRACTIONS OF TILLS X-RAY DETERMINATION OF LAYER SILICATES (adjusted to 100%)

	Mica	Kaolinite	Chlorite	Vermiculite	Smectite
HT1/1	27	32	5	28	8
HT1/5	37	24	4	25	10
HT2/1	13	24	-	49	14
HT2/5	17	22	-	45	16
HT3	14	24	-	46	16
HT5	31	16	2	34	17
HT7	37	25	3	26	9
HT8	33	21	2	34	10
HT9	34	25	3	27	11
HT10	35	26	3	25	11
HT11	21	20	-	44	15
HT12	27	22	-	40	11
HT13	31	22	-	35	12
HT14	21	43	4	25	7
HT15	19	27	-	35	19
HT16	24	22	-	35	19
HT17	21	29	-	34	16
HT18	27	28	-	30	15
HT19	27	29	-	35	9

TABLE 8 (contd.)

<2μm CLAY FRACTIONS OF TILLS X-RAY DETERMINATION OF LAYER SILICATES (adjusted to 100%)

	Mica	Kaolinite	Chlorite	Vermiculite	Smectite
MT2	33	23	-	36	8
MT4	36	23	-	29	12
MT6	32	17	-	28	23
MT8	34	28	-	33	5
MT9	27	15	-	38	20
MT12	27	21	-	37	15
MT13	36	20	-	33	11
MT15	29	23	-	36	12
PT1	29	17	4	30	20
DT1	29	17	4	31	19
DT2	26	19	3	32	20
BT1/1	30	9	2	28	31
BT1/5	32	9	2	27	30
BT2	35	11	4	21	29
PTE	28	14	2	20	36*
BTRC	35	9	4	25	27
SBC1	36	8	3	29	24

* Interstratified Mica-Montmorillonite

TABLE 9 20-53μm : HEAVY (>2.9 S.G.) FRACTIONATION

Sample	% Heavies	Sample	% Heavies	Sample	% Heavies
HT1/6	1.3	MT2	1.8	DT1	3.3
HT2/5	0.9	MT3	3.0	DT2	5.5
HT3	2.1	MT4	2.7	DT3	5.1
HT4	1.2	MT5	2.9	DT7	5.0
HT5	1.8	MT6	2.5	DT8	5.6
HT6	2.9	MT7	3.4	DT9	5.5
HT7	1.6	MT8	2.3	BT2	3.4
HT8	2.7	MT9	2.6	BT6	3.1
HT9	1.9	MT10	2.3	BT7	3.6
HT10	2.0	MT11	3.7	BT9	4.4
HT11	2.4	MT12	3.0	SE1	2.8
HT12	3.2	MT13	3.2	SE2	3.5
HT13	3.3	MT14	3.4	KMF3	2.0
HT14	1.8	MT15	1.7	RP1	3.1
HT15	2.6	PT1	2.8	HG1	2.0
HT16	2.3	PT2	4.6	EP1	3.0
HT17	3.0	PT3	5.2	HCW7	2.2
HT18	1.3	PT4	5.7	BK1	1.7
HT19	1.3	PT5	5.1	SM1	0.9

TABLE 10 20-53µm LIGHT (<2.9 S.G.) FRACTION MINERALOGY (‰)

	HT1/6	HT2/5	HT3	HT5	HT6	HT7	HT8	HT9	HT10	HT11	HT12	HT13	HT14
Quartz	84	86	87	81	83	83	84	86	85	81	80	81	82
Alkali Feldspar	10	9	9	2	13	10	9	9	10	12	13	12	15
Muscovite	3	1	2	13	1	4	3	4	2	2	3	3	2
Flint	2	2	1	1	2	2	3	1	3	4	3	4	<1
Glauconite	<1	2	1	3	<1	<1	<1	<1	<1	1	1	<1	<1

	HT15	HT16	HT17	HT18	HT19	MT2	MT3	MT4	MT5	MT6	MT7	MT8	MT9	MT10
Quartz	82	85	80	82	81	82	80	83	85	84	85	82	82	87
Alkali Feldspar	12	10	13	12	14	10	13	10	10	11	13	11	12	9
Muscovite	2	2	3	3	3	4	2	2	2	2	1	3	2	1
Flint	3	2	3	2	1	4	4	4	2	2	1	3	3	2
Glauconite	1	1	1	1	1	<1	1	<1	1	1	<1	1	1	1

	MT11	MT12	MT13	MT14	MT15	PT1	PT2	PT3	PT4	PT5	DT1	DT2	DT3	DT7
Quartz	84	84	84	82	85	86	86	86	88	86	83	84	86	87
Alkali Feldspar	11	11	12	14	10	10	9	9	7	10	11	11	11	10
Muscovite	2	2	1	1	3	1	3	2	2	2	2	2	1	1
Flint	3	2	2	2	2	3	2	3	3	2	3	3	2	2
Glauconite	<1	1	1	1	<1	<1	-	<1	<1	<1	1	<1	<1	<1

	DT8	DT9	BT2	BT6	BT7	BT9
Quartz	85	87	84	83	84	84
Alkali Feldspar	12	10	12	13	12	14
Muscovite	1	1	2	1	1	1
Flint	2	2	2	3	3	1
Glauconite	<1	<1	-	<1	<1	<1

TABLE 11 20-53µm HEAVY (>2.9 S.G.) OPAQUE MINERALS (‰)

	HT1/6	HT2/5	HT3	HT5	HT6	HT7	HT8	HT9	HT10	HT11	HT12	HT13	HT14
Limonite/ Haematite	612	460	579	724	621	641	705	457	608	643	684	694	170
Magnetite/ Ilmenite	163	280	312	159	218	170	59	220	218	145	117	113	234
Leucoxene	225	260	209	117	161	189	236	323	174	212	199	193	596
Pyrite	-	-	-	-	-	-	-	-	-	-	-	-	-
Total Opaques*	690	526	644	665	639	712	701	693	668	621	628	656	667

	HT15	HT16	HT17	HT18	HT19	MT2	MT3	MT4	MT5	MT6	MT7	MT8	MT9	MT10
Limonite/ Haematite	662	612	660	619	496	608	573	634	627	535	552	611	622	649
Magnetite/ Ilmenite	147	179	173	214	246	209	226	242	153	286	228	175	250	170
Leucoxene	191	209	167	167	258	183	201	124	220	150	169	214	128	174
Pyrite	-	-	-	-	-	-	-	-	-	29	51	-	-	-
Total Opaques*	673	681	693	676	693	626	720	635	662	587	669	696	576	627

	MT11	MT12	MT13	MT14	MT15	PT1	PT2	PT3	PT4	PT5	DT1	DT2	DT3	DT7
Limonite/ Haematite	584	660	694	645	508	522	390	697	703	652	450	481	481	487
Magnetite/ Ilmenite	162	215	132	207	308	105	115	46	117	155	256	272	118	150
Leucoxene	254	125	174	148	184	123	134	180	149	125	196	143	131	168
Pyrite	-	-	-	-	-	250	361	77	31	68	98	104	270	195
Total Opaques*	652	600	659	727	694	629	492	678	467	582	694	701	563	642

	DT8	DT9	BT2	BT6	BT7	BT9
Limonite/ Haematite	497	546	369	263	293	82
Magnetite/ Ilmenite	139	116	476	498	541	649
Leucoxene	160	88	128	202	146	235
Pyrite	204	250	27	37	20	34
Total Opaques*	602	601	670	611	657	577

* As ‰ of Heavy Fraction

TABLE 12 20-53μm FRACTION : NON-OPAQUE HEAVY MINERALS

	HT1/6	HT2/5	HT3	HT4	HT5	HT6	HT7	HT8	HT9	HT10	HT11	HT12
Garnet	36	70	67	44	38	85	60	54	71	43	87	81
Epidote	82	217	286	320	82	302	59	46	39	82	258	187
Zoisite/ Clinozoisite	9	22	19	51	16	21	11	13	8	14	17	16
Zircon	124	155	209	73	139	122	159	144	129	207	135	128
Rutile(brown)	5	10	8	9	9	9	5	9	5	9	7	5
Rutile(yellow)	25	44	54	35	20	27	15	18	19	28	24	13
Rutile(red)	2	2	5	3	3	2	4	1	2	1	4	2
Anatase	11	27	19	3	9	16	8	7	26	15	21	17
Brookite	-	-	-	-	3	4	4	3	6	3	9	5
Tourmaline	39	39	27	47	22	40	55	42	78	34	37	34
Augite	34	44	32	9	19	13	46	24	28	38	6	28
Hypersthene	-	-	-	-	-	-	-	-	-	-	-	-
Hornblende	16	126	113	288	75	214	28	31	26	37	176	199
Staurolite	2	-	-	-	5	6	8	10	4	6	4	10
Kyanite	2	10	24	32	1	4	-	3	1	5	1	-
Apatite	58	85	35	13	28	-	42	33	40	40	1	25
Collophane	5	2	3	-	-	-	-	-	-	1	-	-
Chlorite/ Chamosite	325	99	75	60	335	127	251	336	356	294	182	204
Biotite	225	48	24	13	196	8	245	226	162	144	31	46
Siderite	-	-	-	-	-	-	-	-	-	-	-	-

TABLE 12 (contd) 20-53μm FRACTION : NON-OPAQUE HEAVY MINERALS

	HT13	HT14	HT15	HT16	HT17	HT18	HT19
Garnet	84	55	93	74	80	104	66
Epidote	212	254	243	235	253	202	212
Zoisite/ Clinozoisite	13	14	30	21	14	26	18
Zircon	114	350	113	129	243	213	324
Rutile(brown)	6	13	12	7	14	6	13
Rutile(yellow)	21	23	16	12	34	19	24
Rutile(red)	1	3	1	1	8	3	3
Anatase	9	45	9	14	13	9	20
Brookite	2	10	4	4	3	4	1
Tourmaline	37	21	39	26	21	35	39
Augite	23	15	36	30	34	26	8
Hypersthene	-	-	-	-	-	-	-
Hornblende	217	111	221	220	170	178	110
Staurolite	6	7	7	4	5	5	6
Kyanite	1	1	4	1	3	1	4
Apatite	26	3	1	26	9	23	7
Collophane	-	-	-	-	-	-	-
Chlorite/ Chamosite	186	67	141	156	83	107	84
Biotite	42	8	30	40	13	39	61
Siderite	-	-	-	-	-	-	-

TABLE 12 (contd.) 20-53μm FRACTION : NON-OPAQUE HEAVY MINERALS

	MT2	MT3	MT4	MT5	MT6	MT7	MT8	MT9
Garnet	83	90	67	78	49	58	72	70
Epidote	268	235	225	216	194	215	223	164
Zoisite/ Clinozoisite	25	13	23	26	16	29	20	19
Zircon	70	139	90	144	113	111	74	118
Rutile(brown)	11	5	9	6	4	6	9	8
Rutile(yellow)	17	14	14	20	7	11	19	22
Rutile(red)	5	3	1	2	2	2	4	3
Anatase	10	18	13	15	13	5	19	3
Brookite	3	6	2	7	3	1	7	3
Tourmaline	24	37	34	22	22	11	30	16
Augite	5	15	28	20	8	2	12	19
Hypersthene	-	-	-	-	-	-	-	-
Hornblende	168	199	197	176	318	274	114	275
Staurolite	3	4	8	6	7	2	6	7
Kyanite	2	1	2	5	3	3	2	5
Apatite	2	-	23	22	18	21	12	52
Collophane	1	-	-	-	-	-	3	-
Chlorite/ Chamosite	240	204	182	169	115	168	274	180
Biotite	63	17	82	66	25	21	100	36
Siderite	-	-	-	-	83	60	-	-

TABLE 12 (contd.) 20-53µm FRACTION : NON-OPAQUE HEAVY MINERALS

	MT10	MT11	MT12	MT13	MT14	MT15
Garnet	75	54	73	68	29	76
Epidote	219	119	190	201	290	213
Zoisite/ Clinozoisite	16	21	17	17	21	16
Zircon	114	100	141	104	198	97
Rutile(brown)	12	7	5	4	15	7
Rutile(yellow)	21	11	16	9	23	29
Rutile(red)	2	1	3	2	3	2
Anatase	15	4	9	13	23	18
Brookite	4	3	3	2	3	5
Tourmaline	29	31	40	50	43	20
Augite	23	14	24	23	2	9
Hypersthene	-	-	-	-	-	-
Hornblende	205	237	225	236	156	153
Staurolite	10	2	10	8	5	4
Kyanite	2	1	2	6	6	2
Apatite	34	27	37	55	5	10
Collophane	-	-	-	-	-	3
Chlorite/ Chamosite	180	282	166	151	162	270
Biotite	39	86	39	51	16	66
Siderite	-	-	-	-	-	-

TABLE 12(contd.) 20-53µm FRACTION : NON-OPAQUE HEAVY MINERALS

	PT1	PT2	PT3	PT4	PT5
Garnet	19	23	27	23	29
Epidote	100	56	66	80	91
Zoisite/ Clinozoisite	7	9	9	8	6
Zircon	92	36	48	55	57
Rutile(brown)	4	4	1	3	2
Rutile(yellow)	12	4	7	5	6
Rutile(red)	1	-	-	1	-
Anatase	7	5	4	8	3
Brookite	2	2	2	7	2
Tourmaline	8	15	19	21	22
Augite	9	9	20	13	7
Hypersthene	-	-	-	-	-
Hornblende	27	28	20	42	48
Staurolite	3	2	8	1	7
Kyanite	1	1	-	-	2
Apatite	24	17	12	25	19
Collophane	-	-	-	-	-
Chlorite/ Chamosite	389	473	471	398	436
Biotite	143	198	164	168	167
Siderite	152	118	122	142	96

TABLE 12 (contd.) 20–53µm FRACTION : NON-OPAQUE HEAVY MINERALS

	DT1	DT2	DT3	DT7	DT8	DT9
Garnet	69	44	88	56	50	28
Epidote	155	112	135	136	112	76
Zoisite/ Clinozoisite	13	13	17	9	7	7
Zircon	86	80	65	72	53	54
Rutile(brown)	6	5	4	9	7	5
Rutile(yellow)	5	6	4	4	7	10
Rutile(red)	1	1	–	1	1	2
Anatase	9	6	5	5	6	6
Brookite	6	5	3	1	2	3
Tourmaline	14	15	19	15	14	10
Augite	42	16	26	11	12	8
Hypersthene	–	–	–	–	–	–
Hornblende	145	169	211	203	199	56
Staurolite	4	3	7	5	6	5
Kyanite	1	2	2	3	2	1
Apatite	25	20	11	15	17	15
Collophane	–	–	–	–	–	–
Chlorite/ Chamosite	275	274	269	286	276	323
Biotite	87	88	76	76	100	109
Siderite	57	141	58	93	129	282

TABLE 12 (contd.) 20-53µm FRACTION : NON-OPAQUE HEAVY MINERALS

	BT2	BT6	BT7	BT9
Garnet	79	120	84	64
Epidote	209	210	192	184
Zoisite/ Clinozoisite	29	25	28	24
Zircon	82	109	72	59
Rutile(brown)	5	3	7	3
Rutile(yellow)	6	7	3	6
Rutile(red)	2	1	-	1
Anatase	1	6	4	4
Brookite	1	2	1	1
Tourmaline	8	6	10	5
Augite	46	39	30	19
Hypersthene	-	-	-	1
Hornblende	261	316	289	306
Staurolite	3	1	4	5
Kyanite	-	3	1	2
Apatite	8	19	12	12
Collophane	-	-	-	-
Chlorite/ Chamosite	183	86	163	213
Biotite	36	18	36	46
Siderite	41	29	64	45

TABLE 12(contd.) 20-53μm FRACTION : NON-OPAQUE HEAVY MINERALS

	KMF2	KMF3	RP1	HG1	EP1	HCW7	SE1	SE2	BK1
Garnet	86	66	71	50	39	40	69	92	54
Epidote	302	325	234	298	270	346	392	306	298
Zoisite/ Clinozoisite	21	25	23	20	26	17	21	13	26
Zircon	122	100	72	131	112	99	100	93	108
Rutile(brown)	9	7	9	14	7	13	9	8	4
Rutile(yellow)	27	11	11	31	26	18	33	24	15
Rutile(red)	2	7	1	2	2	2	3	1	3
Anatase	16	17	6	24	20	24	21	11	19
Brookite	4	4	4	12	4	3	1	3	4
Tourmaline	40	21	22	63	23	55	26	34	41
Augite	13	3	6	14	4	-	8	3	3
Hypersthene	-	-	-	-	-	-	-	-	-
Hornblende	214	172	340	224	151	202	206	254	219
Staurolite	6	13	2	5	6	8	5	8	4
Kyanite	4	4	4	3	3	6	3	3	6
Monazite	-	-	-	-	-	-	-	-	1
Apatite	-	9	18	5	8	-	4	7	2
Collophane	-	-	-	-	-	-	-	-	-
Chlorite/ Chamosite	127	190	169	89	284	156	90	118	180
Biotite	8	26	8	15	15	11	9	22	13
Siderite	-	-	-	-	-	-	-	-	-

TABLE 12 (contd) 20-53μm FRACTION : NON-OPAQUE HEAVY MINERALS

	SM1	AN1	HT4	BM1	CN1
Garnet	53	65	44	48	58
Epidote	454	431	320	502	306
Zoisite/ Clinozoisite	34	30	51	33	46
Zircon	89	104	73	109	111
Rutile(brown)	8	15	9	19	12
Rutile(yellow)	20	32	35	35	41
Rutile(red)	4	5	3	3	2
Anatase	22	15	3	14	15
Brookite	-	2	-	3	-
Tourmaline	12	25	47	12	10
Augite	4	2	9	7	7
Hypersthene	-	-	-	-	3
Hornblende	226	228	288	175	312
Staurolite	10	7	-	3	3
Kyanite	14	3	32	9	9
Monazite	-	-	-	-	-
Apatite	-	-	13	-	-
Collophane	-	-	-	-	-
Chlorite/ Chamosite	36	33	60	23	62
Biotite	14	3	13	5	3
Siderite	-	-	-	-	-

TABLE 13 20-53µm FRACTION : NON-OPAQUE MINERALS (excl. Siderite)

	PT1	PT2	PT3	PT4	PT5	DT1	DT2	DT3	DT7	DT8	DT9	BT2	BT6	BT7	BT9	MT6	MT7
Garnet	22	26	31	27	32	73	51	93	62	57	39	82	124	90	67	53	62
Epidote	118	63	75	93	100	164	130	143	150	129	106	218	216	205	193	212	229
Zoisite/ Clinozoisite	8	10	10	9	7	14	15	18	10	8	10	30	26	30	25	17	31
Zircon	108	41	55	64	63	91	93	69	79	61	75	85	112	77	62	123	118
Rutile	20	10	9	10	9	12	14	8	15	17	24	13	11	10	10	14	20
Anatase	8	6	5	9	3	10	7	5	6	7	8	1	6	4	4	14	5
Brookite	2	2	2	8	2	6	6	3	1	2	4	1	2	1	1	3	1
Tourmaline	9	17	22	24	24	15	17	20	17	16	14	8	6	11	5	24	12
Pyroxene	11	10	23	15	8	45	19	28	12	14	11	48	40	32	21	9	2
Amphibole	32	32	23	49	53	154	197	224	224	229	78	272	326	309	320	347	292
Staurolite	4	2	9	1	8	4	3	7	6	7	7	3	1	4	5	8	2
Kyanite	1	1	-	-	2	1	2	2	3	2	1	-	3	1	2	3	3
Apatite	28	19	14	29	21	27	23	12	17	20	21	8	20	13	13	20	22
Chlorite/ Chamosite	458	536	536	465	482	292	320	287	314	316	450	193	88	175	225	125	179
Biotite	169	225	186	197	186	92	103	81	84	115	152	38	19	38	48	27	22

TABLE 14 20-53µm FRACTION : NON-OPAQUE "RESISTANT" HEAVY MINERALS

	HT1/6	HT2/5	HT3	HT4	HT5	HT6	HT7	HT8	HT9	HT10	HT11	HT12
Garnet	94	92	78	48	86	98	130	133	161	82	111	112
Epidote	212	284	333	351	187	349	128	114	88	157	327	258
Zoisite/ Clinozoisite	24	28	22	55	36	24	24	32	18	27	22	22
Zircon	321	202	242	80	316	141	343	357	292	396	172	176
Rutile	81	73	77	51	72	43	52	68	59	73	45	28
Anatase	28	35	22	3	20	19	17	17	59	29	27	23
Brookite	-	-	-	-	7	5	9	7	14	6	11	7
Tourmaline	102	51	31	52	50	46	119	104	176	65	47	47
Pyroxene	89	57	37	10	43	15	100	59	63	73	8	39
Amphibole	41	165	130	315	170	248	61	77	59	71	224	274
Staurolite	4	-	-	-	11	7	17	25	9	11	5	14
Kyanite	4	13	28	35	2	5	-	7	2	10	1	-

	HT13	HT14	HT15	HT16	HT17	HT18	HT19	PT1	PT2	PT3	PT4	PT5
Garnet	113	60	112	95	89	125	78	65	119	117	86	103
Epidote	284	276	295	303	282	243	250	343	289	287	299	323
Zoisite/ Clinozoisite	17	15	36	27	16	31	21	24	46	39	30	21
Zircon	153	379	137	166	272	257	382	315	186	208	206	202
Rutile	37	42	34	25	63	34	47	58	42	34	34	28
Anatase	12	49	11	18	15	11	24	24	26	17	30	11
Brookite	3	11	5	5	3	5	1	7	10	9	26	7
Tourmaline	50	23	47	33	23	42	46	27	77	82	79	78
Pyroxene	31	16	43	39	38	31	9	31	46	86	49	25
Amphibole	291	120	267	283	190	214	130	93	144	86	157	170
Staurolite	8	8	8	5	6	6	7	10	10	35	4	25
Kyanite	1	1	5	1	3	1	5	3	5	-	-	7

TABLE 14 (contd.) 20-53μm FRACTION : NON-OPAQUE "RESISTANT" HEAVY MINERALS

	MT2	MT3	MT4	MT5	MT6	MT7	MT8	MT9	MT10	MT11	MT12	MT13
Garnet	120	115	94	105	65	79	118	96	101	89	96	92
Epidote	387	303	316	291	256	294	364	224	292	196	251	270
Zoisite/ Clinozoisite	36	17	32	35	21	40	33	26	21	35	22	23
Zircon	101	178	126	193	149	152	121	161	153	165	186	139
Rutile	47	28	34	38	17	26	53	45	47	32	32	20
Anatase	14	23	18	20	17	7	31	4	20	7	12	18
Brookite	4	8	3	9	4	1	11	4	5	5	4	3
Tourmaline	35	47	48	30	29	15	49	22	39	51	53	68
Pyroxene	7	19	39	27	11	3	20	26	31	23	32	31
Amphibole	242	256	276	237	418	376	187	375	275	392	296	317
Staurolite	4	5	11	8	9	3	10	10	13	3	13	11
Kyanite	3	1	3	7	4	4	3	7	3	2	3	8

	MT14	MT15	DT1	DT2	DT3	DT7	DT8	DT9	BT2	BT6	BT7	BT9
Garnet	35	117	124	92	150	106	104	103	108	142	116	94
Epidote	356	326	278	235	230	257	234	281	286	248	265	270
Zoisite/ Clinozoisite	26	25	23	27	29	17	15	26	40	29	39	35
Zircon	243	149	155	168	111	136	111	200	112	129	99	86
Rutile	50	59	22	25	14	27	32	62	18	13	14	14
Anatase	28	28	16	13	9	9	13	22	1	7	6	6
Brookite	4	8	11	10	5	2	4	11	1	2	1	1
Tourmaline	52	31	25	31	32	28	29	37	11	7	14	7
Pyroxene	2	14	76	34	44	21	25	29	63	46	41	29
Amphibole	191	234	261	355	361	382	416	207	356	372	399	448
Staurolite	6	6	7	6	12	9	13	18	4	1	5	7
Kyanite	7	3	2	4	3	6	4	4	–	4	1	3

TABLE 14 (contd.) 20-53µm FRACTION : NON-OPAQUE "RESISTANT" HEAVY MINERALS

	KMF3	RP1	EP1	HG1	HCW7	SE1	SE2	BK1	SM1	CN1	AN1	BM1
Garnet	85	88	56	56	48	77	108	67	56	62	67	49
Epidote	420	291	390	334	415	436	359	370	478	327	448	516
Zoisite/ Clinozoisite	32	29	28	22	20	23	15	32	36	49	31	34
Zircon	129	89	162	147	119	111	109	134	94	119	108	113
Rutile	32	26	41	53	40	50	38	28	33	59	54	59
Anatase	22	7	29	27	29	23	13	24	23	16	16	14
Brookite	5	5	6	13	4	1	4	5	-	-	2	3
Tourmaline	27	27	33	71	66	29	40	51	13	11	26	12
Pyroxene	4	7	6	16	-	9	4	4	4	10	2	7
Amphibole	222	424	218	252	242	229	298	272	238	334	236	181
Staurolite	17	2	9	6	10	6	9	5	11	3	7	3
Kyanite	5	5	4	3	7	3	4	7	15	10	3	9
Monazite	-	-	-	-	-	-	-	1	-	-	-	-

TABLE 15 53-250µm FRACTION : HEAVY (>2.9 S.G.) FRACTION

Sample	HT1/6	HT2/5	HT3	HT5	HT6	HT7	HT8	HT9	HT10	HT11	HT12	HT13
% Heavy Minerals	0.9	1.1	0.7	0.8	0.7	0.7	0.4	0.5	0.6	1.0	0.7	0.9
‰ Opaque Minerals	534	488	679	647	826	742	803	735	673	806	665	745

Sample	HT14	HT15	HT16	HT17	HT18	HT19	HT20	HT21	HT22	HT23	HT24	HT25
% Heavy Minerals	0.2	0.5	0.8	0.9	0.5	1.4	1.1	0.9	0.7	1.3	0.5	1.0
‰ Opaque Minerals	747	792	561	741	550	719	661	610	680	700	597	755

Sample	HT26	HT27	HT28	HT29	HT30	HT31	HT32	HT33	HT34	HT35	HT36	HT37
% Heavy Minerals	0.6	0.6	0.3	0.4	1.0	0.7	0.6	0.3	0.9	0.9	0.4	0.5
‰ Opaque Minerals	684	745	830	763	552	743	801	532	479	540	491	693

Sample	HT38	HT39	MT1	MT2	MT3	MT4	MT5	MT6	MT7	MT8	MT9	MT10
% Heavy Minerals	0.8	1.1	0.9	1.1	1.2	1.0	0.9	0.7	0.8	0.7	0.7	0.6
‰ Opaque Minerals	432	489	672	642	715	585	640	551	498	766	677	673

Sample	MT11	MT12	MT13	MT14	MT15	MT16	MT17	PT1	PT2	PT3	PT4	PT5
% Heavy Minerals	0.6	0.5	0.7	1.6	0.7	1.1	1.4	2.2	1.3	1.5	1.2	1.2
‰ Opaque Minerals	630	673	712	901	774	621	691	445	528	625	640	572

Sample	PT6	DT1	DT2	DT3	DT4	DT5	DT6	DT7	DT8	DT9	DT10	DT11
% Heavy Minerals	0.9	2.1	1.9	1.7	1.8	1.7	1.6	1.2	1.4	2.2	0.8	1.8
‰ Opaque Minerals	522	487	571	565	485	487	493	545	562	474	770	579

Sample	DT12	DT13	DT14	BT2	BT3	BT5	BT6	BT7	BT8	BT9	DMS1	DMS2
% Heavy Minerals	1.6	2.0	2.2	1.8	1.8	1.0	1.1	1.1	1.4	1.3	1.4	0.8
‰ Opaque Minerals	528	485	591	432	425	411	380	359	359	300	330	476

Sample	SBC1	BTRC	PTE	LHH	Y185/8	ITC1	ITH1	2TM1	3TM1	NB1	NB2	LT1/6
% Heavy Minerals	2.1	1.2	1.4	0.4	0.4	0.4	0.7	0.9	0.5	0.4	0.8	0.6
‰ Opaque Minerals	164	644	725	618	857	226	278	355	330	652	761	544

Sample	LT2	LT5/2	LT5/3	LT5/4	LT5/7	PGT1	W01/1	W02/1
% Heavy Minerals	4.6	1.1	1.7	1.1	1.1	1.0	2.4	2.2
‰ Opaque Minerals	385	683	792	778	795	485	750	740

TABLE 15 (Cont.). 53-250 µm FRACTION : HEAVY (2.9 S.G.) FRACTION

Sample	HT40	HT41	HT42	HT43	HT44	HT45	HT46	HT47	HT48	HT49	HT50
% Heavy Minerals	1.4	N.D.	0.6	0.6	0.4	0.5	0.6	0.7	0.5	1.3	0.3
% Opaque Minerals	621	N.D.	N.D.	N.D.	623	709	563	N.D.	656	559	544

Sample	HT51	HT52	HT53	HT54	HT55	PT 7	PT 8	PT 9	DT15	DT16	DT17
% Heavy Minerals	0.5	0.6	0.8	0.4	0.4	1.1	0.9	2.1	1.4	2.1	1.5
% Opaque Minerals	677	582	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

Sample	D 1	D 2	D 3	D 4	D 5	D 6	D 7	D 8	D 10	D 12	D 14
% Heavy Minerals	0.4	0.6	0.9	0.8	0.8	1.2	1.4	1.9	2.2	2.4	2.3
% Opaque Minerals	670	552	473	469	668	N.D.	565	488	495	N.D.	444

Sample	D 16	A 1	A 2	A 3	A 4	A 5	A 6	S 1	S 2	S 3	S 4
% Heavy Minerals	1.9	2.6	2.6	2.9	2.7	1.8	1.9	0.9	0.8	1.0	1.0
% Opaque Minerals	N.D.	N.D.	459	N.D.	486	575	602	N.D.	N.D.	N.D.	N.D.

Sample	S 5	S 6	S 7	S 8	S 9	MT18	MT19	MT20	CT 1	GH 1
% Heavy Minerals	1.1	1.2	1.3	1.8	1.9	1.0	1.1	1.2	1.1	0.9
% Opaque Minerals	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

TABLE 16 53-250µm FRACTION : OPAQUE HEAVY MINERALS

	Magnetite/Ilmenite	Leucoxene	Haematite	Limonite	Pyrite
HT1/6	168	90	305	437	-
HT2/5	106	136	251	507	-
HT3	90	76	262	572	-
HT5	172	115	293	419	1
HT7	71	71	474	384	-
HT11	158	46	483	313	-
MT6	11	67	368	462	2
PT1	71	44	212	487	186
PT6	49	61	398	252	240
DT1	63	35	182	588	133
DT2	42	84	156	617	102
BT2	119	94	315	370	24
BT3	246	75	349	302	28
SBC1	310	140	220	30	300
BTRC	58	73	219	650	-
PTE	13	59	98	595	235
1TC1	365	212	270	141	12
1TH1	356	192	246	192	14
2TM1	171	120	188	231	290
3TM1	338	176	176	204	108
NB1	174	87	134	605	-
NB2	114	34	126	726	-
PGT1	89	73	173	15	650
LT2	25	11	29	25	910

TABLE 17 53-250μm FRACTION : PYRITE and SIDERITE

	Pyrite	Siderite		Pyrite	Siderite
HT2/5	-	1	DT7	102	102
HT3	-	1	DT8	113	115
HT5	1	4	DT9	63	345
HT9	1	-	DT10	-	5
HT21	-	7	DT11	52	176
HT22	-	3	DT12	41	69
HT27	2	-	DT13	68	206
HT28	1	-	DT14	17	22
HT31	-	10	BT2	10	21
HT36	-	1	BT3	12	9
HT37	-	2	BT5	9	15
MT6	1	4	BT6	2	16
MT7	9	4	BT7	17	20
MT17	73	9	BT8	13	22
PT1	83	192	BT9	11	22
PT2	196	218	DMS1	10	8
PT3	111	152	SBC1	49	4
PT4	100	141	BTRC	-	2
PT5	104	186	PTE	170	76
PT6	125	309	1TC1	3	3
DT1	65	72	1TH1	4	24
DT2	58	101	2TM1	103	54
DT3	91	105	3TM1	36	78
DT4	66	123	LT2	350	517
DT5	51	99	PGT1	315	130
DT6	224	152			

(% of total heavy minerals)

TABLE 17 (Cont.). 53-250 μm FRACTION : PYRITE AND SIDERITE

	Pyrite	Siderite		Pyrite	Siderite
D 1	-	-	A 2	226	360
D 2	-	-	A 4	295	367
D 3	-	-	A 5	266	244
D 4	-	13	A 6	256	202
D 5	183	42	GH 1	49	2
D 7	164	141			
D 8	132	125			
D 10	155	183			
D 14	262	272			

TABLE 18 53-250µm FRACTION : NON-OPAQUE HEAVY MINERALS

(a)	HT1/6	HT2/5	HT3	HT5	HT6	HT7	HT8	HT9
Garnet (Clear)	74	165	181	87	219	102	99	54
Garnet (Pink)	8	81	50	14	65	20	17	9
Epidote	26	121	147	56	127	58	72	49
Zoisite/Clinozoisite	10	38	35	9	14	19	8	8
Zircon	44	74	106	50	61	58	72	62
Rutile (brown)	5	8	3	5	7	4	6	1
Rutile (yellow)	7	17	12	29	51	28	33	25
Rutile (red)	4	11	3	2	7	13	6	6
Anatase	1	2	3	9	3	-	8	10
Brookite	4	6	6	-	3	-	3	1
Tourmaline	36	83	79	38	34	48	61	52
Augite	87	59	62	127	87	164	173	113
Hypersthene	-	19	15	7	20	2	3	1
Hornblende (Dark Green)	13	147	204	99	127	37	39	44
Hornblende (Pale Green)	6	34	32	22	17	6	8	14
Hornblende (Brown)	1	10	6	13	10	-	6	5
Staurolite	1	2	-	5	3	9	3	4
Kyanite	2	6	6	2	-	4	-	1
Andalusite	-	-	-	-	-	-	3	1
Sillimanite	-	-	-	-	-	-	-	-
Monazite	-	-	-	-	3	-	-	-
Apatite	86	78	3	70	20	88	129	95
Collophane	11	4	3	30	3	9	28	19
Chlorite/Chamosite	232	27	29	188	95	126	116	161
Biotite	342	6	12	128	24	203	107	265
Glauconite	-	-	-	-	-	2	-	-
Siderite	-	2	3	10	-	-	-	-

TABLE 18 (contd.) 53–250μm FRACTION : NON-OPAQUE HEAVY MINERALS

(b)	HT10	HT11	HT12	HT13	HT14	HT15	HT16	HT17	HT18
Garnet (clear)	83	189	119	205	176	184	219	156	161
Garnet (pink)	14	55	15	30	49	54	46	26	36
Epidote	28	217	92	135	146	126	136	101	108
Zoisite/Clinozoisite	9	27	9	30	26	16	38	29	24
Zircon	44	60	33	56	180	49	28	75	78
Rutile (brown)	1	5	-	-	7	-	3	13	6
Rutile (yellow)	23	15	6	46	62	8	20	33	30
Rutile (red)	7	10	-	7	10	-	8	26	6
Anatase	4	-	3	3	3	3	3	7	6
Brookite	-	-	3	3	-	-	-	-	-
Tourmaline	48	50	56	33	49	44	33	42	42
Augite	117	55	109	63	65	145	62	78	135
Hypersthene	1	-	6	3	10	11	2	3	3
Hornblende (dark green)	23	186	249	166	173	184	235	175	170
Hornblende (pale green)	10	25	62	20	19	57	40	33	33
Hornblende (brown)	1	2	6	13	13	5	7	3	6
Staurolite	7	2	15	3	3	3	5	10	15
Kyanite	1	12	6	7	3	5	5	10	3
Andalusite	-	-	-	-	3	3	-	-	-
Sillimanite	-	-	-	-	3	-	-	-	-
Monazite	-	-	-	-	-	-	-	3	-
Apatite	96	-	65	63	-	-	40	65	54
Collophane	6	-	18	16	-	5	8	7	12
Chlorite/Chamosite	120	75	84	46	-	81	35	98	51
Biotite	357	15	44	49	-	14	20	7	21
Glauconite	-	-	-	3	-	3	7	-	-
Siderite	-	-	-	-	-	-	-	-	-

TABLE 18 (contd.) 53-250μm FRACTION : NON-OPAQUE HEAVY MINERALS

(c)	HT19	HT20	HT21	HT22	HT23	HT24	HT25	HT26	HT27
Garnet (clear)	178	198	176	139	186	180	140	125	89
Garnet (pink)	42	55	46	30	26	31	29	13	13
Epidote	150	135	99	134	104	139	123	84	28
Zoisite/Clinozoisite	17	29	25	20	13	12	10	13	9
Zircon	102	106	67	85	79	71	93	88	59
Rutile (brown)	6	10	4	5	3	2	7	2	2
Rutile (yellow)	35	29	18	25	23	24	38	19	37
Rutile (red)	2	3	11	10	3	7	12	6	9
Anatase	6	16	11	10	8	9	17	13	28
Brookite	-	-	-	-	-	-	-	2	2
Tourmaline	60	26	39	20	37	49	43	46	71
Augite	127	106	113	124	99	132	81	156	142
Hypersthene	10	6	4	5	10	-	7	4	4
Hornblende (dark green)	169	133	169	193	183	141	158	104	26
Hornblende (pale green)	31	32	39	55	57	56	33	31	7
Hornblende (brown)	6	6	18	25	10	7	10	13	4
Staurolite	6	6	11	-	10	5	-	4	-
Kyanite	4	10	4	10	5	9	2	8	2
Andalusite	-	-	-	-	3	-	2	2	-
Sillimanite	-	-	-	-	-	2	-	-	-
Monazite	-	6	-	-	-	2	-	-	-
Apatite	-	16	53	40	60	73	100	109	137
Collophane	8	10	7	-	-	2	14	13	17
Chlorite/Chamosite	37	38	61	45	57	33	57	106	171
Biotite	4	19	7	15	21	12	17	35	141
Glauconite	-	3	-	-	3	2	7	4	2
Siderite	-	-	18	10	-	-	-	-	-

TABLE 18 (contd.) 53-250μm FRACTION : NON-OPAQUE HEAVY MINERALS

(d)	HT28	HT29	HT30	HT31	HT32	HT33	HT34	HT35	HT36
Garnet (clear)	146	253	256	175	189	242	181	189	132
Garnet (pink)	25	52	29	47	69	77	43	37	25
Epidote	57	85	131	92	118	128	162	104	70
Zoisite/Clinozoisite	10	9	6	22	11	17	20	15	15
Zircon	67	50	79	44	55	57	101	57	105
Rutile (brown)	2	2	-	6	2	10	14	2	-
Rutile (yellow)	45	26	25	13	22	34	37	25	38
Rutile (red)	5	12	6	3	13	3	3	7	8
Anatase	25	14	10	6	7	13	9	7	19
Brookite	-	-	2	-	-	-	3	2	-
Tourmaline	47	33	35	28	42	27	46	32	53
Augite	140	113	79	109	104	115	84	92	147
Hypersthene	10	2	2	6	2	-	9	-	8
Hornblende (dark green)	90	118	150	165	189	121	139	201	91
Hornblende (pale green)	30	21	37	57	27	34	26	52	25
Hornblende (brown)	7	12	8	16	16	10	12	10	8
Staurolite	-	-	2	3	2	7	3	5	11
Kyanite	10	5	4	9	7	7	9	7	8
Andalusite	-	2	-	-	-	-	3	-	2
Sillimanite	-	-	-	-	-	-	-	-	-
Monazite	-	-	-	-	2	3	-	2	-
Apatite	87	52	73	68	51	47	78	47	80
Collophane	22	31	4	19	13	17	-	2	11
Chlorite/Chamosite	125	82	33	60	53	3	12	55	102
Biotite	45	24	27	16	2	7	6	40	34
Glauconite	5	2	2	-	4	-	-	10	6
Siderite	-	-	-	38	-	-	-	-	2

TABLE 18 (contd.) 53–250µm FRACTION: NON-OPAQUE HEAVY MINERALS

(e)	HT37	HT38	HT39
Garnet (clear)	159	163	51
Garnet (pink)	48	34	6
Epidote	164	102	20
Zoisite/Clinozoisite	26	27	4
Zircon	48	32	40
Rutile (brown)	-	10	4
Rutile (yellow)	11	19	13
Rutile (red)	5	-	3
Anatase	-	10	6
Brookite	-	-	-
Tourmaline	58	46	40
Augite	122	119	72
Hypersthene	26	5	1
Hornblende (dark green)	174	160	14
Hornblende (pale green)	37	41	5
Hornblende (brown)	16	12	3
Staurolite	11	5	-
Kyanite	-	5	4
Andalusite	5	-	1
Sillimanite	-	-	-
Monazite	5	2	-
Apatite	-	41	93
Collophane	5	22	15
Chlorite/Chamosite	59	90	235
Biotite	16	53	370
Glauconite	-	2	-
Siderite	5	-	-

TABLE 18(contd) 53–250 μm FRACTION : NON-OPAQUE HEAVY MINERALS

(f)	HT40	HT44	HT45	HT46	HT48	HT49	HT50	HT51	HT52
Garnet (clear)	235	185	121	199	252	209	274	222	292
Garnet (pink)	17	48	12	18	45	25	34	23	38
Epidote	136	45	61	78	117	130	145	91	108
Zoisite/Clinozoisite	13	11	10	15	16	37	14	11	17
Zircon	83	78	97	85	117	65	138	109	114
Rutile (brown)	7	6	10	5	11	6	7	4	9
Rutile (yellow)	23	34	49	47	56	28	57	53	50
Rutile (red)	7	3	2	5	8	6	11	15	12
Anatase	7	3	6	21	11	17	14	15	9
Brookite	–	–	–	–	–	–	–	–	3
Tourmaline	33	25	46	41	27	31	34	45	26
Augite	119	134	125	106	104	113	68	147	96
Hypersthene	17	11	8	3	19	11	2	11	3
Hornblende (dark green)	142	95	42	126	93	155	66	49	96
Hornblende (pale green)	43	17	10	49	24	48	11	19	17
Hornblende (brown)	7	3	10	5	5	14	16	11	6
Staurolite	7	3	2	5	5	3	2	–	3
Kyanite	–	3	8	3	–	11	2	4	3
Andalusite	–	–	2	–	–	–	–	–	–
Sillimanite	7	–	–	–	–	–	–	–	3
Monazite	3	–	–	–	–	–	–	–	–
Apatite	36	20	53	67	37	34	50	72	47
Collophane	3	11	14	13	27	6	9	26	6
Chlorite/Chamosite	40	118	129	60	18	31	32	38	38
Biotite	13	143	182	47	8	20	14	34	6
Glauconite	–	6	–	3	–	–	–	–	–
Siderite	3	–	–	–	–	–	–	–	–

TABLE 18(contd.) 53-250 μm FRACTION : NON-OPAQUE HEAVY MINERALS

(9)

	D1	D2	D3	D4	D5	D7	D8	D10
Garnet (clear)	123	105	100	90	134	105	125	124
Garnet (pink)	5	7	11	13	26	10	11	15
Epidote	47	27	25	21	19	16	70	50
Zoisite/Clinozoisite	7	9	7	4	9	5	17	7
Zircon	88	57	46	43	47	36	62	37
Rutile (brown)	7	9	2	4	4	2	4	4
Rutile (yellow)	49	18	14	13	11	10	11	7
Rutile (red)	5	2	7	2	4	3	2	1
Anatase	15	16	9	6	9	7	2	1
Brookite	–	–	2	2	–	–	–	1
Tourmaline	61	18	25	24	30	21	43	19
Augite	103	102	116	99	145	109	89	73
Hypersthene	7	5	7	6	2	5	2	3
Hornblende (dark green)	57	59	43	63	62	38	85	92
Hornblende (pale green)	10	14	9	21	11	12	21	23
Hornblende (brown)	2	2	–	2	2	3	6	3
Staurolite	10	2	5	9	4	3	2	3
Kyanite	2	–	–	2	2	3	2	4
Andalusite	–	2	–	–	–	2	–	3
Sillimanite	–	–	–	–	–	–	–	1
Monazite	–	–	–	–	–	–	–	–
Apatite	79	55	39	56	43	28	51	33
Collophane	15	7	7	7	6	7	8	5
Chlorite/Chamosite	145	146	132	122	59	55	70	55
Biotite	162	337	385	366	237	190	66	57
Glauconite	–	–	5	2	6	3	6	15
Siderite	–	–	–	24	126	324	244	362

TABLE 18(contd) 53-250 μm FRACTION : NON-OPAQUE HEAVY MINERALS

(h)

	A 2	A 4	A 5	A 6
Garnet (clear)	49	40	47	59
Garnet (pink)	6	3	7	7
Epidote	23	16	12	21
Zoisite/Clinozoisite	2	5	3	6
Zircon	15	22	45	43
Rutile (brown)	3	1	1	1
Rutile (yellow)	4	6	5	11
Rutile (red)	-	1	-	2
Anatase	1	-	1	1
Brookite	-	-	-	-
Tourmaline	3	8	10	27
Augite	37	33	65	65
Hypersthene	4	3	3	8
Hornblende (dark green)	40	21	33	30
Hornblende (pale green)	4	5	5	8
Hornblende (brown)	1	2	1	1
Staurolite	1	2	2	1
Kyanite	2	3	-	2
Andalusite	-	1	-	-
Sillimanite	-	-	-	1
Monazite	1	-	-	-
Apatite	17	14	23	34
Collophane	6	8	6	4
Chlorite/Chamosite	55	43	49	58
Biotite	43	40	99	96
Glauconite	18	9	7	4
Siderite	665	714	574	508

TABLE 18(contd.) 53-250μm FRACTION : NON-OPAQUE HEAVY MINERALS

(i)	MT1	MT2	MT3	MT4	MT5	MT6	MT7	MT8	MT9
Garnet (clear)	147	202	158	137	99	98	143	68	108
Garnet (pink)	22	45	32	33	8	16	19	13	49
Epidote	165	147	167	92	122	158	135	112	143
Zoisite/Clinozoisite	41	32	18	23	28	21	19	13	20
Zircon	79	50	121	47	38	37	49	64	25
Rutile (brown)	-	10	7	9	3	5	8	6	2
Rutile (yellow)	33	20	41	21	30	18	19	26	14
Rutile (red)	6	7	7	9	-	2	3	13	-
Anatase	2	2	2	2	3	2	3	-	-
Brookite	-	-	-	2	-	-	-	-	-
Tourmaline	43	45	41	52	58	68	46	64	33
Augite	53	92	88	82	96	25	30	142	110
Hypersthene	4	5	4	-	5	-	-	6	-
Hornblende (dark green)	214	170	147	140	221	326	315	139	255
Hornblende (pale green)	41	15	45	14	38	32	43	23	41
Hornblende (brown)	8	7	9	14	5	5	11	3	8
Staurolite	4	7	2	2	5	5	5	10	6
Kyanite	4	15	4	5	5	4	11	16	6
Andalusite	-	-	2	2	-	4	-	3	-
Sillimanite	-	-	-	-	-	-	-	-	-
Monazite	-	-	-	-	-	-	-	-	-
Apatite	53	25	2	54	91	48	32	51	78
Collophane	4	12	-	16	23	12	3	10	10
Chlorite/Chamosite	65	65	81	99	56	68	76	109	43
Biotite	12	22	22	143	63	28	11	103	41
Glauconite	-	5	-	2	3	9	11	6	8
Siderite	-	-	-	-	-	9	8	-	-

TABLE 18(contd.) 53-250µm FRACTION : NON-OPAQUE HEAVY MINERALS

(j)	MT10	MT11	MT12	MT13	MT14	MT15	MT16	MT17
Garnet (clear)	139	112	136	140	132	152	146	125
Garnet (pink)	40	29	24	29	27	25	27	19
Epidote	98	101	126	99	103	100	166	100
Zoisite/Clinozoisite	13	16	21	18	27	30	27	15
Zircon	51	31	64	51	35	30	113	75
Rutile (brown)	-	3	3	4	3	3	5	6
Rutile (yellow)	35	10	33	40	27	15	44	24
Rutile (red)	8	5	2	2	3	3	8	4
Anatase	7	-	12	4	14	3	7	8
Brookite	2	-	2	2	-	3	3	4
Tourmaline	45	57	33	53	86	57	39	60
Augite	119	106	123	62	57	110	81	115
Hypersthene	5	3	5	2	8	3	5	-
Hornblende (dark green)	176	198	150	173	130	127	150	119
Hornblende (pale green)	43	52	39	37	32	22	22	24
Hornblende (brown)	3	8	8	9	8	5	8	9
Staurolite	5	3	6	11	11	3	3	4
Kyanite	3	5	3	2	3	3	7	4
Andalusite	-	-	-	-	3	3	2	2
Sillimanite	-	-	-	-	-	-	-	-
Monazite	-	-	-	-	-	-	-	-
Apatite	69	26	85	79	-	30	57	70
Collophane	20	10	23	29	11	42	10	23
Chlorite/Chamosite	71	80	67	66	261	127	52	96
Biotite	45	145	35	81	19	67	15	53
Glauconite	3	-	-	7	-	37	3	11
Siderite	-	-	-	-	-	-	-	30

TABLE 18(contd.) 53-250μm FRACTION : NON-OPAQUE HEAVY MINERALS

(k)	PT1	PT2	PT3	PT4	PT5	PT6
Garnet (clear)	12	43	36	22	36	24
Garnet (pink)	2	3	5	4	5	-
Epidote	6	23	32	44	23	25
Zoisite/Clinozoisite	1	4	7	6	5	6
Zircon	11	31	43	39	22	26
Rutile (brown)	3	1	2	4	-	1
Rutile (yellow)	2	8	18	4	3	2
Rutile (red)	1	-	-	2	-	-
Anatase	1	1	11	6	3	4
Brookite	1	-	-	-	-	1
Tourmaline	11	22	45	37	19	15
Augite	23	63	83	78	62	56
Hypersthene	1	4	5	4	5	-
Hornblende (dark green)	8	36	34	43	35	12
Hornblende (pale green)	1	12	7	7	14	1
Hornblende (brown)	1	1	2	4	1	1
Staurolite	-	1	2	2	3	1
Kyanite	1	1	-	6	-	1
Andalusite	-	2	-	-	-	-
Sillimanite	-	-	-	-	-	-
Monazite	-	-	-	-	-	-
Apatite	37	45	74	83	59	20
Collophane	12	11	7	9	5	4
Chlorite/Chamosite	198	74	82	96	111	61
Biotite	321	137	94	104	151	87
Glauconite	-	15	4	4	3	5
Siderite	346	462	407	392	435	647

TABLE 18(contd.) 53-250μm FRACTION : NON-OPAQUE HEAVY MINERALS

(l)	DT1	DT2	DT3	DT4	DT5	DT6	DT7
Garnet (clear)	131	87	80	148	152	138	117
Garnet (pink)	13	9	20	25	36	26	23
Epidote	104	114	120	68	93	58	100
Zoisite/Clinozoisite	15	12	16	10	18	6	13
Zircon	35	40	36	40	23	36	30
Rutile (brown)	-	2	-	3	8	2	5
Rutile (yellow)	10	7	7	13	15	10	10
Rutile (red)	-	-	-	-	-	-	-
Anatase	3	2	-	3	8	4	-
Brookite	-	-	-	-	-	-	-
Tourmaline	20	19	11	18	18	16	18
Augite	94	71	102	98	121	80	113
Hypersthene	3	-	2	8	10	12	2
Hornblende (dark green)	137	129	146	138	147	90	136
Hornblende (pale green)	43	38	36	30	36	30	33
Hornblende (brown)	5	2	16	8	5	4	8
Staurolite	5	2	-	5	3	2	2
Kyanite	5	-	7	-	5	-	2
Andalusite	-	-	-	-	-	-	-
Sillimanite	-	-	-	-	-	-	-
Monazite	-	2	-	3	-	-	-
Apatite	55	31	56	40	23	32	43
Collophane	17	17	2	3	3	6	-
Chlorite/Chamosite	71	59	62	58	41	50	50
Biotite	80	111	27	35	26	84	60
Glauconite	14	10	13	8	15	14	10
Siderite	140	236	241	238	194	300	225

TABLE 18(contd.) 53–250µm FRACTION : NON-OPAQUE MINERALS

(m)	DT8	DT9	DT10	DT11	DT12	DT13	DT14
Garnet (clear)	86	19	143	81	183	75	161
Garnet (pink)	15	4	35	19	21	15	28
Epidote	118	18	101	65	118	71	116
Zoisite/Clinozoisite	12	2	14	12	26	20	17
Zircon	27	8	67	43	52	48	60
Rutile (brown)	–	1	3	2	9	6	3
Rutile (yellow)	12	2	14	7	21	12	20
Rutile (red)	2	–	–	–	–	3	–
Anatase	–	2	9	2	9	11	3
Brookite	–	–	–	–	2	2	–
Tourmaline	27	5	35	22	32	29	42
Augite	104	47	125	86	114	68	102
Hypersthene	–	1	14	5	4	3	14
Hornblende (dark green)	126	39	133	93	110	72	165
Hornblende (pale green)	37	5	26	19	26	31	71
Hornblende (brown)	2	5	9	2	4	9	20
Staurolite	2	2	–	–	4	6	8
Kyanite	5	1	9	7	6	3	3
Andalusite	–	1	3	2	2	2	–
Sillimanite	–	–	–	–	–	–	–
Monazite	2	–	–	–	–	2	–
Apatite	22	25	58	41	62	38	45
Collophane	5	12	14	12	4	5	6
Chlorite/Chamosite	59	54	101	38	23	34	51
Biotite	59	66	67	19	13	29	8
Glauconite	15	25	–	5	9	5	3
Siderite	263	656	20	418	146	401	54

TABLE 18(contd.) 53–250μm FRACTION : NON–OPAQUE HEAVY MINERALS

(n)	BT2	BT3	BT5	BT6	BT7	BT8	BT9
Garnet (clear)	153	170	195	117	182	225	197
Garnet (pink)	18	40	54	47	35	30	55
Epidote	165	139	110	140	127	147	175
Zoisite/Clinozoisite	21	29	18	21	20	19	26
Zircon	76	32	26	21	29	51	36
Rutile (brown)	6	3	3	–	3	–	–
Rutile (yellow)	3	8	10	12	9	12	10
Rutile (red)	–	–	–	–	–	2	–
Anatase	6	3	5	3	3	2	–
Brookite	–	–	–	–	–	–	–
Tourmaline	15	24	13	9	17	12	26
Augite	73	77	120	112	145	112	97
Hypersthene	18	5	10	3	3	16	6
Hornblende (dark green)	169	213	233	305	223	204	227
Hornblende (pale green)	73	67	56	68	52	47	49
Hornblende (brown)	15	11	18	18	12	9	10
Staurolite	3	8	8	12	3	9	3
Kyanite	6	14	3	3	6	–	3
Andalusite	–	–	–	–	3	–	–
Sillimanite	–	3	–	–	–	–	–
Monazite	3	–	–	3	3	–	–
Apatite	70	64	28	41	44	35	26
Collophane	3	11	–	3	–	–	3
Chlorite/Chamosite	43	45	33	30	26	19	19
Biotite	21	16	13	3	14	9	–
Glauconite	3	3	18	3	9	5	–
Siderite	37	16	26	26	32	35	32

TABLE 18(contd.) 53-250μm FRACTION : NON-OPAQUE HEAVY MINERALS

(o)	PTE	SBC1	BTRC	DMS1	DMS2	Y185/8	LHH	GH1
Garnet (clear)	18	104	154	192	115	21	53	55
Garnet (pink)	-	28	51	31	43	7	-	-
Epidote	18	215	79	124	161	28	160	74
Zoisite/Clinozoisite	5	23	9	19	23	-	38	3
Zircon	120	14	84	48	33	84	395	222
Rutile (brown)	5	3	-	2	-	-	15	13
Rutile (yellow)	18	2	9	7	3	42	133	63
Rutile (red)	5	-	-	-	-	-	4	3
Anatase	5	-	14	2	3	-	26	29
Brookite	3	3	-	-	-	-	-	-
Tourmaline	59	20	144	17	43	63	84	113
Augite	74	19	84	97	154	35	8	63
Hypersthene	-	5	9	10	13	-	-	-
Hornblende (dark green)	3	268	159	232	240	7	15	34
Hornblende (pale green)	-	50	46	73	62	7	8	11
Hornblende (brown)	-	28	-	24	26	-	4	-
Staurolite	3	2	9	10	13	-	26	-
Kyanite	3	3	9	5	3	-	-	8
Andalusite	-	5	5	-	-	-	-	5
Sillimanite	-	-	-	-	-	-	4	-
Monazite	-	-	-	-	-	-	-	-
Apatite	69	26	56	48	39	133	-	161
Collophane	18	-	14	2	3	21	-	5
Chlorite/Chamosite	143	70	37	26	16	538	23	63
Biotite	149	107	23	17	7	14	4	53
Glauconite	5	-	-	2	-	-	-	8
Siderite	277	5	5	12	-	-	-	8

TABLE 18(contd.) 53-250µm FRACTION : NON-OPAQUE HEAVY MINERALS

(P)	1TC1	1TH1	2TM1	3TM1	NB1	NB2	PGT1	LT2	LT5/2	LT5/3	LT5/4	LT5/7
Garnet (clear)	172	153	110	119	17	100	72	20	270	188	278	190
Garnet (pink)	68	49	53	31	11	34	29	11	32	23	26	43
Epidote	229	194	163	180	446	316	83	19	166	176	155	157
Zoisite/ Clinozoisite	38	39	47	51	82	59	18	6	37	45	35	33
Zircon	42	48	20	34	70	53	40	3	181	131	146	65
Rutile (brown)	4	9	6	2	3	8	7	1	5	-	9	3
Rutile(yellow)	13	11	2	7	28	42	4	1	55	15	46	33
Rutile (red)	8	-	-	-	6	17	-	1	11	4	7	11
Anatase	-	-	-	-	3	-	4	-	3	4	-	3
Brookite	4	5	6	2	9	2	-	1	-	-	-	-
Tourmaline	101	60	88	90	114	82	61	17	74	38	96	89
Augite	2	16	12	19	3	2	11	1	18	15	13	24
Hypersthene	6	-	2	3	-	-	4	-	-	-	2	5
Hornblende(dark green)	216	266	300	235	76	161	179	29	87	116	124	141
Hornblende(pale green)	27	39	35	25	46	32	15	2	16	19	13	35
Hornblende (brown)	8	7	10	8	-	11	14	1	-	4	7	5
Staurolite	8	7	4	2	23	28	7	1	13	11	13	16
Kyanite	11	7	4	3	40	32	22	2	11	19	11	11
Andalusite	2	11	2	8	6	2	-	-	-	8	-	8
Sillimanite	2	5	-	3	6	6	-	-	-	-	-	-
Monazite	-	2	-	3	-	-	22	2	13	53	17	19
Apatite	27	19	14	24	-	-	51	28	5	60	2	76
Collophane	2	5	8	3	-	-	76	6	-	26	-	-
Chlorite/ Chamosite	4	14	16	24	11	13	7	3	-	34	-	-
Biotite	-	2	6	5	-	-	22	3	3	11	-	33
Glauconite	2	-	8	2	-	-	252	842	-	-	-	-
Siderite	4	32	84	117	-	-						

TABLE 18(contd.) 53-250μm FRACTION : NON-OPAQUE HEAVY MINERALS

(9)	W01/1	W02/1	LT1/6	LT5/4
Garnet (clear)	179	205	169	278
Garnet (pink)	29	35	15	26
Epidote	94	85	198	155
Zoisite/Clinozoisite	11	13	19	35
Zircon	365	272	160	146
Rutile (brown)	5	-	2	9
Rutile (yellow)	80	56	42	46
Rutile (red)	5	11	8	7
Anatase	-	-	2	-
Brookite	-	-	-	-
Tourmaline	97	155	65	96
Augite	38	19	23	13
Hypersthene	-	-	8	2
Hornblende (dark green)	46	90	177	124
Hornblende (pale green)	-	11	34	13
Hornblende (brown)	-	3	13	7
Staurolite	21	16	17	13
Kyanite	3	16	19	11
Andalusite	-	-	4	-
Sillimanite	-	-	-	-
Monazite	-	-	2	-
Apatite	24	13	15	17
Collophane	-	-	-	2
Chlorite/Chamosite	3	-	8	-
Biotite	-	-	-	-
Glauconite	-	-	-	-
Siderite	-	-	-	-

TABLE 19 53-250μm FRACTION : NON-OPAQUE HEAVY MINERALS (excl. Siderite)

	HT2/5	HT3	HT5	HT21	HT22	HT31	HT36	HT37	MT6	MT7	MT17
Garnet (clear)	166	182	88	179	141	182	132	160	99	144	130
Garnet (pink)	81	50	14	47	30	49	25	48	16	19	20
Epidote	121	148	57	102	135	96	70	165	160	136	103
Zoisite/Clinozoisite	38	35	9	26	20	23	15	26	21	19	15
Zircon	74	106	51	68	86	46	104	48	37	50	77
Rutile (brown)	8	3	5	4	5	6	-	-	5	8	6
Rutile (yellow)	17	12	29	18	25	14	38	11	18	19	25
Rutile (red)	11	3	2	11	10	3	8	5	2	3	4
Anatase	2	3	9	11	10	6	19	-	2	3	8
Brookite	6	6	-	-	-	-	-	-	-	-	4
Tourmaline	83	79	38	40	20	29	53	59	69	47	62
Augite	59	62	128	115	125	113	147	123	25	30	119
Hypersthene	19	15	7	4	5	6	8	26	-	-	-
Hornblende(dark green)	148	205	100	172	195	171	91	175	330	319	124
Hornblende(pale green)	34	32	22	40	56	59	25	37	32	43	25
Hornblende(brown)	10	6	13	18	25	17	8	16	5	11	9
Staurolite	2	-	5	11	-	3	11	11	5	5	4
Kyanite	6	6	2	4	10	9	8	-	4	11	4
Andalusite	-	-	-	-	-	-	2	5	4	-	2
Sillimanite	-	-	-	-	-	-	-	-	-	-	-
Monazite	-	-	-	-	-	-	-	5	-	-	-
Apatite	78	3	71	54	41	71	80	-	49	32	72
Collophane	4	3	30	7	-	20	11	5	12	3	24
Chlorite/Chamosite	27	29	190	62	46	62	102	59	69	77	99
Biotite	6	12	130	7	15	17	34	16	28	11	55
Glauconite	-	-	-	-	-	-	6	-	9	11	11

TABLE 19 (contd.) 53-250µm FRACTION : NON-OPAQUE HEAVY MINERALS (excl.Siderite)

	PT1	PT2	PT3	PT4	PT5	PT6	DT1	DT2	DT3	DT4	DT5
Garnet (clear)	18	80	61	36	64	67	152	114	105	193	188
Garnet (pink)	3	6	8	7	9	-	15	12	26	33	45
Epidote	9	44	54	72	41	70	121	148	159	89	115
Zoisite/Clinozoisite	2	8	12	10	9	18	17	16	21	13	22
Zircon	17	57	73	64	39	75	41	52	47	53	29
Rutile (brown)	4	2	3	7	-	3	-	3	-	4	10
Rutile (yellow)	3	15	30	7	5	7	12	9	9	17	19
Rutile (red)	2	-	-	3	-	-	-	-	-	-	-
Anatase	2	2	19	10	5	11	3	3	-	4	10
Brookite	2	-	-	-	-	3	-	-	-	-	-
Tourmaline	17	42	76	61	34	42	23	25	14	24	22
Augite	35	117	140	127	110	155	109	93	134	129	150
Hypersthene	2	8	8	7	9	-	3	-	3	10	12
Hornblende (dark green)	12	66	57	71	62	35	160	168	193	181	182
Hornblende (pale green)	2	23	12	12	25	3	50	50	47	39	45
Hornblende (brown)	2	2	3	7	2	3	6	3	21	10	6
Staurolite	-	2	3	3	5	3	6	3	-	7	4
Kyanite	2	2	-	10	-	3	6	-	9	-	6
Andalusite	-	4	-	-	-	-	-	-	-	-	-
Sillimanite	-	-	-	-	-	-	-	-	-	-	-
Monazite	-	-	-	-	-	-	-	3	-	4	-
Apatite	57	83	125	136	104	56	64	41	74	53	29
Collophane	18	21	12	15	9	11	20	22	3	4	4
Chlorite/Chamosite	303	136	138	158	196	173	83	77	82	77	51
Biotite	492	252	159	170	267	248	93	145	36	46	32
Glauconite	-	28	7	7	5	14	16	13	17	10	19

TABLE 19 (contd.) 53-250μm FRACTION : NON-OPAQUE HEAVY MINERALS (excl.Siderite)

	DT6	DT7	DT8	DT9	DT10	DT11	DT12	DT13	DT14
Garnet (clear)	197	151	117	55	147	139	213	126	171
Garnet (pink)	37	30	20	12	36	33	25	26	30
Epidote	83	129	160	52	103	111	138	118	123
Zoisite/Clinozoisite	9	17	17	6	14	20	30	33	18
Zircon	51	39	37	24	68	74	60	80	63
Rutile (brown)	3	6	-	3	3	4	10	10	3
Rutile (yellow)	14	13	17	6	14	12	25	21	21
Rutile (red)	-	-	3	-	-	-	-	5	-
Anatase	6	-	-	6	9	4	10	18	3
Brookite	-	-	-	-	-	-	3	3	-
Tourmaline	23	23	37	15	36	37	38	49	45
Augite	114	145	140	136	128	148	133	113	108
Hypersthene	17	3	-	3	14	8	5	5	15
Hornblende (dark green)	128	175	169	112	136	161	128	121	172
Hornblende (pale green)	43	43	50	15	27	33	30	51	75
Hornblende (brown)	6	10	3	15	9	4	5	15	21
Staurolite	3	3	3	6	-	-	5	10	9
Kyanite	-	3	7	3	9	12	8	5	3
Andalusite	-	-	-	3	3	4	3	3	-
Sillimanite	-	-	-	-	-	-	-	-	-
Monazite	-	-	3	-	-	-	-	3	-
Apatite	46	56	30	73	59	70	73	64	48
Collophane	9	-	7	36	14	20	5	8	6
Chlorite/Chamosite	71	64	80	157	103	65	28	56	54
Biotite	120	77	80	189	68	33	15	49	9
Glauconite	20	13	20	73	-	8	10	8	3

TABLE 19 (contd) 53-250µm FRACTION : NON-OPAQUE HEAVY MINERALS (Excl.Siderite)

	BT2	BT3	BT5	BT6	BT7	BT8	BT9	DMS1	DMS2	SBC1	BTRC	PTE
Garnet (clear)	159	173	200	120	188	234	204	195	115	105	154	25
Garnet (pink)	19	41	55	48	36	31	57	31	43	28	51	-
Epidote	170	140	113	144	132	152	181	126	161	217	80	25
Zoisite/Clinozoisite	22	29	19	22	21	20	27	19	23	23	9	7
Zircon	79	33	27	22	30	53	37	47	33	14	85	167
Rutile (brown)	6	3	3	-	3	-	-	2	-	3	-	7
Rutile (yellow)	3	8	10	12	9	12	10	7	3	2	9	25
Rutile (red)	-	-	-	-	-	2	-	-	-	-	-	7
Anatase	6	3	5	3	3	2	-	2	3	-	14	7
Brookite	-	-	-	-	-	-	-	-	-	3	-	4
Tourmaline	16	24	13	9	18	12	27	17	43	20	143	82
Augite	76	78	123	115	149	116	100	98	154	19	85	106
Hypersthene	19	5	10	3	3	17	6	10	13	5	9	-
Hornblende(dark green)	175	216	240	313	230	212	234	235	240	271	159	4
Hornblende(pale green)	76	68	57	70	54	49	51	72	62	50	46	-
Hornblende(brown)	16	11	19	19	12	9	10	24	26	28	-	-
Staurolite	3	8	8	12	3	9	3	10	13	2	9	4
Kyanite	6	13	3	3	6	-	3	5	3	3	9	4
Andalusite	-	-	-	-	3	-	-	-	-	5	5	-
Sillimanite	-	3	-	-	-	-	-	-	-	-	-	-
Monazite	3	-	-	3	3	-	-	-	-	-	-	-
Apatite	73	65	29	42	46	36	27	47	39	26	56	96
Collophane	3	11	-	3	-	-	3	2	3	-	14	25
Chlorite/Chamosite	45	46	34	31	27	20	20	26	16	70	37	199
Biotite	22	16	13	3	15	9	-	17	7	108	23	206
Glauconite	3	3	19	3	9	5	-	2	-	-	-	7

TABLE 20 53-250µm "RESISTANT" NON-OPAQUE HEAVY MINERALS

	Amphiboles	Epidote Zoisite Clinozoisite	Garnet	Tourmaline	Rutile Anatase Brookite	Zircon	Pyroxenes	Others
HT1/6	61	109	249	109	64	134	265	9
HT2/5	217	180	279	94	49	84	88	9
HT3	255	192	243	83	28	112	81	6
HT5	233	114	176	66	78	88	233	12
HT6	179	163	328	40	84	71	127	8
HT7	75	134	215	85	79	101	288	23
HT8	84	129	188	98	88	116	289	8
HT9	138	123	137	113	93	135	248	13
HT10	82	86	230	113	85	103	281	20
HT11	235	268	267	55	32	66	60	17
HT12	401	128	169	71	16	41	147	27
HT13	241	201	286	40	72	68	80	12
HT14	205	172	225	49	82	180	75	12
HT15	274	159	266	48	12	55	174	12
HT16	315	196	298	37	39	32	71	12
HT17	256	158	221	51	96	91	99	28
HT18	244	153	229	49	56	90	159	20
HT19	217	175	230	63	53	107	144	11
HT20	186	180	275	28	65	117	124	25
HT21	266	145	262	46	49	79	137	16
HT22	307	173	190	22	56	95	146	11
HT23	292	136	247	43	42	91	128	21
HT24	233	171	239	56	49	80	150	22
HT25	249	166	210	53	92	115	109	6
HT26	201	133	189	63	58	120	218	18
HT27	70	69	193	134	145	112	274	3

TABLE 20 (contd.) 53-250μm "RESISTANT" NON-OPAQUE HEAVY MINERALS

	Amphiboles	Epidote Zoisite Clinozoisite	Garnet	Tourmaline	Rutile Anatase Brookite	Zircon	Pyroxenes	Others
HT28	177	94	238	66	108	94	209	14
HT29	187	117	374	41	68	61	143	9
HT30	226	159	333	40	49	92	94	7
HT31	296	143	276	36	36	55	142	16
HT32	262	147	293	48	51	63	122	14
HT33	182	160	354	30	67	63	126	18
HT34	194	200	248	51	76	112	103	16
HT35	309	141	266	38	53	67	108	18
HT36	163	110	205	69	86	136	203	28
HT37	247	208	225	64	18	52	162	24
HT38	270	163	249	58	48	40	157	15
HT39	76	85	201	138	89	138	256	17
MT1	304	237	195	49	47	92	66	10
MT2	220	205	283	51	46	57	112	26
MT3	224	206	211	45	64	136	103	11
MT4	244	167	248	75	65	68	120	13
MT5	344	199	139	76	46	50	132	14
MT6	443	218	137	82	31	45	30	14
MT7	431	179	189	53	37	57	35	19
MT8	228	174	112	89	63	89	206	39
MT9	372	199	192	40	19	30	134	14
MT10	282	140	226	56	64	65	157	10
MT11	349	158	190	77	25	42	148	11
MT12	251	186	203	42	65	80	161	12
MT13	298	158	229	71	72	68	86	18
MT14	240	183	226	122	65	50	91	23

TABLE 20 (contd.) 53–250µm "RESISTANT" NON-OPAQUE HEAVY MINERALS

	Amphiboles	Epidote Zoisite Clinozoisite	Garnet	Tourmaline	Rutile Anatase Brookite	Zircon	Pyroxenes	Others
MT15	221	187	254	83	38	43	162	12
MT16	209	223	199	45	79	131	100	14
MT17	215	160	202	84	62	105	159	13
PT1	116	84	162	129	76	129	291	13
PT2	188	107	177	87	40	119	266	16
PT3	130	119	124	135	91	131	265	5
PT4	174	162	84	120	48	126	262	24
PT5	212	120	178	80	22	91	286	11
PT6	84	175	133	84	49	147	314	14
DT1	297	192	232	32	20	57	154	16
DT2	313	234	182	35	21	75	132	8
DT3	331	226	167	19	11	60	175	11
DT4	286	126	282	29	28	65	172	12
DT5	269	159	270	26	44	33	188	11
DT6	241	125	319	31	31	70	179	4
DT7	287	184	231	29	24	49	188	8
DT8	285	225	175	47	25	47	179	17
DT9	302	122	141	32	32	51	295	25
DT10	227	157	239	47	36	90	188	16
DT11	246	163	214	46	25	92	194	20
DT12	188	194	273	43	56	69	159	18
DT13	230	186	187	60	69	98	145	25
DT14	307	160	229	51	30	71	139	13

TABLE 20 (contd.) 53-250 μm "RESISTANT" NON-OPAQUE HEAVY MINERALS (‰)

	Amphiboles	Epidote Zoisite Clinozoisite	Garnet	Tourmaline	Rutile Anatase Brookite	Zircon	Pyroxene	Others
HT 40	212	165	278	37	47	92	149	17
HT 44	163	80	330	36	64	111	207	8
HT 45	100	113	214	75	107	156	214	19
HT 46	224	115	268	51	96	106	134	9
HT 48	134	147	328	29	94	129	134	6
HT 49	240	183	258	34	62	71	136	15
HT 50	104	177	344	38	99	154	79	6
HT 51	96	123	295	55	105	132	191	5
HT 52	131	138	364	29	91	126	109	9
D 1	114	90	212	102	127	147	184	20
D 2	165	80	245	40	100	125	235	10
D 3	121	74	258	58	79	105	284	11
D 4	203	58	243	58	61	102	247	26
D 5	143	53	307	57	52	90	282	12
D 7	137	53	294	53	57	92	291	22
D 8	202	157	245	77	35	111	165	8
D 10	251	121	294	40	32	78	161	24
D 14	251	151	254	32	32	77	180	22
A 2	226	129	279	16	40	77	210	20
A 4	163	127	254	44	44	127	210	32
A 5	163	62	225	43	29	186	282	10
A 6	134	91	224	91	54	144	247	16

TABLE 20(contd) 53-250µm "RESISTANT" NON-OPAQUE HEAVY MINERALS (‰)

	Amphiboles	Epidote Zoisite Clinozoisite	Garnet	Tourmaline	Rutile Anatase Brookite	Zircon	Pyroxenes	Others
BT2	311	226	207	19	18	93	111	15
BT3	345	197	250	28	16	38	97	29
BT5	348	145	282	15	21	29	148	12
BT6	438	181	185	10	16	23	128	19
BT7	329	169	249	20	16	33	168	16
BT8	289	185	284	13	19	57	143	10
BT9	309	218	274	28	11	39	113	8
DMS1	367	161	249	19	14	54	120	16
DMS2	350	196	169	46	8	35	178	18
SBC1	437	301	166	26	10	18	30	12
BTRC	236	102	236	167	27	97	108	27
PTE	8	68	53	174	106	355	220	16
LHH	28	203	55	86	184	405	8	31
Y185/8	48	95	96	214	143	285	119	-
GH 1	64	109	79	162	154	316	90	19

TABLE 21 53-250μm FRACTION : MINERAL RATIOS (Amphibole/Pyroxene; Epidote/Zircon)

Sample	HT1/6	HT2/5	HT3	HT5	HT6	HT7	HT8	HT9	HT10	HT11	HT12	HT13
A/A+P x 100	19	71	76	50	58	21	23	36	23	80	73	75
E/+Z x 100	45	68	63	56	70	57	53	48	46	80	76	75
Sample	HT14	HT15	HT16	HT17	HT18	HT19	HT20	HT21	HT22	HT23	HT24	HT25
A/A+P x 100	73	61	82	72	61	60	60	66	68	70	61	70
E/E+Z x 100	49	74	86	63	63	62	61	65	65	60	68	59
Sample	HT26	HT27	HT28	HT29	HT30	HT31	HT32	HT33	HT34	HT35	HT36	HT37
A/A+P x 100	48	20	46	57	71	68	68	59	65	74	45	60
E/E+Z x 100	53	38	50	66	63	72	70	72	64	68	45	80
Sample	HT38	HT39	MT1	MT2	MT3	MT4	MT5	MT6	MT7	MT8	MT9	MT10
A/A+P x 100	63	23	82	66	69	67	72	94	92	53	74	64
E/E+Z x 100	80	38	72	78	60	71	80	83	76	66	87	68
Sample	MT11	MT12	MT13	MT14	MT15	MT16	MT17	PT1	PT2	PT3	PT4	PT5
A/A+P x 100	70	61	78	73	58	68	57	29	41	33	40	43
E/E+Z x 100	79	70	70	79	81	63	60	39	47	48	56	57
Sample	PT6	DT1	DT2	DT3	DT4	DT5	DT6	DT7	DT8	DT9	DT10	DT11
A/A+P x 100	21	66	70	65	62	59	57	60	61	51	55	56
E/E+Z x 100	54	77	76	79	66	83	64	79	83	71	64	64
Sample	DT12	DT13	DT14	BT2	BT3	BT5	BT6	BT7	BT8	BT9	DMS1	DMS2
A/A+P x 100	54	61	69	74	78	70	77	66	67	73	75	66
E/E+Z x 100	74	66	69	71	84	83	89	84	77	85	75	85
Sample	SBC1	BTRC	PTE	LHH	Y185/8	GH1	A2	A4	A5	A6		
A/A+P x 100	93	69	4	78	29	41	52	44	37	35		
E/E+Z x 100	94	51	16	33	25	26	63	50	25	39		
Sample	D1	D2	D3	D4	D5	D7	D8	D10	D14			
A/A+P x 100	38	41	30	45	34	32	55	61	58			
E/E+Z x 100	38	39	41	36	37	36	59	61	66			
Sample	HT40	HT44	HT45	HT46	HT48	HT49	HT50	HT51	HT52			
A/A+P x 100	59	44	32	63	50	64	57	33	55			
E/E+Z x 100	64	42	42	52	53	72	53	48	52			

TABLE 22 TUNSTALL PROFILE, DESCRIPTION

Site Description

Profile No.	HT1
Date	10.12.1969
Grid Reference	TA314318
Locality	Section dug at top of cliff-face, 10 m east of mid-point of fence surrounding chicken farm, Tunstall. O.S. Sheet 99, Hull.
Elevation	17 m O.D.
Relief	Gently undulating boulder clay plateau, bounded to the east by an actively receding cliff. Profile sampled is at highest point in the vicinity, in centre of flat area at cliff edge. Land surface slopes gently away from this area in all other directions, the slopes being shallow convex-concave. Flat micro-relief.
Surface Drainage	Normal site. Artificially drained in surface horizons by inverted U-shaped tile drains at 40 - 45 cm depth, spaced 10 m apart. Care taken to ensure that the sample site was remote from the disturbed ground around these drains.
Parent Material	Hessle Till, Upper Devensian. Reddish-brown boulder clay; calcareous, with a few chalk pebbles; Triassic and Carboniferous sandstone erratics abundant; shale, flint, vein quartz and miscellaneous igneous and metamorphic erratics also present.

Vegetation	Holderness is mostly arable, largely for cereals (barley, wheat). Trees are not abundant, none near the profile site. The immediate area is covered with a short grass sward, and has probably not been ploughed for several years past, since the edge of the cliff is but 10 m from the fence of the chicken farm, and coastal recession averages 1.5 m a year in this area. The presence of tile drainage, and of a few small pieces of brick at a few cms depth indicate past cultivation. The uppermost horizon represents the plough layer.
Weather Conditions	Several inches of snow recorded a few days before sampling took place, but this had by then melted. The autumn was unusually dry, though more normal rainfall had followed during November and December. Profile moist throughout.

Profile Description

Horizons	
HT1/1 0 to 20 cm Ap	Dark greyish brown (10 YR 4/2) loam; mottling absent. Slightly stony; sub-angular to rounded gravel and small stones, mainly flint. Moderately developed medium sub-angular blocky structure. Consistence when wet: sticky, plastic; moist: friable; dry: hard. Common fine pores; slow to moderate permeability. Low intimate humus; abundant fine fibrous roots, mostly living; much earthworm activity. Merging even boundary. Sampled at 10 - 18 cm.

HT1/2 20 to 33 (28-38) cm B1w(g)	Brown (10 YR 5/3) clay loam; common distinct fine mottles, mainly strong brown (7.5 YR 5/8), some light yellowish brown (10 YR 6/4), some mottles due to rotten stones. Slightly stony; sub-angular to rounded gravel and small stones, types as for parent material (except chalk), many thoroughly rotted. Moderately developed coarse angular blocky structure where affected by earthworm activity; well developed prismatic structure on drier part of cliff-face. Consistence when wet: sticky, plastic; moist: firm; dry: very hard. Common to abundant, fine to medium pores; slow to moderate permeability. Low intimate humus in earthworm channels; common fine fibrous roots, mostly living. Clay skins in pores, root and worm channels, and on many ped faces. Sharp, undulating boundary. Thickness varies from 8 - 18 cm; sampled at 20 - 30 cm.
HT1/3 33 (28-38) to 71 cm B2wg	Yellowish red (5 YR 4/6) clay loam; common faint fine olive grey (5 Y 5/2) mottles; few distinct fine brown mottles, due to rotten stones; ped faces mainly brown (7.5 YR 5/4) due to clay skins, some dark grey (5 Y 4/1) to neutral grey (N 4/1). Stony; gravel and small stones, types as for parent material (except chalk), many in various stages of decomposition. Weakly developed medium prismatic to structureless, becoming moderately developed coarse angular blocky on drying. Consistence when wet: sticky, plastic; moist: firm (harder than HT1/2); dry: very hard. Common to abundant, very fine to medium pores, few fine fissures; slow to moderate permeability. Few fine fibrous roots,

mostly living; rare earthworms. Merging boundary. Thickness varies from 33 - 43 cm; sampled at 46 - 58 cm.

HT1/4
71 - 140 cm
C1gca

Yellowish red (5 YR 4/6) calcareous clay loam; common faint fine olive grey (5 Y 5/2) mottles; few distinct fine brown mottles, due to rotten stones, very prominent grey (5 GY 5/1) coatings on structure faces; both vertical and horizontal. A few irregular small (up to 1 cm) light reddish brown (5 YR 6/4) nodular carbonate concretions. Stony; gravel and small stones, types as for parent material, many in various stages of decomposition. Weakly developed coarse prismatic structure, breaking down into coarse angular blocky structure when dry. Consistence when wet: sticky, plastic; moist: very firm; dry: very hard. Abundant fine pores and fine fissures; slow to moderate permeability. Rare fine fibrous roots, many dead; no earthworms. Merging boundary. Sampled at 84 - 96 cm.

HT1/5
140 to 213 cm
C2g

Dark reddish brown (5 YR 3/4) calcareous clay loam; few faint fine olive grey (5 Y 5/2) mottles; prominent grey (5 GY 5/1) coatings on structure faces. No concretions. Stony; gravel and small stones, types as for parent material, some slightly rotten. Weakly developed coarse prismatic structure, breaking down into medium to coarse angular blocky structure when dry. Consistence when wet: sticky, plastic; moist: firm; dry: hard. Few fine pores and fissures; slow permeability. Roots absent. Merging boundary. Sampled at 190 - 202 cm.

HT1/6 213 cm + C3	Dark reddish brown (5 YR 3/4) calcareous clay loam; mottling absent; stony; gravel and small stones, types as for parent material. Weakly developed coarse prismatic structure, breaking down into medium to coarse angular blocky structure when dry. Consistence when wet: sticky, plastic; moist: firm; dry: hard. Rare fine pores and fissures; slow permeability. Roots absent. Sampled at 244 - 270 cm.
PT1 (HT1/7) 5 m + C4	Unoxidised Purple Till. Dark brown (7.5 YR 3/2) calcareous clay loam; mottling absent; stony; gravel and small stones, types as for parent material. Almost structureless. Consistence when wet: sticky, plastic; moist: firm; dry: hard. Rare fine fissures; very slow permeability. Roots absent. Sampled at 8 m.
Drainage of Profile:	imperfectly to poorly drained soil, with impedance due to heavy textured sub-surface horizons. Drainage aided by prominent vertical fissures.
HT1/8 150 cm	Dark grey (5 Y 4/1) calcareous clay loam; material lining a prominant vertical fissure, 10 m north of profile on cliff-face. Slightly stony; gravel and small stones, types as for parent material. Medium platy structure. Reddish brown (5 YR 4/4) interiors to some of the larger platy peds.
HT1/9 150 cm	Reddish brown (5 YR 4/4) calcareous clay loam; material from interior of large prismatic ped adjacent to HT1/8. Other details as for HT1/5.

TABLE 23 TUNSTALL PROFILE: MISCELLANEOUS ANALYSES

Sample	pH	Calcium Carbonate (%)	Organic Carbon (%)	Bulk Density of Soil (g/cc)	Bulk Density of Analysed Material (g/cc)
HT1/1	7.84	0.5	1.79	1.77	1.71
HT1/2	7.64	0.0	0.64	1.80	1.78
HT1/3	8.02	0.1	0.58	1.90	1.86
HT1/4	8.46	8.7	N.D.	1.99	1.76
HT1/5	8.26	8.2	N.D.	1.99	1.72
HT1/6	8.20	8.2	N.D.	1.99	1.72
PT1	N.D.	9.5	N.D.	N.D.	N.D.
HT1/8	N.D.	11.6	N.D.	N.D.	N.D.
HT1/9	N.D.	8.1	N.D.	N.D.	N.D.

TABLE 24 TUNSTALL PROFILE: PARTICLE SIZE ANALYSES (% wt.)

Ø range	HT1/1	HT1/2	HT1/3	HT1/4	HT1/5	HT1/6	PT1	HT1/8	HT1/9
-1/0	1.2	0.4	0.8	1.5	2.3	2.6	2.0	2.2	2.1
0/1	2.9	1.0	1.0	1.6	2.2	2.4	2.2	2.6	2.0
1/2	8.8	3.8	2.8	2.9	3.5	3.6	3.3	3.5	3.3
2/3	13.6	10.7	8.6	8.5	8.1	8.1	7.3	7.9	8.1
3/4	12.4	11.7	9.8	9.0	9.6	8.9	8.6	9.4	9.0
4/5	13.6	12.1	10.5	8.4	10.0	8.8	8.6	10.1	10.1
5/6	11.8	10.8	9.2	8.5	9.3	8.9	8.6	9.2	9.8
6/7	6.5	7.6	7.6	9.3	9.0	8.9	8.6	8.4	9.2
7/8	4.9	5.7	7.1	8.9	8.8	9.1	8.6	8.1	8.4
8/9	4.1	4.6	6.4	7.7	7.4	8.3	8.7	7.9	8.2
9/12	6.2	10.5	13.3	14.5	13.8	14.2	33.5	12.9	13.3
< 12	14.0	21.1	22.9	19.2	16.0	16.2		17.8	16.5

TABLE 25 TUNSTALL PROFILE: PARTICLE SIZE SEPARATES (% wt.)

µm	HT1/1	HT1/2	HT1/3	HT1/4	HT1/5	HT1/6	PT1	HT1/8	HT1/9
250-2000	12.9	5.2	4.6	6.0	8.0	8.6	7.5	8.3	7.4
53- 250	29.4	25.4	21.3	19.7	20.1	19.3	18.0	19.7	19.6
20- 53	19.0	17.4	14.4	12.6	14.4	13.2	13.0	14.8	14.9
5- 20	13.2	14.5	15.4	18.0	18.1	17.9	17.2	16.7	18.0
2- 5	5.3	5.9	8.1	10.0	9.6	10.6	10.8	9.8	10.3
0.25-2	6.2	10.5	13.3	14.5	13.8	14.2	33.5	12.9	13.3
< 0.25	14.0	21.1	22.9	19.2	16.0	16.0		17.8	16.5

TABLE 26 TUNSTALL PROFILE: FINE CLAY/TOTAL CLAY RATIO

HT1/1	HT1/2	HT1/3	HT1/4	HT1/5	HT1/6	PT1	HT1/8	HT1/9
0.69	0.67	0.63	0.57	0.54	0.53	N.D.	0.58	0.55

TABLE 27 TUNSTALL PROFILE: TEXTURE CLASS

HT1/1	HT1/2	HT1/3	HT1/4	HT1/5	HT1/6	PT1	HT1/8	HT1/9
Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam

TABLE 28 TUNSTALL PROFILE : PARTICLE SIZE DISTRIBUTION (CLAY-FREE BASIS) (weight %)

0 range	HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6	PT 1
-1/0	1.5	0.6	1.2	2.3	3.3	3.7	3.0
0/1	3.6	1.5	1.6	2.4	3.1	3.4	3.3
1/2	11.0	5.6	4.4	4.4	5.0	5.2	5.0
2/3	17.0	15.6	13.5	12.8	11.5	11.6	11.1
3/4	15.5	17.1	15.4	13.6	13.7	12.8	12.9
4/5	17.0	17.7	16.5	12.7	14.2	12.7	12.9
5/6	14.8	15.8	14.4	12.8	13.2	12.8	12.9
6/7	8.2	11.1	11.9	14.0	12.9	12.8	12.9
7/8	6.2	8.3	11.1	13.4	12.6	13.1	12.9
8/9	5.2	6.7	10.0	11.6	10.5	11.9	13.1

TABLE 29 TUNSTALL PROFILE: Detailed Particle Size Analysis of Sand Fractions by Dry Sieving at $\frac{1}{4}$ ϕ Intervals (% wt.)

µm	HT1/1	HT1/2	HT1/3	HT1/4	HT1/5	HT1/6	PT1	HT1/8	HT1/9
1680-2000	0.7	0.2	1.4	1.9	2.5	2.8	2.9	2.1	2.9
1400-1680	0.6	0.4	0.8	1.6	2.5	2.9	1.9	2.6	2.2
1200-1400	0.7	0.2	0.7	1.3	2.0	2.1	1.9	1.9	1.7
1000-1200	0.8	0.4	0.7	1.2	1.8	2.0	1.9	1.8	1.3
850-1000	1.0	0.4	0.8	1.3	1.8	2.0	2.2	2.3	1.7
710- 850	1.6	0.8	1.0	1.7	2.1	2.4	2.5	2.7	2.1
600- 710	2.5	1.3	1.5	2.0	2.6	2.7	2.9	3.0	2.4
500- 600	2.0	1.0	1.0	1.3	1.7	1.9	1.9	1.8	1.6
420- 500	5.4	2.8	2.5	2.5	3.2	3.5	3.5	3.2	3.0
355- 420	5.3	2.8	2.5	2.5	2.9	3.0	3.1	3.0	2.9
300- 355	4.6	2.9	2.5	2.5	2.7	2.9	2.9	2.7	2.8
250- 300	6.6	4.9	4.5	4.4	4.4	4.3	4.2	4.2	4.3
210- 250	7.9	7.7	7.0	7.0	6.6	6.4	6.5	6.2	6.4
180- 210	6.2	7.5	7.1	7.0	6.3	6.2	6.0	6.2	6.4
150- 180	11.8	13.6	12.7	12.1	10.5	10.1	9.7	10.0	10.0
125- 150	7.6	8.8	8.9	8.3	7.4	7.5	7.9	7.3	8.8
105- 125	9.1	10.1	10.3	10.4	9.7	9.1	9.3	9.6	10.6
90- 105	6.7	8.4	8.4	7.8	6.6	6.7	7.0	6.9	6.8
75- 90	9.8	13.5	13.0	12.4	11.9	11.6	12.1	11.6	11.5
63- 75	9.1	12.3	12.7	10.8	10.8	10.1	9.7	10.9	10.6

TABLE 30 STONES: SIZE FRACTIONATION (% wt. of total sample)

Size Fraction (mm)	HT1/1	HT57 (=HT1/2)	HT58 (=HT1/3)	HT59 (=HT1/5)	PT9	DT18	HT56
> 25	N.D.	-	0.2	-	0.2	0.6	-
16 - 25	N.D.	0.2	0.3	0.7	0.9	1.2	0.5
6 - 16	N.D.	0.2	0.8	1.8	1.6	1.8	1.3
2 - 6	N.D.	0.8	1.0	2.7	2.7	2.7	2.1
Total > 2 mm	3.3	1.2	2.3	5.2	5.4	6.5	3.9

TABLE 31 STONES: LITHOLOGICAL FRACTIONATION (% wt. of total stones)

	HT1/1	HT57	HT58	HT59	PT9	DT18	HT56
Sandstone	30.6	42.7	64.6	39.8	27.5	37.6	22.2
Flint, Chert	12.0	0.9	2.7	1.5	1.8	4.0	9.9
Vein Quartz; Quartzite	34.1	3.5	2.3	2.1	0.7	4.2	4.9
Igneous; Metamorphic	11.0	13.8	22.6	14.1	9.0	13.6	10.9
Shale, Siltstone	0.3	1.1	3.4	16.2	26.0	5.7	4.1
Ironstone	2.5	6.5	2.7	0.9	0.5	0.7	1.4
Secondary Iron Oxide Concretions	2.3	31.4	1.6	-	-	-	-
Coal	0.5	0.1	0.1	0.3	0.6	0.6	0.1
Chalk	3.1	-	-	6.8	5.0	9.3	33.8
Limestones other than Chalk	-	-	-	15.9	28.8	24.2	12.8
Secondary Carbonate Concretions	-	-	-	2.5	-	-	-
"Clinker"	3.6	-	-	-	-	-	-

TABLE 32 STONES: Relative Proportions of Each Lithological Type Compared with the Amounts Present in the Calcareous Till, HT59

	HT1/1	HT57	HT58	HT59
Sandstones	19.4	9.9	28.6	39.8
Flint, Chert	7.6	0.2	1.2	1.5
Vein Quartz, Quartzite	21.6	0.8	1.0	2.1
Igneous, Metamorphic	7.0	3.2	10.0	14.1
Shale, Siltstone	0.2	0.3	1.5	16.2
Ironstones	1.6	1.5	1.2	0.9
Secondary Iron Oxide Concretions	1.5	7.3	0.7	-
Coal	0.3	<0.1	<0.1	0.3
Chalk	2.0	-	-	6.8
Limestones other than Chalk	-	-	-	15.9
Secondary Carbonate Concretions	-	-	-	2.5
"Clinker"	2.3	-	-	-
Total	63.5	23.2	44.2	100.0

TABLE 33 TUNSTALL PROFILE: COARSE SAND FRACTIONS: LITHOLOGY

(% wt.)

(a) 250 - 500 µm

	HT1/1	HT1/2	HT1/3	HT1/4	HT1/5	HT1/6
Quartz/Sandstone	N.D.	N.D.	92	N.D.	N.D.	66
Shale/Siltstone	N.D.	N.D.	2	N.D.	N.D.	29
Ironstone/Iron Concretions	N.D.	N.D.	6	N.D.	N.D.	-
Coal	N.D.	N.D.	-	N.D.	N.D.	1
Igneous/Metamorphic	N.D.	N.D.	-	N.D.	N.D.	-
Limestone	N.D.	N.D.	-	N.D.	N.D.	4

(b) 500 - 1000 µm

	HT1/1	HT1/2	HT1/3	HT1/4	HT1/5	HT1/6
Quartz/Sandstone	92	93	79	65	64	55
Shale/Siltstone	-	1	4	22	28	30
Ironstone/Iron Concretions	7	5	15	1	1	1
Coal	1	-	1	1	2	5
Igneous/Metamorphic	-	1	1	3	2	4
Limestone	-	-	-	5	3	5
Secondary Carbonate Concretions	-	-	-	3	-	-

(c) 1000 - 2000 µm

	HT1/1	HT1/2	HT1/3	HT1/4	HT1/5	HT1/6
Quartz/Sandstone	N.D.	N.D.	58	N.D.	N.D.	43
Shale/Siltstone	N.D.	N.D.	3	N.D.	N.D.	45
Ironstone/Iron Concretions	N.D.	N.D.	32	N.D.	N.D.	-
Coal	N.D.	N.D.	-	N.D.	N.D.	-
Igneous/Metamorphic	N.D.	N.D.	7	N.D.	N.D.	5
Limestone	N.D.	N.D.	-	N.D.	N.D.	7

TABLE 34 TUNSTALL PROFILE: 53 - 250 µm FRACTION: HEAVY MINERAL ANALYSES

	HT1/1	HT1/2	HT1/3	HT1/4	HT1/5	HT1/6	PT1
% Heavy Minerals, > 2.9 S.G.	1.15	0.33	0.49	0.69	0.75	0.91	2.20
‰ Opaque Minerals	654	608	622	627	496	534	445
‰ Non-Opaque Minerals	346	392	378	373	504	466	555

TABLE 35 OPAQUE MINERALS (as ‰ of total opaque heavy minerals)

	HT1/1	HT1/2	HT1/3	HT1/4	HT1/5	HT1/6	PT1
Limonite	476	463	532	517	459	437	487
Haematite	250	138	182	259	264	305	212
Ilmenite/Magnetite	161	154	151	129	170	168	71
Leucoxene	113	244	135	95	107	90	44
Pyrite	-	-	-	-	-	-	186

TABLE 36 LIGHT MINERALS (< 2.9 S.G.) (as ‰ of total light minerals)

	HT1/1	HT1/2	HT1/3	HT1/4	HT1/5	HT1/6	PT1
Quartz	913	875	824	770	820	806	N.D.
Flint	14	8	17	30	30	29	N.D.
Orthoclase	43	74	71	76	54	51	N.D.
Microcline	7	11	17	19	10	14	N.D.
Sodic Plagioclase	14	19	37	37	21	22	N.D.
Calcic Plagioclase	4	3	3	12	6	11	N.D.
Muscovite	-	3	26	35	41	46	N.D.
Opaline Silica	-	-	-	7	6	11	N.D.
Coal	4	6	6	14	12	13	N.D.

TABLE 37 TUNSTALL PROFILE: 53 - 250 µm FRACTION: NON-OPAQUE HEAVY MINERALS (% of total Non-Opaque Heavy Minerals)

	HT1/1	HT1/2	HT1/3	HT1/4	HT1/5	HT1/6	PT1
Garnet (clear)	217	230	148	120	72	74	12
Garnet (pink)	94	47	31	38	7	8	2
Epidote	112	131	58	48	29	26	6
Zoisite/Clinozoisite	19	34	16	12	8	10	1
Zircon	110	118	71	78	41	44	11
Rutile (brown)	13	12	7	15	6	5	3
Rutile (yellow)	45	34	35	28	18	7	2
Rutile (red)	21	19	18	15	7	4	1
Anatase	11	9	7	7	4	1	1
Brookite	3	3	-	5	2	4	1
Tourmaline (brown/yellow)	40	44	35	25	11	13	3
Tourmaline (brown/green)	40	37	50	30	20	21	7
Tourmaline (blue; clear)	8	6	2	-	3	2	1
Augite	124	134	148	170	85	87	23
Hypersthene	37	16	12	10	-	-	1
Hornblende (dark green)	45	65	27	18	13	13	8
Hornblende (pale green)	11	12	2	7	3	6	1
Hornblende (brown)	3	6	2	5	1	1	1
Staurolite	-	3	3	-	1	1	-
Kyanite	5	-	2	-	1	2	1
Apatite	-	-	93	70	66	86	37
Collophane	-	-	2	12	15	11	12
Chlorite/Chamosite (green)	19	22	61	93	187	174	136
Chamosite (brown)	8	6	140	122	46	58	62
Biotite	15	12	30	72	354	342	321
Siderite	-	-	-	-	-	-	346

TABLE 38 TUNSTALL PROFILE: 20 - 53 μm FRACTION: HEAVY MINERALS (wt. %)

	HT1/1	HT1/2	HT1/3	HT1/4	HT1/5	HT1/6	PT1
% Heavy Minerals	1.18	0.61	0.55	0.79	1.08	1.30	2.80

TABLE 39 TUNSTALL PROFILE: 20 - 53 μm FRACTION: NON-OPAQUE HEAVY MINERALS (‰ of total Non-Opaque Heavy Minerals)

	HT1/1	HT1/2	HT1/3	HT1/4	HT1/5	HT1/6	PT1
Garnet	103	83	92	65	39	36	19
Epidote	133	179	120	119	92	82	100
Zoisite/Clinozoisite	4	13	6	7	8	9	7
Zircon	240	325	220	243	154	124	92
Rutile (brown)	12	13	9	2	10	5	4
Rutile (yellow)	103	87	71	56	41	25	12
Rutile (red)	4	8	6	5	2	2	1
Anatase	12	21	18	17	16	11	7
Brookite	-	-	-	-	-	-	2
Tourmaline	99	63	74	51	27	39	8
Augite	130	83	71	61	35	34	9
Hypersthene	4	-	-	-	-	-	-
Hornblende	32	33	25	17	16	16	27
Stautolite	-	-	-	2	2	2	3
Kyanite	12	8	3	2	2	2	1
Apatite	24	13	132	94	74	58	24
Collophane	8	8	3	2	4	5	-
Chlorite/Chamosite	44	42	86	143	274	325	389
Biotite	36	21	64	114	204	225	143
Siderite	-	-	-	-	-	-	152

TABLE 40 TUNSTALL PROFILE : 53-250 μm FRACTION, "RESISTANT" NON-OPAQUE HEAVY MINERALS (‰)

	Amphiboles	Epidote Zoisite Clinozoisite	Garnet	Tourmaline	Rutile Anatase Brookite	Zircon	Pyroxene	Others
HT 1/1	62	137	324	92	97	115	168	5
HT 1/2	87	172	288	91	80	123	156	3
HT 1/3	46	110	266	129	99	105	238	7
HT 1/4	48	95	250	87	111	124	285	0
HT 1/5	51	112	238	102	111	124	256	6
HT 1/6	61	109	249	110	64	134	264	9
PT 1	116	81	163	128	93	128	279	12

TABLE 41 TUNSTALL PROFILE : 20-53μ m FRACTION, "RESISTANT" NON-OPAQUE HEAVY MINERALS (‰)

	Amphiboles	Epidote Zoisite Clinozoisite	Garnet	Tourmaline	Rutile Anatase Brookite	Zircon	Pyroxene	Others
HT 1/1	36	154	116	112	147	270	151	14
HT 1/2	36	209	91	69	141	354	91	9
HT 1/3	35	176	129	104	146	307	99	4
HT 1/4	26	195	101	79	124	375	94	6
HT 1/5	36	225	88	61	155	347	79	9
HT 1/6	41	235	93	101	111	321	88	10
PT 1	93	366	65	27	89	315	31	14

TABLE 42 TUNSTALL PROFILE: X-RAY DETERMINATIONS OF LAYER SILICATE MINERALS (as % of total layer silicates)

(a) < 0.25 μm

	Mica*	Kaolinite	Chlorite	Vermiculite	Smectite
HT1/1	19	23	4	42	12
HT1/2	19	22	4	41	14
HT1/3	25	13	2	45	15
HT1/4	27	12	2	43	16
HT1/5	36	11	2	37	14
HT1/6	37	10	2	36	15
HT1/8	31	11	1	41	16
HT1/9	30	11	2	38	19

(b) 0.25 - 2 μm

	Mica*	Kaolinite	Chlorite	Vermiculite	Smectite
HT1/1	28	42	4	25	1
HT1/2	21	50	5	22	2
HT1/3	28	28	3	33	8
HT1/4	29	29	4	26	12
HT1/5	37	26	4	19	14
HT1/6	36	24	4	21	15

(c) 2 - 5 μm

	Mica*	Kaolinite	Chlorite	Vermiculite	Smectite
HT1/1	34	26	4	28	8
HT1/2	32	37	4	22	5
HT1/3	32	24	3	27	14
HT1/4	36	29	4	21	10
HT1/5	36	33	5	15	11
HT1/6	35	35	5	15	10

(d) 5 - 20 μm

	Mica*	Kaolinite	Chlorite	Vermiculite	Smectite
HT1/1	25	33	9	22	11
HT1/2	30	38	9	15	8
HT1/3	29	32	7	12	20
HT1/4	38	32	6	8	16
HT1/5	40	33	7	11	9
HT1/6	40	31	7	12	10

* Mica percentage from potassium determination.

TABLE 43 TUNSTALL PROFILE: CHEMICAL DETERMINATIONS (wt. %)

	HT1/1	HT1/2	HT1/3	HT1/4	HT1/5	HT1/6	HT1/8	HT1/9
Amorphous Silica								
< 0.25 µm	2.9	2.1	1.6	1.7	1.3	1.5	N.D.	N.D.
0.25 - 2 µm	1.6	0.9	0.8	0.8	0.7	0.6	N.D.	N.D.
2 - 5 µm	0.4	0.4	0.4	0.4	0.4	0.3	N.D.	N.D.
Amorphous Alumina								
< 0.25 µm	2.1	2.2	1.8	1.2	0.9	0.8	N.D.	N.D.
0.25 - 2 µm	0.6	0.5	0.5	0.4	0.5	0.4	N.D.	N.D.
2 - 5 µm	0.1	0.1	0.1	0.1	0.1	0.1	N.D.	N.D.
"Free" Iron Oxides (as Fe_2O_3)								
< 0.25 µm	10.4	8.9	8.4	7.7	7.9	7.6	N.D.	N.D.
0.25 - 2 µm	3.6	3.3	4.0	4.0	4.4	4.4	N.D.	N.D.
2 - 5 µm	2.2	1.9	2.3	2.3	2.5	2.4	N.D.	N.D.
< 2 mm	2.4	2.8	3.6	3.4	3.0	3.0	2.0	3.0
Mica								
< 0.25 µm	16.1	16.3	22.3	24.3	32.3	33.2	30.5	29.9
0.25 - 2 µm	21.3	16.1	22.1	23.7	30.2	29.0	N.D.	N.D.
2 - 5 µm	16.7	16.1	20.1	22.7	24.0	22.7	N.D.	N.D.
5 - 20 µm	5.8	7.8	12.4	16.3	17.2	17.5	N.D.	N.D.
20 - 53 µm	2.1	2.5	5.1	5.5	6.5	6.2	N.D.	N.D.
53 - 250 µm	0.4	0.6	3.2	2.4	3.0	4.8	N.D.	N.D.
Quartz								
< 0.25 µm	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
0.25 - 2 µm	11.5	12.8	9.7	9.1	8.5	8.6	N.D.	N.D.
2 - 5 µm	36.5	36.2	25.5	25.6	23.2	24.0	N.D.	N.D.
5 - 20 µm	56.7	55.2	42.3	41.7	41.3	41.9	N.D.	N.D.
20 - 53 µm	74.2	73.4	65.3	64.4	64.4	64.4	N.D.	N.D.
53 - 250 µm	85.1	85.1	80.8	79.6	79.8	79.8	N.D.	N.D.
K - Feldspar								
< 0.25 µm	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
0.25 - 2 µm	3.4	2.3	2.2	2.2	1.9	2.3	N.D.	N.D.
2 - 5 µm	5.4	5.0	3.6	3.5	3.5	3.2	N.D.	N.D.
5 - 20 µm	8.6	7.5	5.7	5.6	5.7	4.9	N.D.	N.D.
20 - 53 µm	8.8	8.5	7.7	7.7	7.2	7.6	N.D.	N.D.
53 - 250 µm	6.7	6.7	6.6	6.7	6.7	6.8	N.D.	N.D.
Na - Feldspar								
< 0.25 µm	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
0.25 - 2 µm	2.6	2.1	2.3	2.1	2.4	2.4	N.D.	N.D.
2 - 5 µm	6.0	5.2	4.2	4.4	4.2	4.1	N.D.	N.D.
5 - 20 µm	10.9	10.5	8.8	8.5	8.9	8.8	N.D.	N.D.
20 - 53 µm	9.9	9.8	9.9	9.8	10.4	10.0	N.D.	N.D.
53 - 250 µm	4.7	4.7	5.1	5.2	4.9	4.9	N.D.	N.D.
Ca - Feldspar								
< 0.25 µm	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
0.25 - 2 µm	0.1	0.1	0.1	0.1	0.2	0.2	N.D.	N.D.
2 - 5 µm	0.6	0.5	0.4	0.4	0.4	0.4	N.D.	N.D.
5 - 20 µm	0.8	0.7	0.6	0.6	0.6	0.6	N.D.	N.D.
20 - 53 µm	0.5	0.5	0.3	0.3	0.3	0.3	N.D.	N.D.
53 - 250 µm	0.3	0.3	0.3	0.4	0.3	0.3	N.D.	N.D.

TABLE 43 (Cont.) TUNSTALL PROFILE: CHEMICAL DETERMINATIONS (wt. %)

	HT1/1	HT1/2	HT1/3	HT1/4	HT1/5	HT1/6	HT1/8	HT1/9
Quartz + Feldspar (Na - Bisulphate Residue) 250 - 2000 µm	89.9	97.0	88.7	88.0	76.6	82.0	N.D.	N.D.

	HT1/1	HT1/3	HT1/8	HT1/9	PT1
Total Iron as % Fe_2O_3 < 2 mm	3.63	5.46	4.25	5.32	5.24

TABLE 44 TUNSTALL PROFILE: MINERALOGY OF FINE AND COARSE CLAYS (%)

< 0.25 μm	HT1/1	HT1/2	HT1/3	HT1/4	HT1/6	HT1/7
Kaolinite	20	19	11	11	10	9
Chlorite	4	4	1	2	2	1
Vermiculite	35	36	40	38	34	33
Smectite	10	12	14	14	12	14
Mica	16	16	22	24	32	33
Amorphous Silica	3	2	2	2	1	1
Amorphous Alumina	2	2	2	1	1	1
"Free Iron"	10	9	8	8	8	8
Lepidocrocite	**	***	–	–	–	–
Goethite	**	**	*	*	*	*
0.25 - 2 μm	HT1/1	HT1/2	HT1/3	HT1/4	HT1/6	HT1/7
Kaolinite	32	39	23	23	21	19
Chlorite	3	4	2	3	3	3
Vermiculite	19	17	27	21	16	17
Smectite	1	2	6	10	11	13
Mica	21	16	22	24	30	29
K - Feldspar	3	2	2	2	2	2
Na - Feldspar	3	2	2	2	2	2
Ca - Feldspar	–	–	–	–	–	–
Quartz	11	13	10	9	9	9
Amorphous Silica	2	1	1	1	1	1
Amorphous Alumina	1	1	1	1	1	1
"Free Iron"	4	3	4	4	4	4
Lepidrocrocite	*	***	–	–	–	–
Goethite	**	**	**	*	*	*

*, **, *** Estimate of abundance, in ascending order, based on relative heights of 6.27 Å and 4.18 Å peaks.

TABLE 45 TUNSTALL PROFILE: MINERALOGY OF FINE AND MEDIUM SILTS (%)

2-5 μm	HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6
Kaolinite	13	19	15	19	22	23
Chlorite	1	2	2	3	3	3
Vermiculite	14	11	18	11	10	10
Smectite	4	3	9	8	7	7
Mica	17	16	20	23	24	23
K-felspar	5	5	4	4	4	3
Na-felspar	6	5	4	4	4	4
Ca-felspar	1	1	–	–	–	–
Quartz	37	36	26	26	23	24
"Free iron"	2	2	2	2	3	3
Lepidocrocite	–	**	–	–	–	–
Goethite	*	**	**	*	–	–

5-20 μm						
Kaolinite	8	10	14	14	14	14
Chlorite	2	2	3	3	3	3
Vermiculite	5	4	5	4	5	5
"Smectite"	2	2	8	6	4	4
Mica	6	8	12	16	17	17
K-felspar	8	8	6	6	6	5
Na-felspar	11	10	9	8	9	9
Ca-felspar	1	1	1	1	1	1
Quartz	57	55	42	42	41	42
"Free iron"	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Lepidocrocite	–	*	–	–	–	–
Goethite	–	*	*	–	–	–

TABLE 46 TUNSTALL PROFILE : MINERALOGY OF COARSE SILTS AND FINE SANDS (%)

20-53 μm	HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6
Mica	2	2	5	5	7	6
K-felspar	9	9	8	8	7	8
Na-felspar	10	10	10	10	10	10
Ca-felspar	1	1	-	-	-	-
Quartz	74	73	65	65	65	65
"Free iron"	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Remainder*	4	5	12	12	11	11
53-250 μm						
Mica	-	-	3	2	3	5
K-felspar	7	7	7	7	7	7
Na-felspar	5	5	5	5	5	5
Ca-felspar	-	-	-	-	-	-
Quartz	85	85	81	80	80	80
"Free iron"	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Remainder*	3	3	4	6	5	3

* Includes layer silicates other than mica, destroyed by the bisulphate fusion, also iron oxides. N.D. : Not determined.

TABLE 47 BASIC DATA FOR QUANTITATIVE ESTIMATION OF WEATHERING CHANGES IN THE TUNSTALL PROFILE

	HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6
1. Bulk Density of soil (g/cc)	1.77	1.80	1.90	1.99	1.99	1.99
2. Bulk Density of Analysed soil (g / cc)	1.71	1.78	1.86	1.76	1.72	1.72
3. Thickness of Horizon (cm)	20	13	38	69	73	213
4. Present volume/horizon/cm^2 of surface area (cc)	20	13	38	69	73	213
5. Present weight of soil under unit surface area (g)	34.2	23.1	70.7	121.6	125.5	366.4
6. Weight % of Index Mineral	62.9	56.3	44.7	43.9	46.5	46.5
7. Weight of Index Mineral in horizon (g)	21.5	13.0	31.6	53.4	58.4	170.3
8. Original weight of 1g of present soil from horizon	1.35	1.21	0.96	0.95	1.00	1.00
9. Original weight of soil/ horizon/cm^2 surface area (g)	46.5	27.0	62.8	112.1	125.5	366.4
10. Original Volume/horizon/ cm^2 of surface area (cc)	27.0	15.7	36.5	65.2	73.0	213.0
11. Change in volume (cc)	-7.0	-2.7	+1.5	+3.8	0.0	0.0
12. % Change in volume	-25.9	-17.2	+4.1	+5.8	0.0	0.0

TABLE 48 TUNSTALL PROFILE, PRESENT WEIGHTS OF PARTICLE SIZE FRACTIONS (g/horizon/cm^2 surface area)

	HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6
<0.25 μm	4.8	4.9	16.2	23.3	20.1	59.4
0.25 - 2 μm	2.1	2.4	9.4	17.6	17.3	52.1
2 - 5 μm	1.8	1.4	5.7	12.2	12.1	38.8
5-20 μm	4.5	3.3	10.9	21.9	22.7	65.7
20-53 μm	6.5	4.0	10.2	15.3	18.1	48.4
53-250 μm	10.1	5.9	15.1	24.0	25.2	70.8
250-2000 μm	4.4	1.2	3.2	7.3	10.0	31.5
Total	34.2	23.1	70.7	121.6	125.5	366.4

TABLE 49 TUNSTALL PROFILE, ORIGINAL WEIGHTS OF PARTICLE SIZE FRACTIONS (g/horizon/cm^2 surface area)

	HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6
<0.25 μm	7.6	4.4	10.2	18.2	20.3	59.4
0.25 - 2 μm	6.6	3.8	8.9	15.9	17.8	52.1
2 - 5 μm	4.9	2.9	6.7	11.9	13.3	38.8
5-20 μm	8.3	4.8	11.2	20.1	22.5	65.7
20-53 μm	6.1	3.6	8.3	14.8	16.6	48.4
53-250 μm	9.0	5.2	12.1	21.6	24.2	70.8
250-2000 μm	4.0	2.3	5.4	9.6	10.8	31.5
Total	46.5	27.0	62.8	112.1	125.5	366.4

TABLE 50 TUNSTALL PROFILE, CHANGE IN AMOUNTS OF PARTICLE SIZE FRACTIONS (g/horizon/cm^2 surface area)

	HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6
< 0.25 μm	-2.8	+0.5	+6.0	+5.1	-0.2	0.0
0.25 - 2 μm	-4.5	-1.4	+0.5	+1.5	-0.5	0.0
2 - 5 μm	-3.1	-1.5	-1.0	+0.3	-1.2	0.0
5-20 μm	-3.8	-1.5	-0.3	+1.8	+0.2	0.0
20-53 μm	+0.4	+0.4	+1.9	+0.5	+1.5	0.0
53-250 μm	+1.1	+0.7	+3.0	+2.4	+1.0	0.0
250-2000 μm	+0.4	-1.1	-2.2	-2.3	-0.8	0.0
Total change	-12.3	-3.9	+7.9	+9.5	0.0	0.0

TABLE 51 TUNSTALL PROFILE, CHANGE IN FRACTIONS AS % OF ORIGINAL AMOUNT OF EACH FRACTION IN HORIZON

	HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6
< 0.25 μm	-36.8	+11.4	+58.8	+28.0	-1.0	-
0.25 - 2 μm	-68.2	-36.8	+5.6	+9.4	-2.8	-
2 - 5 μm	-63.2	-51.7	-14.9	+2.5	-9.0	-
5-20 μm	-45.8	-31.2	-2.7	+9.0	+0.9	-
20-53 μm	+6.7	+11.1	+22.9	+3.4	+9.0	-
53-250 μm	+12.2	+13.4	+24.8	+11.1	+4.1	-
250-2000 μm	+10.0	-47.8	-40.7	-24.0	-7.4	-
Total change	-25.6	-14.4	+12.6	+8.5	0.0	-

TABLE 52 TUNSTALL PROFILE: WEIGHTS OF FRACTIONS AS mg/cc OF SOIL

	HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6*
<0.25 µm	240	377	426	338	275	279
0.25 - 2 µm	105	185	247	255	237	244
2 - 5 µm	90	108	150	177	166	182
5 - 20 µm	225	254	287	317	311	308
20 - 53 µm	325	308	268	222	248	227
53-250 µm	505	454	397	348	345	332
250-2000 µm	220	92	84	106	137	148

* figures for HT 1/6 represent also the original weight (mg/cc) of the fraction in other horizons.

TABLE 53 TUNSTALL PROFILE: TOTAL WEIGHT (g) OF FRACTIONS IN HORIZONS 1-4

	Present Weight	Original Weight	Change (g)	Change as % of original weight of soil
<0.25 µm	49.2	40.4	+8.8	+3.5
0.25 - 2 µm	31.5	35.2	-3.7	-1.5
2 - 5 µm	21.1	26.4	-5.3	-2.1
5 - 20 µm	40.6	44.4	-3.8	-1.5
20 - 53 µm	36.0	32.8	+3.2	+1.3
53-250 µm	55.1	47.9	+7.2	+2.9
250-2000 µm	16.1	21.3	-5.2	-2.1
Totals	249.6	248.4	+1.2	+0.5

TABLE 54 TUNSTALL PROFILE : ESTIMATES OF CHANGES IN AMOUNTS OF STONES (>2mm)

	HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6
Present weight of >2mm material (g)	1.2	0.3	1.6	5.2	6.8	19.8
Original weight of >2mm material (g)	1.9	1.2	3.5	6.4	6.8	19.8
Change in >2mm material (g)	-0.7	-0.9	-1.9	-1.2	0.0	0.0
Change in <2mm material (g)	-12.3	-3.9	+7.9	+9.5	0.0	0.0
Net Change in Total soil (g)	-13.0	-4.8	+6.0	+8.3	0.0	0.0

TABLE 55 TUNSTALL PROFILE: WEIGHTS (mg) OF MINERALS PER HORIZON PER CM^2 COLUMN

		HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6
<0.25 μm Fraction							
Kaolinite	PW	960	931	1782	2563	2010	5346
	OW	684	396	918	1638	1827	5346
	Change	+276	+535	+864	+925	+183	-
Chlorite	PW	192	196	162	466	402	594
	OW	76	44	102	182	203	594
	Change	+116	+152	+60	+284	+199	-
Vermiculite	PW	1680	1764	6480	8854	6834	19602
	OW	2508	1452	3366	6006	6699	19602
	Change	-828	+312	+3114	+2848	+135	-
Smectite	PW	480	588	2268	3262	2412	8316
	OW	1064	616	1428	2548	2842	8316
	Change	-584	-28	+840	+714	-430	-
Mica	PW	768	784	3564	5592	6432	19602
	OW	2508	1452	3366	6006	6699	19602
	Change	-1740	-668	+198	-414	-267	-
Amorphous silica	PW	139	103	259	396	261	891
	OW	114	66	153	273	305	891
	Change	+25	+37	+106	+123	-44	-
Amorphous alumina	PW	101	108	292	280	181	475
	OW	61	35	82	146	162	475
	Change	+40	+73	+210	+134	+19	-
"Free" iron oxides	PW	499	436	1361	1794	1588	4514
	OW	578	334	775	1383	1543	4514
	Change	-79	+102	+586	+411	+45	-

PW = Present weight; OW = Original weight

TABLE 55 (Cont.). TUNSTALL PROFILE: WEIGHTS (mg) OF MINERALS PER HORIZON PER CM^2 COLUMN

		HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6
0.25-2 μm Fraction							
Kaolinite	PW	672	936	2162	4048	3633	9899
	OW	1254	722	1691	3021	3382	9899
	Change	-582	+214	+471	+1027	+251	-
Chlorite	PW	63	96	188	528	519	1563
	OW	198	114	267	477	534	1563
	Change	-135	-18	-79	+51	-15	-
Vermiculite	PW	399	408	2538	3696	2768	8857
	OW	1122	646	1513	2703	3026	8857
	Change	-723	-238	+1025	+993	-258	-
Smectite	PW	21	48	564	1760	1903	6773
	OW	858	494	1157	2067	2314	6773
	Change	-837	-446	-593	-307	-411	-
Mica	PW	441	384	2068	4224	5190	15109
	OW	1914	1102	2581	4611	5162	15109
	Change	-1473	-718	-513	-387	+28	-
Amorphous silica	PW	34	22	75	141	121	313
	OW	40	23	53	95	107	313
	Change	-6	-1	+22	+46	+14	-
Amorphous alumina	PW	13	12	47	70	87	208
	OW	26	15	36	64	71	208
	Change	-13	-3	+11	+6	+16	-
"Free" iron oxides	PW	76	79	376	704	761	2292
	OW	290	167	392	700	783	2292
	Change	-214	-88	-16	+4	-22	-
K-felspar	PW	71	55	207	387	329	1198
	OW	152	87	205	366	409	1198
	Change	-81	-32	+2	+21	-80	-
Na-felspar	PW	55	50	216	370	415	1250
	OW	158	91	214	382	427	1250
	Change	-103	-41	+2	-12	-12	-
Ca-felspar	PW	2	2	9	18	35	104
	OW	13	8	18	32	36	104
	Change	-11	-6	-9	-14	-1	-
Quartz	PW	242	307	912	1602	1471	4481
	OW	568	327	765	1367	1531	4481
	Change	-324	-20	+147	+235	-60	-

PW = Present weight; OW = Original weight

TABLE 55 (Cont.). TUNSTALL PROFILE: WEIGHTS (mg) OF MINERALS PER HORIZON PER CM^2 COLUMN

		HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6
2 - 5 µm Fraction							
Kaolinite	PW	234	266	855	2318	2662	8924
	OW	1127	667	1541	2737	3059	8924
	Change	-893	-401	-686	-419	-397	-
Chlorite	PW	18	28	114	366	363	1164
	OW	147	87	201	357	399	1164
	Change	-129	-59	-87	+9	-36	-
Vermiculite	PW	252	154	1026	1342	1210	3880
	OW	490	290	670	1190	1330	3880
	Change	-238	-136	+356	+152	-120	-
Smectite	PW	72	42	513	976	847	2716
	OW	343	203	469	833	931	2716
	Change	-271	-161	+44	+143	-84	-
Mica	PW	306	224	1140	2806	2904	8924
	OW	1127	667	1541	2737	3059	8924
	Change	-821	-443	-401	+69	-155	-
Amorphous silica	PW	7	6	23	49	43	116
	OW	15	9	20	36	40	116
	Change	-8	-3	+3	+13	+8	-
Amorphous alumina	PW	2	1	6	12	12	39
	OW	5	3	7	12	13	39
	Change	-3	-2	-1	-	-1	-
"Free" iron oxides	PW	40	27	131	281	303	931
	OW	118	70	161	286	319	931
	Change	-78	-43	-30	-5	-16	-
K-felspar	PW	97	70	205	427	424	1242
	OW	157	93	214	381	426	1242
	Change	-60	-23	-9	+46	-2	-
Na-felspar	PW	108	73	239	537	508	1591
	OW	201	119	275	488	545	1591
	Change	-93	-46	-36	+49	-37	-
Ca-felspar	PW	11	7	23	49	48	155
	OW	20	12	27	48	53	155
	Change	-9	-5	-4	+1	-5	-
Quartz	PW	657	507	1454	3123	2807	9312
	OW	1176	696	1608	2856	3192	9312
	Change	-519	-189	-154	+267	-385	-

PW = Present weight; OW = Original weight

TABLE 55 (Cont,). TUNSTALL PROFILE: WEIGHTS (mg) OF MINERALS PER HORIZON PER CM^2 COLUMN

		HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6
5 - 20 µm Fraction							
Kaolinite	PW	360	330	1526	3066	3178	9198
	OW	1162	672	1568	2814	3150	9198
	Change	-802	-342	-42	+252	+28	-
Chlorite	PW	90	66	327	657	681	1971
	OW	249	144	336	603	675	1971
	Change	-159	-78	-9	+54	+6	-
Vermiculite	PW	225	132	545	876	1135	3285
	OW	415	240	560	1005	1125	3285
	Change	-190	-108	-15	-129	+10	-
Smectite	PW	90	66	872	1314	908	2628
	OW	332	192	448	804	900	2628
	Change	-242	-126	+424	+510	+8	-
Mica	PW	270	264	1308	3504	3859	11169
	OW	1411	816	1904	3417	3825	11169
	Change	-1141	-552	-596	+87	+34	-
K-felspar	PW	387	248	621	1226	1294	3219
	OW	407	235	549	985	1103	3219
	Change	-20	+13	+72	+241	+191	-
Na-felspar	PW	491	347	959	1862	2020	5781
	OW	730	422	986	1769	1980	5781
	Change	-239	-75	-27	+93	+40	-
Ca-felspar	PW	36	23	65	131	136	394
	OW	50	29	67	121	135	394
	Change	-14	-6	-2	+10	+1	-
Quartz	PW	2552	1822	4611	9132	9375	27528
	OW	3478	2011	4693	8422	9428	27528
	Change	-926	-189	-82	+710	-53	-

PW = Present weight; OW = Original weight

TABLE 55 (Cont.). TUNSTALL PROFILE: WEIGHTS (mg) OF MINERALS PER HORIZON PER CM^2 COLUMN

		HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6
20 - 53 µm Fraction							
Mica	PW	137	100	520	842	1177	3001
	OW	378	223	515	918	1029	3001
	Change	-241	-123	+5	-76	+148	-
K-felspar	PW	572	340	785	1178	1303	3678
	OW	464	274	631	1125	1261	3678
	Change	+108	+66	+154	+53	+42	-
Na-felspar	PW	644	392	1010	1499	1882	4840
	OW	610	360	830	1480	1660	4840
	Change	+34	+32	+180	+19	+222	-
Ca-felspar	PW	33	20	31	46	54	145
	OW	18	11	25	44	50	145
	Change	+15	+9	+6	+2	+4	-
Quartz	PW	4823	2936	6569	9853	11656	31170
	OW	3928	2318	5345	9531	10690	31170
	Change	+895	+618	+1224	+322	+966	-
Remainder	PW	260	200	1224	1836	1991	5324
	OW	671	396	913	1628	1826	5324
	Change	-411	-196	+311	+208	+165	-

PW = Present weight; OW = Original weight

TABLE 55 (Cont.). TUNSTALL PROFILE: WEIGHTS (mg) OF MINERALS PER HORIZON PER CM^2 COLUMN

		HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6
53-250 µm Fraction							
Mica	PW	40	35	483	634	759	3398
	OW	432	250	581	1037	1162	3398
	Change	-392	-215	-98	-403	-403	-
K-felspar	PW	677	395	997	1769	1695	4814
	OW	612	354	823	1469	1646	4814
	Change	+65	+41	+174	+300	+49	-
Na-felspar	PW	475	277	770	1373	1240	3469
	OW	441	255	593	1058	1186	3469
	Change	+34	+22	+177	+315	+54	-
Ca-felspar	PW	30	18	45	106	76	212
	OW	27	16	36	65	73	212
	Change	+3	+2	+9	+41	+3	-
Quartz	PW	8595	5021	12201	19104	20189	56498
	OW	7182	4150	9656	17237	19312	56498
	Change	+1413	+871	+2545	+1867	+877	-
Remainder	PW	303	177	604	1584	1265	2124
	OW	270	156	363	648	726	2124
	Change	+33	+21	+241	+936	+539	-

PW = Present weight, OW = Original weight

TABLE 56 TUNSTALL PROFILE: WEIGHTS (mg) OF MINERALS PER cc OF SOIL

	HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6*
<0.25 μm Fraction						
Kaolinite	48.0	71.6	46.9	37.1	27.5	25.1
Chlorite	9.6	15.1	4.3	6.8	5.5	2.8
Vermiculite	84.0	135.7	170.6	128.3	93.6	91.9
Smectite	24.0	45.2	59.7	47.3	33.0	39.0
Mica	38.4	60.3	93.8	81.0	88.1	91.9
Amorphous silica	7.0	7.9	6.8	5.7	3.6	4.2
Amorphous alumina	5.1	8.3	7.7	4.1	2.5	2.2
"Free" iron oxides	25.0	33.5	35.8	26.0	21.8	21.2
0.25 - 2 μm Fraction						
Kaolinite	33.6	72.0	56.9	58.7	49.8	46.4
Chlorite	3.2	7.4	4.9	7.7	7.1	7.3
Vermiculite	20.0	31.4	66.8	53.6	37.9	41.5
Smectite	1.1	3.7	14.8	25.5	26.1	31.8
Mica	22.1	29.5	54.4	61.2	71.1	70.9
Amorphous silica	1.7	1.7	2.0	2.0	1.7	1.5
Amorphous alumina	0.7	0.9	1.2	1.0	1.2	1.0
"Free" iron oxides	3.8	6.1	9.9	10.2	10.4	10.7
K-felspar	3.6	4.2	5.4	5.6	4.5	5.6
Na-felspar	2.8	3.8	5.7	5.4	5.7	5.9
Ca-felspar	0.1	0.2	0.2	0.3	0.5	0.5
Quartz	12.1	23.6	24.0	23.2	20.2	21.0

* represents the original weight of the mineral in all horizons.

TABLE 56 (Cont.). TUNSTALL PROFILE: WEIGHTS (mg) OF MINERALS PER cc OF SOIL

	HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6*
2 -5 μm Fraction						
Kaolinite	11.7	20.5	22.5	33.6	36.5	41.9
Chlorite	0.9	2.2	3.0	5.3	5.0	5.5
Vermiculite	12.6	11.8	27.0	19.4	16.6	18.2
Smectite	3.6	3.2	13.5	14.1	11.6	12.7
Mica	15.3	17.2	30.0	40.7	39.8	41.9
Amorphous silica	0.4	0.5	0.6	0.7	0.7	0.5
Amorphous alumina	0.1	0.1	0.2	0.2	0.2	0.2
"Free" iron oxides	2.0	2.1	3.4	4.1	4.2	4.4
K-felspar	4.9	5.4	5.4	6.2	5.8	5.8
Na-felspar	5.4	5.6	6.3	7.8	7.0	7.5
Ca-felspar	0.6	0.5	0.6	0.7	0.7	0.7
Quartz	32.9	39.0	38.3	45.3	38.5	43.7
5 - 20 μm Fraction						
Kaolinite	18.0	25.4	40.2	44.4	43.5	43.1
Chlorite	4.5	5.1	8.6	9.5	9.3	9.2
Vermiculite	11.3	10.2	14.3	12.7	15.5	15.4
Smectite	4.5	5.1	23.0	19.0	12.4	12.3
Mica	13.5	20.3	34.4	50.8	52.9	52.4
K-felspar	19.4	19.1	16.3	17.8	17.7	15.1
Na-felspar	24.6	26.7	25.2	27.0	27.7	27.1
Ca-felspar	1.8	1.8	1.7	1.9	1.9	1.8
Quartz	127.6	140.1	121.4	132.3	128.4	129.1

*represents the original weight of the mineral in all horizons.

TABLE 56 (Cont.). TUNSTALL PROFILE, WEIGHTS (mg) OF MINERALS PER cc OF SOIL

	HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6*
20 - 53 µm Fraction						
Mica	6.9	7.7	13.7	12.2	16.1	14.1
K-felspar	28.6	26.2	20.7	17.1	17.9	17.2
Na-felspar	32.2	30.2	26.6	21.7	25.8	22.7
Ca-felspar	1.7	1.5	0.8	0.7	0.7	0.7
Quartz	241.2	225.8	172.9	142.8	159.7	146.2
Remainder	13.0	15.4	32.2	26.6	27.3	25.0
53 - 250 µm Fraction						
Mica	2.0	2.7	12.7	9.2	10.4	15.9
K-felspar	33.9	30.4	26.2	25.6	23.2	22.6
Na-felspar	23.8	21.3	20.3	19.9	17.0	16.3
Ca-felspar	1.5	1.4	1.2	1.5	1.0	1.0
Quartz	429.8	386.2	321.1	276.8	276.6	265.0
Remainder	15.2	13.6	16.0	23.0	17.3	10.0
250-2000 µm Fraction						
Quartz + Felspar	197.7	89.6	74.7	93.2	104.9	121.3
Remainder	22.2	2.8	9.5	12.7	32.0	26.6
<2 mm FRACTION						
"Free" iron oxides	41.0	49.8	67.0	59.9	51.6	51.6

*represents the original weight of the mineral in all horizons.

TABLE 57 TUNSTALL PROFILE : OVERALL MINERALOGICAL COMPOSITION
(g/cm^2 surface area/horizon)

		HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6
Quartz	PW	20.1	11.5	28.0	47.9	51.6	149.7
	OW	19.0	11.0	25.6	45.7	51.2	149.7
Felspar	PW	4.4	2.5	6.7	12.3	13.0	37.3
	OW	4.7	2.7	6.4	11.4	12.8	37.3
Mica	PW	2.0	1.8	9.1	17.6	20.3	61.2
	OW	7.8	4.5	10.5	18.7	20.9	61.2
Vermiculite	PW	2.6	2.5	10.6	14.8	11.9	35.6
	OW	3.5	2.6	6.1	10.9	12.2	35.6
Smectite	PW	0.7	0.7	4.2	7.3	6.1	20.4
	OW	2.6	1.5	3.5	6.3	7.0	20.4
Kaolinite	PW	2.2	2.5	6.3	12.0	11.5	33.4
	OW	4.2	2.5	5.7	10.2	11.4	33.4
Chlorite	PW	0.4	0.4	0.8	2.0	2.0	5.3
	OW	0.7	0.4	0.9	1.6	1.8	5.3
"Free" Iron Oxides	PW	0.8	0.6	2.5	4.1	3.8	11.0
	OW	1.4	0.8	1.9	3.4	3.8	11.0
Amorphous silica	PW	0.2	0.1	0.4	0.6	0.4	1.3
	OW	0.2	0.1	0.2	0.4	0.5	1.3
Amorphous alumina	PW	0.1	0.1	0.3	0.4	0.3	0.7
	OW	0.1	0.1	0.1	0.2	0.2	0.7
Remainder*	PW	0.8	0.3	1.5	2.9	4.5	9.9
	OW	1.3	0.7	1.7	3.0	3.4	9.9

* Material not analysed in 20-2000 μm fractions, mainly layer silicates.

TABLE 58 TUNSTALL PROFILE : OVERALL MINERALOGICAL COMPOSITION (%)

	HT 1/1	HT 1/2	HT 1/3	HT 1/4	HT 1/5	HT 1/6
Quartz	58.9	49.9	39.8	39.3	41.2	40.9
Felspar	12.9	10.9	9.5	10.1	10.3	10.2
Mica	5.7	7.8	12.9	14.4	16.2	16.8
Vermiculite	7.5	10.6	15.0	12.1	9.5	9.7
Smectite	1.9	3.2	6.0	6.0	4.8	5.6
Kaolinite	6.5	10.7	9.0	9.8	9.2	9.1
Chlorite	1.1	1.7	1.1	1.7	1.6	1.4
"Free" Iron Oxides	2.4	2.8	3.6	3.4	3.1	3.0
Amorphous silica	0.5	0.6	0.5	0.5	0.3	0.4
Amorphous alumina	0.3	0.5	0.5	0.3	0.2	0.2
Remainder*	2.3	1.3	2.1	2.4	3.6	2.7

* Material not analysed in 20-2000 μm fractions, mainly layer silicates.

TABLE 59 MINERALOGICAL CHANGES IN HORIZONS 1 - 4 (mg)

		< 0.25μm	0.25-2μm	2-5μm	5-20μm	20-53μm	53-250μm	250-2000μm
Kaolinite	PW	6236	7818	3673	5282	N.D.	N.D.	N.D.
	OW	3636	6688	6072	6216			
	Change	+2600	+1130	-2399	-934			
Chlorite	PW	1016	876	526	1140	N.D.	N.D.	N.D.
	OW	404	1056	792	1332			
	Change	+612	-180	-266	-192			
Vermiculite	PW	18778	7041	2774	1778	N.D.	N.D.	N.D.
	OW	13332	5984	2640	2220			
	Change	+5446	+1057	+134	-442			
Smectite	PW	6598	2393	1603	2342	N.D.	N.D.	N.D.
	OW	5656	4576	1848	1776			
	Change	+942	-2183	-245	+566			
Mica	PW	10708	7117	4476	5346	1599	1192	N.D.
	OW	13332	10208	6072	7548	2034	2300	
	Change	-2624	-3091	-1596	-2202	-435	-1108	
Amorphous Silica	PW	897	272	85	N.D.	N.D.	N.D.	N.D.
	OW	606	211	80				
	Change	+291	+61	+5				
Amorphous Alumina	PW	781	142	21	N.D.	N.D.	N.D.	N.D.
	OW	324	141	27				
	Change	+487	+1	-6				
"Free" Iron Oxide	PW	4090	1235	479	N.D.	N.D.	N.D.	N.D.
	OW	3070	1549	635				
	Change	+1020	-314	-156				
K-Feldspar	PW	N.D.	720	799	2482	2875	3838	N.D.
	OW		810	845	2176	2494	3258	
	Change		-90	-46	+306	+381	+580	
Na-Feldspar	PW	N.D.	691	957	3659	3545	2895	N.D.
	OW		845	1083	3907	3280	2347	
	Change		-154	-126	-248	+265	+548	
Ca-Feldspar	PW	N.D.	31	90	255	130	199	N.D.
	OW		71	107	267	98	144	
	Change		-40	-17	-12	+32	+55	
Quartz	PW	N.D.	3063	5741	18117	24181	44921	N.D.
	OW		3027	6336	18604	21122	38225	
	Change		+36	-595	-487	+3059	+6696	
Quartz and Feldspar	PW	-	-	-	-	-	-	14382
	OW							17466
	Change							-3084
Remainder	PW	-	-	-	-	3520	2668	1718
	OW					3608	1437	3834
	Change					-88	+1231	-2116

PW = Present Weight OW = Original Weight

TABLE 60 TUNSTALL PROFILE : OVERALL MINERALOGICAL COMPOSITION OF UPPERMOST FOUR HORIZONS

	Present Weight*	Original Weight*	% of present soil material	% of original soil material
Quartz	107.5	101.3	43.0	40.9
Felspar	25.9	25.2	10.4	10.2
Mica	30.5	41.5	12.2	16.8
Vermiculite	30.5	23.1	12.2	9.7
Smectite	12.9	13.9	5.2	5.6
Kaolinite	23.0	22.6	9.2	9.1
Chlorite	3.6	3.6	1.4	1.4
"Free" Iron Oxides	8.0	7.5	3.3	3.0
Amorphous silica	1.3	0.9	0.5	0.4
Amorphous alumina	0.9	0.5	0.4	0.2
Remainder (+)	5.5	6.7	2.2	2.7

* as g/cm^2 surface area/horizon

(+) Material not analysed in 20-2000 μm fractions, mainly layer silicates

TABLE 61 HOLKHAM PROFILE : DESCRIPTION

Site Description

Profile No. HT 2

Date 27-7-1970

Grid Reference TF 863428

Locality Section dug at southern end of east face of disused clay pit, immediately north of line of old railway, Holkham brickyard, south of Peterstone Farm. O.S. Sheet 125, Fakenham

Elevation 14m O.D.

Relief Almost flat, convex slope of 1-2° to south

Surface drainage Shedding site

Parent material Hunstanton Till, Devensian. Reddish brown boulder clay, calcareous, variable laterally from clay loam to very stony sandy clay loan at 20m north of profile pit. Erratic stones similar to those in Hessle Till at Tunstall (HT 1).

Vegetation Barley field 1m to east of pit face. Grass growing on headland around top of pit face.

Weather conditions Rain in last 6 hours; mostly dry in previous two months Profile dry in top 35 cm; moist below this.

Profile Description

Horizons

HT 2/1 A1	0-23 cm	Brown/dark brown (10YR 4/3) loam; mottling absent. Slightly stony; angular to sub-angular gravel and small stones, mostly flint, some chalk. Poorly to moderately developed fine to medium sub-angular blocky structure; moderately developed fine angular blocky structure on exposed face of brickpit. Consistence : friable. Extremely abundant very fine pores, few fine fissures; moderate permeability. Low intimate humus, abundant fine and few medium fibrous roots, mostly

living; abundant earthworms. Narrow, even boundary.

(Sampled at 5-20 cm)

HT 2/2 23-36 cm
A2(g)

Brown/dark brown (10YR 4/3) loam; common faint medium brown (7.5YR 5/4) mottles. Slightly stony; angular to rounded gravel and small stones, mainly flint, some chalk, a few rotten sandstone fragments. Moderately developed medium sub-angular blocky structure. Consistence : hard. Abundant fine to very fine pores; rare fine fissures, mostly vertical; moderate permeability. Low intimate humus; common fine and few small fibrous roots, mostly living; abundant earthworms. Sharp, slightly undulating boundary.

(Sampled at 25-35 cm)

HT 2/3 36-69 cm
B1w(g)

Brown/dark brown (7.5YR 4/2) clay loam to silty clay loam; common faint medium to fine reddish brown (5YR 4/4) mottles. Slightly stony; angular to rounded gravel and small stones, mostly flint, some rotten sandstone fragments, no chalk. Strongly developed coarse prismatic structure. Consistence : firm to very firm. Abundant fine to very fine pores; few fine fissures, mostly vertical; slow to moderate permeability. Common fine fibrous roots; few earthworms. Clay skins on ped faces. Narrow even boundary.

(Sampled at 40-60 cm)

HT 2/4 69-96 cm
B2(g)

Brown/dark brown (7.5YR 4/2) silty clay loam to clay loam; many fine to extremely fine faint reddish brown (5YR 4/4) mottles. Slightly stony; angular to rounded gravel and small stones, mostly flint, a few very small chalk pellets, some rotten sandstone fragments. Moderately developed medium prismatic structure. Consistence : firm. Abundant fine to very fine pores, rare fine fissures, mostly vertical; slow to moderate permeability. Few fleshy roots (thistle) on ped faces; rare earthworms. Clay skins on ped faces. Merging, even boundary. (Sampled at 75-90 cm)

HT 2/5 96-125 cm Cg_{ca} Reddish brown (5YR 4/4) calcareous clay loam; common fine to extremely fine grey (10YR 5/1) mottling; distinct grey (10YR 5/1) coatings on ped faces, along root channels, and around stones. Slightly stony; angular to rounded gravel and small stones, mostly flint and chalk. Moderately developed medium sub-angular block structure. Consistence: firm. Abundant fine to very fine pores; rare fine fibrous and fleshy roots on ped faces. Few small light reddish brown (5YR 6/4) nodular carbonate concretions; few very small black manganiferous concretions. Clay skins on ped faces. (Sampled at 100-125 cm) Base of pit at 125 cm.

Drainage of profile : imperfectly drained soil, with impedance due to heavy textured sub-surface horizons. Drainage aided by prominent vertical fissures.

HT 2/6 150 cm Reddish brown (5YR 4/4), very stony sandy clay loam, underlying calcareous clay loam at northern end of face of brickpit.

TABLE 62 HOLKHAM PROFILE : PARTICLE SIZE DISTRIBUTION (weight %)

ø Range	HT 2/1	HT 2/2	HT 2/3	HT 2/4	HT 2/5	HT 2/6
-1/0	1.0	1.0	0.4	0.3	1.1	1.7
0/1	2.4	2.4	0.9	0.6	2.2	3.4
1/2	10.0	10.2	3.2	2.6	6.0	16.6
2/3	17.2	17.0	6.7	5.5	8.9	22.6
3/4	12.5	11.8	6.8	7.6	7.3	13.6
4/5	11.4	11.5	9.7	12.6	7.9	7.0
5/6	8.5	9.1	10.0	12.4	8.0	4.3
6/7	6.4	5.9	7.7	8.8	7.7	3.2
7/8	4.8	5.1	6.9	6.7	7.2	3.3
8/9	3.8	4.2	6.4	5.8	6.9	3.8
9/12	11.6	11.1	16.9	14.5	15.1	20.5
< 12	10.4	10.7	24.4	22.6	21.7	

TABLE 63 HOLKHAM PROFILE : PARTICLE SIZE SEPARATES (weight %)

μm	HT 2/1	HT 2/2	HT 2/3	HT 2/4	HT 2/5	HT 2/6
250-2000	13.4	13.6	4.5	3.5	9.3	21.7
53-250	32.8	32.1	15.9	16.0	18.2	38.6
20-53	14.9	15.4	14.6	19.2	12.2	7.9
5-20	12.1	11.8	15.7	18.0	15.1	13.7
2-5	4.8	5.3	8.0	6.2	8.4	7.6
0.25-2	11.6	11.1	16.9	14.5	15.1	20.5
< 0.25	10.4	10.7	24.4	22.6	21.7	

TABLE 64 HOLKHAM PROFILE : PARTICLE SIZE DISTRIBUTION, CLAY-FREE BASIS (%)

Ø Range	HT 2/1	HT 2/2	HT 2/3	HT 2/4	HT 2/5	HT 2/6
-1/0	1.3	1.3	0.7	0.5	1.7	2.1
0/1	3.1	3.1	1.5	1.0	3.5	4.3
1/2	12.8	13.0	5.5	4.1	9.5	20.9
2/3	22.0	21.8	11.4	8.8	14.1	28.4
3/4	16.0	15.1	11.6	12.1	11.6	17.1
4/5	14.6	14.7	16.5	20.0	12.5	8.8
5/6	10.9	11.6	17.0	19.7	12.6	5.4
6/7	8.2	7.5	13.1	14.0	12.2	4.0
7/8	6.2	6.5	11.8	11.6	11.4	4.2
8/9	4.9	5.4	10.9	9.2	10.9	4.8

TABLE 65 HOLKHAM PROFILE : DETAILED PARTICLE SIZE DISTRIBUTION OF SAND FRACTIONS AT ¼ ∅ INTERVALS

µm	HT 2/1	HT 2/2	HT 2/3	HT 2/4	HT 2/5	HT 2/6
1680–2000	0.5	0.5	0.7	0.4	1.1	0.8
1400–1680	0.7	0.7	0.6	0.6	1.2	0.8
1200–1400	0.6	0.5	0.5	0.4	0.9	0.6
1000–1200	0.7	0.5	0.5	0.4	1.1	0.6
850–1000	0.7	0.8	0.7	0.6	1.1	0.7
710–850	1.1	1.2	0.9	0.9	1.8	1.1
600–710	1.8	2.0	1.6	1.2	2.8	2.1
500–600	1.9	1.6	1.6	1.0	2.3	1.9
420–500	4.4	4.5	3.7	2.7	5.2	5.3
355–420	5.2	5.3	1.4	3.2	5.4	6.3
300–355	5.7	5.5	5.0	3.6	5.2	6.4
250–300	7.9	8.3	7.8	5.7	7.3	10.2
210–250	11.1	10.9	10.0	7.7	9.0	11.3
180–210	8.7	8.7	8.3	6.8	7.5	8.5
150–180	12.3	12.3	11.4	10.2	11.2	11.3
125–150	7.6	7.4	7.8	7.3	6.8	7.0
105–125	7.8	8.1	8.7	9.2	8.1	8.2
90–105	5.3	5.1	6.1	6.8	5.2	4.9
75–90	6.5	8.0	11.1	15.3	9.3	7.1
63–75	9.5	8.1	11.6	16.0	7.5	4.9

TABLE 66 HOLKHAM PROFILE : TEXTURE CLASSES

HT 2/1	HT 2/2	HT 2/3	HT 2/4	HT 2/5	HT 2/6
Loam	Loam	Clay	Silty clay loam	Clay loam	Sandy clay loam

TABLE 67 HOLKHAM PROFILE : FINE CLAY/TOTAL CLAY RATIOS

HT 2/1	HT 2/2	HT 2/3	HT 2/4	HT 2/5
0.47	0.49	0.59	0.61	0.59

TABLE 68 HOLKHAM PROFILE : 20-53 µm FRACTION, HEAVY MINERAL ANALYSES

	HT 2/1	HT 2/2	HT 2/3	HT 2/4	HT 2/5
% Heavy Minerals	1.03	0.90	0.68	0.95	0.91

NON-OPAQUE HEAVY MINERALS (as ‰ of total non-opaque heavy minerals)

	HT 2/1	HT 2/2	HT 2/3	HT 2/4	HT 2/5
Garnet	100	123	79	84	70
Epidote	278	273	254	227	217
Zoisite/Clinozoisite	24	27	26	25	22
Zircon	187	175	199	157	155
Rutile (brown)	20	17	15	12	10
Rutile (yellow)	64	43	67	34	44
Rutile (red)	3	3	3	2	2
Anatase	24	13	23	20	27
Tourmaline	67	73	44	44	39
Augite	27	33	26	27	44
Hypersthene	-	-	3	2	-
Hornblende	127	145	105	115	126
Staurolite	-	-	-	-	-
Kyanite	13	20	9	12	10
Apatite	17	26	47	96	85
Collophane	3	3	3	5	2
Chlorite/Chamosite	33	20	79	91	99
Biotite	13	6	18	47	48

TABLE 69 HOLKHAM PROFILE : 53-250 µm FRACTION, HEAVY MINERAL ANALYSES

	HT 2/1	HT 2/2	HT 2/3	HT 2/4	HT 2/5
‰ Heavy Minerals (>2.9 S.G.)	0.75	0.83	0.67	0.64	1.09
‰ Opaque Minerals	487	503	546	570	488
‰ Non-opaque Minerals	513	497	454	430	512

TABLE 70 HOLKHAM PROFILE : 53-250 µm FRACTION, OPAQUE MINERALS (as ‰ of total opaque heavy minerals)

	HT 2/1	HT 2/2	HT 2/3	HT 2/4	HT 2/5
Limonite	394	390	476	448	507
Hematite	244	354	289	284	251
Ilmenite/Magnetite	183	143	106	139	106
Leucoxene	179	113	129	129	136

TABLE 71 HOLKHAM PROFILE : 53-250 µm FRACTION, LIGHT MINERAL ANALYSES (as ‰ of total light minerals)

	HT 2/1	HT 2/2	HT 2/3	HT 2/4	HT 2/5
Quartz	886	886	868	844	882
Flint	29	17	23	25	26
Orthoclase	59	60	62	81	58
Microcline	15	23	14	17	12
Sodic Plagioclase	12	11	20	19	12
Calcic Plagioclase	-	-	-	3	5
Muscovite	-	3	14	11	5

TABLE 72 HOLKHAM PROFILE : 53-250μm FRACTION, NON-OPAQUE HEAVY MINERALS
(as % of total non-opaque heavy minerals)

	HT 2/1	HT 2/2	HT 2/3	HT 2/4	HT 2/5
Garnet (clear)	225	208	168	182	165
Garnet (pink)	76	67	36	32	81
Epidote	151	194	177	133	121
Zoisite/Clinozoisite	50	41	36	18	38
Zircon	89	94	88	69	74
Rutile (brown)	3	7	6	11	8
Rutile (yellow)	16	22	18	39	17
Rutile (red)	7	12	15	11	11
Anatase	3	2	3	4	2
Brookite	3	7	3	4	6
Tourmaline (brown/yellow)	53	26	46	39	30
Tourmaline (brown/green)	33	34	36	39	53
Tourmaline (blue/clear)	-	2	3	4	-
Augite	59	58	49	68	59
Hyperthene /Enstatite	10	14	6	7	19
Hornblende (dark green)	167	152	219	207	147
Hornblende (pale green)	20	38	43	36	34
Hornblende (brown)	3	5	6	14	10
Staurolite	13	5	9	4	2
Kyanite	13	7	9	18	6
Sillimanite	3	-	-	-	-
Apatite	-	-	6	18	78
Collophane	-	-	-	-	4
Chlorite/Chamosite	3	5	18	25	27
Biotite	-	-	-	14	6
Siderite	-	-	-	4	2

TABLE 73 HOLKHAM PROFILE : 53-250 µm FRACTION, "RESISTANT" NON-OPAQUE HEAVY MINERALS (‰)

	Amphiboles	Epidote Zoisite Clinozoisite	Garnet	Tourmaline	Rutile Anatase Brookite	Zircon	Pyroxene	Others
HT 2/1	191	202	302	86	32	89	69	29
HT 2/2	196	236	277	62	50	95	72	12
HT 2/3	275	219	209	87	46	90	56	18
HT 2/4	274	161	228	87	74	73	80	23
HT 2/5	216	180	279	94	50	84	88	9

TABLE 74 HOLKHAM PROFILE : 20-53 µm FRACTION, "RESISTANT" NON-OPAQUE HEAVY MINERALS (‰)

	Amphiboles	Epidote Zoisite Clinozoisite	Garnet	Tourmaline	Rutile Anatase Brookite	Zircon	Pyroxene	Others
HT 2/1	136	323	107	72	119	200	29	14
HT 2/2	154	318	130	77	80	185	35	21
HT 2/3	123	328	93	52	127	233	34	10
HT 2/4	151	332	110	58	89	206	38	16
HT 2/5	165	313	91	51	108	202	57	13

TABLE 75 HOLKHAM PROFILE : X-RAY DETERMINATIONS OF LAYER SILICATES (as % of total layer silicates in each fraction)

	Mica	Kaolinite	Chlorite	Vermiculite	Smectite
< 0.25 µm					
HT 2/1	6	14	-	59	21
HT 2/2	8	16	-	55	21
HT 2/3	11	13	-	52	24
HT 2/4	10	10	-	56	24
HT 2/5	9	9	-	55	27
0.25-2 µm					
HT 2/1	18	38	-	36	8
HT 2/2	18	38	-	35	9
HT 2/3	17	31	-	40	12
HT 2/4	14	23	-	46	17
HT 2/5	17	24	-	43	16
2-5 µm					
HT 2/1	32	35	4	21	8
HT 2/2	26	30	2	31	11
HT 2/3	27	31	3	32	7
HT 2/4	24	30	2	38	6
HT 2/5	31	30	2	32	5
5-20 µm					
HT 2/1	55	17	5	15	8
HT 2/2	48	22	4	17	9
HT 2/3	45	23	4	21	7
HT 2/4	43	31	4	17	5
HT 2/5	47	29	4	16	4

TABLE 76 HOLKHAM PROFILE : ESTIMATE OF RELATIVE ABUNDANCE OF CRYSTALLINE "FREE" IRON OXIDES FROM X-RAY DIFFRACTOGRAMS

	HT 2/1	HT 2/2	HT 2/3	HT 2/4	HT 2/5
Lepidocrocite					
< 0.25 µm	*	*	**	–	–
0.25 – 2 µm	*	*	*****	*	–
2 –5 µm	–	*	***	–	–
5 – 20 µm	*	*	*	–	–
Goethite					
< 0.25 µm	–	–	–	–	–
0.25 – 2 µm	*	*	*	*	*
2 – 5 µm	*	*	**	*	*
5 – 20 µm	–	–	*	–	–

TABLE 77 HOLKHAM PROFILE : CHEMICAL DETERMINATIONS (%)

	HT 2/1	HT 2/2	HT 2/3	HT 2/4	HT 2/5
Amorphous silica					
<0.25 μm	3.6	3.6	3.0	2.7	2.6
0.25-2 μm	1.6	1.5	0.9	0.8	0.8
2-5 μm	0.4	0.4	0.4	0.4	0.4
Amorphous alumina					
<0.25 μm	1.8	1.7	1.8	1.5	1.5
0.25 - 2 μm	0.9	0.8	0.7	0.6	0.6
2 - 5 μm	0.1	0.1	0.1	0.1	0.1
"Free" Iron Oxides (as Fe_2O_3)					
<0.25 μm	6.4	6.7	6.4	7.1	7.1
0.25 - 2 μm	5.0	4.5	5.2	5.8	5.7
2 - 5 μm	2.2	2.2	2.4	2.7	2.6
<2 mm	1.9	1.8	3.5	3.3	2.9
Carbonate (as $CaCO_3$)					
<2mm	0.3	0.0	0.0	0.0	4.9

Abbreviations used in Bibliography

Advan. Agron.	Advances in Agronomy
Am. J. Sci.	American Journal of Science
Am. Min.	American Mineralogist
Am. Soil Survey Ass. Bull.	Bulletin of the American Soil Survey Association
B.A. Rept.	Report of the British Association for the Advancement of Science
B.S.S.S.	British Society of Soil Science
Can. J. Soil Sci.	Canadian Journal of Soil Science
Clay Min. Bull.	Clay Minerals Bulletin
E. Mid. Geographer	East Midlands Geographer
Erdöl u Kohle	Erdöl und Kohle
Geochim. Cosmochim. Acta	Geochimica et Cosmochimica Acta
Geol. Mag.	Geological Magazine
Geol. Soc. Bull. Am.	Bulletin of the Geological Society of America
Heidelberg. Beitr. Min.	Heidelberger Beiträge zur Mineralogie und Petrographie
Ill. Geol. Surv. Circ.	Illinois Geological Survey Circular
Ill. State Geol. Surv.	Illinois State Geological Survey
Imp. Bur. Soil Sci.	Imperial Bureau of Soil Science
Iowa Geol. Survey	Iowa Geological Survey
J. Agr. Sci.	Journal of Agricultural Science
J. Ecol.	Journal of Ecology
J. Geol.	Journal of Geology
J. Geol. Soc.	Journal of the Geological Society of London
J. Geol. Soc. Australia	Journal of the Geological Society of Australia
J. Glac.	Journal of Glaciology
J. Sed. Pet.	Journal of Sedimentary Petrology
J. Soil Sci.	Journal of Soil Science

Mem. Geol. Surv. U.K./G.B.	Memoir of the Geological Survey of the United Kingdom/Great Britain
Mem. & Proc. Manch. Lit. & Phil. Soc.	Memoirs and Proceedings of the Manchester Literary and Philosophical Society
Mem. Soil Surv. G.B.	Memoir of the Soil Survey of Great Britain
Mich. Agr. Exp. Stn. Bull.	Bulletin of the Michigan Agricultural Experimental Station
N.Z. J. Sci. Tech.	New Zealand Journal of Science and Technology
P.G.A.	Proceedings of the Geologists' Association, London
Phil. Trans. Roy. Soc.	Philosophical Transactions of the Royal Society
Proc. Leeds Phil. Soc.	Proceedings of the Leeds Philosophical Society
Proc. Prehist. Soc. E. Ang.	Proceedings of the Prehistoric Society of East Anglia
Proc. Roy. Irish Acad.	Proceedings of the Royal Irish Academy
Proc. Roy. Soc.	Proceedings of the Royal Society
P.S.S.S.A.	Proceedings of the Soil Science Society of America
P.Y.G.S.	Proceedings of the Yorkshire Geological Society
Q.J.G.S.	Quarterly Journal of the Geological Society of London
Q.R.A.	Quaternary Research Association
Res. Bull. Miss. Ag. Exp. Stn.	Research Bulletin of the Missouri Agricultural Experimental Station
Sci. Hort.	Scientific Horticulture
Scott. Geog. Mag.	Scottish Geographical Magazine
Scott.J. Geol.	Scottish Journal of Geology
Soil Sci.	Soil Science
Trans. Comm. Int. Soc. Soil Sci.	Transactions of Commission of the International Society of Soil Science
Trans. Int. Congr. Soil Sci.	Transactions of the International Congress of Soil Science
Trans. Leeds Geol. Ass.	Transactions of the Leeds Geological Association

Trans. Lincs. Nat. Union	*Transactions of the Lincolnshire Naturalists' Union*
Trans. Norf. Norw. Nat. Soc.	*Transactions of the Norfolk and Norwich Naturalists' Society*
Un. Ill. Ag. Exp. Stn. Bull.	*Bulletin of the University of Illinois Agricultural Experimental Station*
U.S.D.A.	*United States Department of Agriculture*
U.S. Geol. Surv. Ann. Rept.	*United States Geological Survey Annual Report*
Zeits. für Geomorph.	*Zeitschrift für Geomorphologie*

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DISCUSSION

In welcoming the paper as a notable and novel contribution the PRESIDENT asked whether the generalization in the abstract limiting English loess deposits to the new records and to those of east Kent and County Durham was wholly true. In particular, had not some of the much more widespread deposits, often termed brick-earths, been claimed to be loessic in origin?

Professor J. E. HEMINGWAY commented on the orange-brown, calcareous loess preserved in gulls in the limestones of the Hambleton Hills. He asked if the "red-lands" north of Pickering owed their character to an addition of loess, or was it a weathering product of one of the sandstones of the Corallian.

Dr. L. F. PENNY joined in congratulating the authors on their important contribution to the Quaternary history of East Yorkshire and asked whether the till overlying the loess, which Dr. Catt had referred to as Devensian, could be more precisely defined in terms of the Holderness sequence.

Dr. I. J. SMALLEY remarked that the paper presented results of considerable local interest but at least one point, that concerning the selective deposition of loess (or its selective retention) on limestone could be of consequence wherever there were loess deposits. Various aspects of loess deposit formation had been investigated at great length but surprisingly little attention had been paid to the actual mechanics of the deposition process. There had crept into the loess folklore an idea that grass or some similar vegetation was needed to "trap" the silt particles and yet there was no proof for this. The only investigations of the actual deposition process appeared to have been those carried out by Cegla in Poland (J. Cegla, 1972. Sedymentacja Lessow Polski, *Acta Univ. Wratislav.*, No. 168) and he demonstrated the critical part played by ground moisture. It might be that limestone surfaces possessed the correct moisture characteristics for optimum loess deposition.

Paradoxically we might be at some advantage in Britain with our thin, newly appreciated loess deposits. Observed differences in depositional style might be obscured in areas where there was a much greater volume of loess material, and loess investigations in East Yorkshire and Lincolnshire might shed useful light on the Cegla hypothesis. Of course it was impossible to ascribe the special distribution of the loess solely to selective deposition; as the authors pointed out, the possibility of cementation existed and their results might help to resolve one of the great continuing problems associated with loess lithology and genesis—the nature of the initial carbonate. Did loess deposits form with carbonate particles distributed among the predominant quartz particles or was all the carbonate introduced as a secondary deposit? The loess remnants on limestone bases could suggest that the second of these possibilities was more likely since only in those areas had the stability-giving chemically deposited carbonate occurred. The loess described had obvious and undeniable glacial connections; it was a cold loess. This seemed a convenient point to propose that in this it fell into line with the overwhelming majority of the loesses of the world. Another element of the loess folklore was the belief that hot or desert loess was a significant material; it was very difficult to disperse those beliefs once they had become established and we should be proposing that Yorkshire loess and Chinese loess were more similar than their geographical separation and difference in volume might suggest—and that they were formed in the same manner.

In a written contribution Mr. J. A. LEACH said that he was a little concerned by the authors' use of expressions of the type "the deposit contained x per cent of loess". Surely loess was not defined in that manner and that type of expression might be confusing. Would it not be better, if the size distribution of a deposit suggested a loessic nature and yet departed from the classic loess distribution, for one of the many additional loess descriptive terms to be used. For example, the sandy material could be *Sandlöss* (the Germans had all these terms in use and we could reasonably adopt them) and the well-known *Schwemlöss* might be distinguished. Now that the INQUA map of the European loess deposits was nearly completed we might begin to look for a usable international terminology and the German terms were the obvious ones to use; we could probably do without *Luvlöss*, *Sumpflöss* and *Flusswinkellöss* but the names in general use could easily be adopted.

In reply, the AUTHORS thanked the President and members of the society for their interest in the paper, and explained that many of the points raised in the discussion reflected the lack of universally accepted definitions for loess and related deposits. Many workers restricted the term "loess" to a yellow or buff, virtually stone-free, porous, calcareous, silt-rich deposit, which was unusually strong and hard when dry or moist, and had a strong prismatic jointing, so that it tended to maintain near vertical faces in natural and artificial exposures. A strong concensus of opinion attributed most of such loess to wind transportation of the finer fractions from accumulations of glacial debris, mainly outwash plains. In this sense, it was probably restricted in Britain to areas adjacent to the Thames estuary and the isolated occurrence near Easington, Co. Durham (Trechmann, 1920), to which the President referred. However, weathering *in situ*, reworking of the deposit, and mixing with other materials resulted in the loss of some of these characteristic properties, and could impose various others. The extensive classifications of loess, such as the German system to which Mr. Leach referred, were based partly on these secondary properties and partly on the geomorphological situation of the deposits. For the INQUA loess map of Europe, many of the German terms had been grouped into larger subdivisions, but even these were difficult to apply with confidence. The authors consequently preferred, for the present, to group under the single heading "loess" all the deposits in Britain that could be shown from laboratory and other studies to contain a moderate or large proportion of silt (4-9ϕ), the presence of which reflected an aeolian phase at or towards the end of the transportational history of the sediment. However, this was not entirely satisfactory, because one needed a term for the well-sorted aeolian silt component of the mixed deposits, and "loess" was then often used again, but with a meaning slightly different from the two already given. There was clearly a need for rationalization of terminology in aeolian as well as in other superficial deposits, but it might not be right to attempt this until more was known about the exact origins of different types.

Within the somewhat broader definition used by the authors would indeed be included many of the deposits mapped as brick-earth by the Institute of Geological Sciences and others. Many were evidently alluvial or colluvial accumulations of reworked aeolian silt, others loess weathered *in situ* without appreciable reworking or transportation. However, some of the deposits corresponding to brick-earth as defined by Hull and Whitaker (1861, The geology of parts of Oxfordshire and Berkshire. *Mem. geol. Surv.U.K.*), for example, on the Chilterns, either contained no loess or incorporated small quantities in their uppermost horizons only. The lack of a widely accepted definition was again a cause of difficulty.

The authors agreed with Dr. Smalley in condemning the idea that a vegetational cover was necessary to stabilize the loess on certain surfaces, but felt that there was no evidence in the Yorkshire and Lincolnshire deposits to support the suggestion that loess accumulated only on limestone surfaces because only they possessed the correct moisture characteristics. They felt that preferential erosion of loess after its deposition on all substrata explained its present distribution better than preferential accumulation on certain rock types, because cementation with secondary carbonate derived from abundant chalk or limestone fragments commingled with aeolian silt in the head deposits provided a positive means of stabilizing loess for a fairly long period (possibly several thousand years) on the limestone surfaces. Stabilization with secondary carbonate was probably important mainly during the wettest part of the Flandrian, the Postglacial Atlantic period; since that time, decalcification of the head deposits had been completed, except where they were covered by a protective layer of till, and the diminished precipitation and run-off had failed to complete the removal of silt.

Some of the carbonate in loess outside northern England must have been wind-transported, because in southern England and many other European countries the loess commonly rested on surfaces other than periglacially disturbed limestone plateaux. However, the almost ubiquitous occurrence of carbonate in unweathered loess was surprising. In the South Island of New Zealand, where there was little limestone, the loess was virtually non-calcareous (J. D. Raeside, 1964. Loess deposits of the South Island, New Zealand, and soils formed on them. *New Zealand J. Geol. Geophys.*, **7**, 811-38), so that the widespread occurrence of carbonate elsewhere might reflect features such as the general abundance of limestones in areas subjected to Pleistocene glaciations, the ease with which limestone was physically disintegrated in glacial and periglacial environments, and its relative chemical stability under the same conditions. The occurrence of derived Chalk foraminifera in the calcareous loess of south-east England showed that at least part of the carbonate there was detrital in origin, and not a secondary deposit.

In reply to Dr. Penny, the authors explained that the Devensian till which the loess resembled most in mineralogical composition was the Drab. The till overlying the silty head deposits near the eastern margin of the Wolds had previously been referred to as the Hessle, a name which had also been applied by most workers except W. S. Bisat to the topmost layer of till throughout Holderness. However, mineralogical analyses suggested that near the Holderness coast the Hessle Till was a weathered form of the Purple Till, and that in other parts of East Yorkshire and Lincolnshire it was weathered Drab Till. In view of this it seemed best to discontinue using the name "Hessle", and to regard the Devensian till sequence of Holderness as bipartite rather than tripartite.

The authors finally thanked Professor Hemingway for reporting the occurrence of calcareous loess in the gulls of the Hambleton Hills. Similar modes of occurrence of loess were fairly common—for example, on the Hythe Beds in Kent—and probably indicated that the formation of gulls in a periglacial environment was approximately contemporaneous with loess deposition. They thought that the reddish soils north of Pickering probably contained no loess, and that the colour resulted from weathering of the sandstones, possibly under similar interglacial conditions to those which P. Bullock, D. M. Carroll and R. A. Jarvis suggested were the cause of red rinds and mottles in soils elsewhere on the North Yorkshire Moors (1973, Palaeosol features in northern England, *Nature Lond.* (Phys. Sci.), **242,** 53-54).

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LOESS IN THE SOILS OF NORTH NORFOLK

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Summary

Thin silty deposits cover large areas of north-east Norfolk, occurring mainly on gently sloping and flat plateau sites and on the floors of valleys cut in the glacial deposits. Particle size and geographic distribution of the deposits suggest that the silt is windblown. The mineralogical composition of the silt fraction resembles that of the silt of Hunstanton Till, suggesting that most of the deposit was derived as loess from outwash of the Weichselian glacier. However, at some localities the sand and clay components of the deposits were derived, at least partly, from subjacent glacial sediments of pre-Weichselian age. The distribution of the silty deposits strongly affects the pattern of soil types and sometimes the growth of crops.

Introduction

DETAILED soil mapping of Ordnance Survey Sheets TG 13 (Barningham), TG 14 (Sheringham), and TG 31 (Horning) showed widespread, thin, silty deposits in north Norfolk, overlying glacial sediments of Elsterian and Saalian age. Similar silty deposits occur in soils east of the Waveney valley near Somerleyton, Suffolk (Corbett and Tatler, 1970), and also along the Norfolk and Suffolk coastline almost continuously from Cromer to Lowestoft, capping the cliff sections. Reconnaissance of near-by areas showed that the deposits are restricted in eastern Norfolk and north-eastern Suffolk to the area shown in Fig. 1. Within this area the silty drifts form a blanket-like cover up to 2 m thick, though they are absent locally on steeper slopes, such as valley sides. In this respect they resemble the coversands of the Netherlands, and we therefore refer to them collectively as coverloam. They probably include the 'loamy drift' of Tansley (1939) in the Norfolk Broads district, but are much more extensive.

Distribution of coverloam

On the coastal plain between Cromer and Weybourne the coverloam occurs only on the floors and lower side-slopes of valleys that cut back into the north-facing slope of the Cromer ridge, but to the south of this area it covers interfluves as well as valley floors. Just south of the crest of the Cromer ridge the deposit is 0·4–0·7 m thick over glacial gravel, but it is slightly thicker in shallow concave sites at the heads of dry valleys. The deposits in a few of these dry valleys are linked via saddles across the ridge to the valley deposits on the coastal plain. Further south, the dissection of the gravels gives a local relief of 15–20 m, and the landscape consists of four distinct facets. The flat interfluve crests, which slope gently to the south, and the gentle, flat or slightly convex, northern and eastern slopes, are both covered by 0·4–0·7 m of silty drift. The narrow valley floors are linked by shallow re-entrants to concave upland sites and

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saddles; these areas have 0·7–2·0 m of silty drift, with the thickest layers on the floors of the re-entrants. The convex southern and western slopes, which are the steepest in the area, carry little or no coverloam. Towards the southern boundary of the Cromer ridge gravels, the interfluves are narrower, and the coverloam occurs mainly along valley floors and on the lower slopes of valley sides.

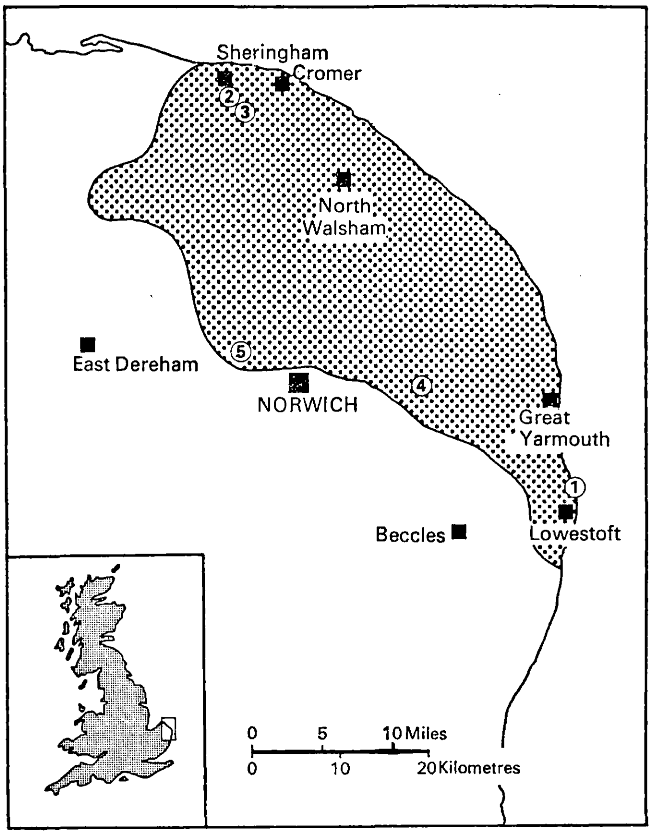

FIG. 1. The distribution of coverloam and location of sampling sites in Norfolk and Suffolk.

On the tills south and east of the gravel outcrop, the extensive flat or gently sloping interfluves have up to 0·7 m of coverloam. Thicker accumulations occur on valley floors, concave upland sites and on re-entrants, but on the steeper slopes, which generally occur to the west of gravel outliers, the coverloam is thin or absent. A similar pattern of distribution occurs on Norwich Brickearth and gravels east and north-east of Norwich (Sheet TG 31), and also on the Lowestoft Till between Beccles and Lowestoft (Sheet TM 49) in the extreme south-east of the coverloam area.

Soils

In all the soils on the silty drifts (Table 1) there is a distinct and usually abrupt textural change at the junction of the coverloam and the substrata. Below this junction the soils range in texture from sandy clays and stony clays to sands and stony sands, but the coverloam horizons are silt loams, loams, or fine sandy loams with only a few stones. Throughout most of north-east Norfolk, the surface horizons of soils are thus texturally more uniform than would be expected from the known distribution of tills and gravels. They are much more valuable agriculturally than soils without coverloam horizons, because many (Hall, Wickmere, Aylsham, and Sheringham series, and Sheringham variant) have large available water capacities, do not need draining, are easily worked, and have moderate or large reserves of many plant nutrients. The mean summer rainfall deficit for Norfolk is about 150 mm, though there is much variation from year to year. Soils developed on glacial sands with no overlying coverloam (e.g. Freckenham series) have a water-holding capacity of 100 mm or less, so that crops suffer drought in most summers. However, drought is very rare on the deep coverloam soils, such as the Sheringham series, which have a water-holding capacity of about 200 mm. During dry summers the pattern of coverloam distribution is often seen in the uneven crop growth in some fields, and partial crop failure commonly occurs on the steeper slopes which have no coverloam.

TABLE 1

*Soil series recognized on the silty drifts**

Soil descriptions	*Soil series*	
1. Thin coverloam (0·4–0·7 m) overlying glacial gravel or sand	Hall	Brown earths
2. Coverloam deeper than 1, sometimes with slight gleying at depth	Sheringham	
3. As for 2, but with clay accumulation in Bt horizons	Sheringham variant	
4. Deep coverloam	Aylsham	Gleyed brown earths
5. Thin coverloam overlying Norwich Brickearth	Wickmere	
6. Deep coverloam	Sustead	Ground-water gley soils
7. Thin coverloam overlying Norwich Brickearth	Gresham	
8. Shallow coverloam over gravels with a very organic surface horizon	Hanworth	Humic gley soils
9. Thin coverloam overlying fine-textured, chalky Lowestoft Till	Beccles (Loamy phase)	Surface-water gley soils

* Fuller descriptions of the soils are given by Corbett and Tatler (1970) and the legend of the soil map of sheet TG 13/14 (Barningham/Sheringham).

Particle size distribution

The particle size distribution and mineralogical composition of the coverloam were studied in samples from:

1. Corton Cliffs (TM 543982) near Lowestoft; overlying Lowestoft Till and 0·2 m below recent blown sand.
2. Old Wood (TG 160416) near Sheringham; overlying glacial gravel and 0·1 m below the surface (Sheringham variant).

3. Aylmerton (TG 173400); overlying glacial gravel and 0·35 m below the surface (Hall series).
4. Burlingham (TG 366109); overlying Norwich Brickearth and 0·35 m below the surface (Wickmere series).
5. Costessey (TG 152123) near Norwich; overlying glacial gravel and 0·45 m below the surface.

Fig. 1 shows the approximate location of the sites.

Each sample was dispersed in an aqueous solution of sodium hexametaphosphate (0·05 per cent w:v) by mild ultrasonic treatment. Sand fractions ($> 50\ \mu$m) were removed by sieving; the clay ($< 2\ \mu$m) and two silt fractions (2–20 μm and 20–50 μm) were separated by repeated settling in dilute suspension. The detailed particle size distribution of fractions $> 50\ \mu$m was determined by dry sieving at quarter ϕ intervals ($\phi = -\log_2 d$, where d is the particle size in mm), and the distribution at quarter ϕ intervals in the 8–105 μm range was obtained from two staggered sets of measurements at half ϕ intervals, taken with the sedimentation apparatus described by Stairmand (1950).

All five particle-size distribution curves (Fig. 2) show a large peak at approximately 40 μm, and all except sample 2 (Old Wood) have a subsidiary peak at various positions in the sand fraction. The sand was either deposited with the silt as part of the original coverloam, or was derived from sandy beds below by frost heaving or other mixing processes after deposition of the silt. Some post-depositional mixing may have occurred at the Burlingham site, where thin coverloam rests on Norwich Brickearth. This sample contains more clay than the other four (Table 2); addition of clay as well as sand would be expected here, as the Norwich Brickearth is a sandy clay loam. The Corton and Costessey samples have very similar distribution curves, but the substrata at these two sites are texturally very different, which suggests that the sand here was part of the original coverloam.

Mineralogical composition

The sand fractions ($> 50\ \mu$m) were sieved to extract the material at the subsidiary peak of each particle size distribution curve. These sands and the coarse silts (20–50 μm) from each sample were then separated into light and heavy fractions with bromoform (s.g. 2·9), and analysed mineralogically with a petrological microscope. The fine silt (2–20 μm) and clay ($< 2\ \mu$m) fractions were analysed mineralogically by X-ray diffractometry, using lightly compressed powders and oriented aggregates. Portions of the coarse and fine silt fractions were fused with sodium bisulphate to remove layer silicate minerals (Kiely and Jackson, 1964), and amounts of felspars (in terms of end members) and quartz were estimated by chemical analysis of the residues. Potassium felspar was also measured by the method of Reynolds and Lessing (1962).

The coarse silt fractions of the five samples have almost the same mineralogical composition (Table 3), which suggests that most of the coverloam material in north-east Norfolk came from only one source. Weir *et al.* (1971) reported a similar mineralogical composition for coarse

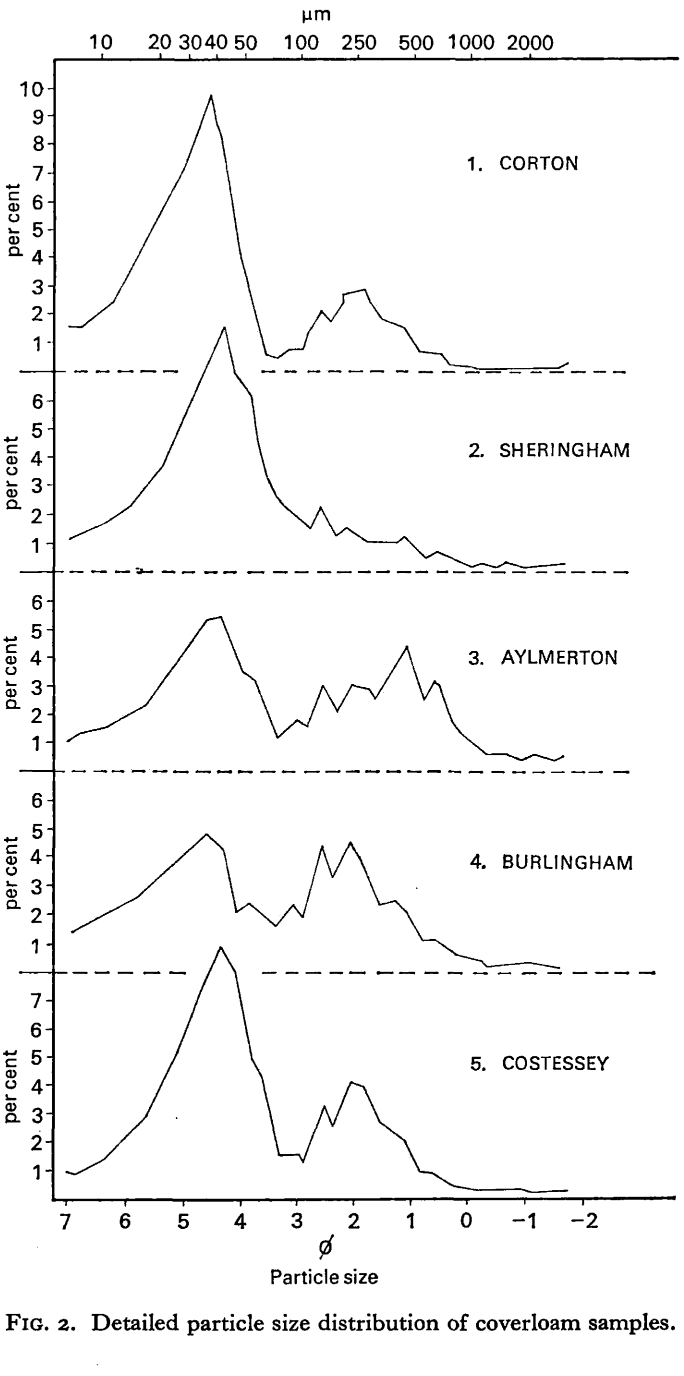

FIG. 2. Detailed particle size distribution of coverloam samples.

silt fractions from weathered horizons of the brickearth at Pegwell Bay, Kent; this deposit was recognized as loess by Pitcher *et al.* (1954), and was tentatively dated by Kerney (1965) as late Middle Weichselian (equivalent to Upper Pleniglacial of van der Hammen *et al.*, 1967). This mineralogical similarity is evident not only in the heavy mineral assemblages and relative amounts of quartz, total felspar, and flint but also in the overall composition of the felspars. The Or:Ab:An ratio[1] in the coarse silt of the Pegwell Bay loess is approximately 4:4:1, and that of the Norfolk coverloam is approximately 6:5:1 (Table 4).

TABLE 2

Particle size distribution of Norfolk coverloam samples

Size Fractions							
	Range						
	µm	*ϕ equivalent*	*1 Corton*	*2 Sheringham*	*3 Aylmerton*	*4 Burlingham*	*5 Costessey*
Gravel	> 2000	> −1·00	0·5	1·5	3·7	0·9	1·0
Sand	1000–2000	0·00 to −1·00	0·4	0·6	2·6	0·8	0·4
	500–1000	+1·00 to 0·00	1·7	1·7	8·4	2·8	1·9
	250–500	+2·00 to +1·00	7·8	4·1	13·3	10·9	10·1
	50–250	+4·25 to +2·00	16·0	27·3	22·2	23·8	30·2
Silt	20–50	+5·75 to +4·25	43·5	34·3	25·4	23·9	34·5
	5–20	+7·50 to +5·75	15·1	12·1	10·0	12·2	10·5
	2–5	+9·00 to +7·50	3·4	3·6	3·0	6·4	3·8
Clay	< 2	< +9·00	8·8	13·0	11·4	18·1	7·0
		Total	97·2	98·2	100·0	99·8	99·4

Many workers (including Rutten, 1954) suggest that loess is derived ultimately from glacial sources, mainly by deflation of silt from the surfaces of proglacial outwash plains. As the Pegwell Bay loess may be contemporaneous with the Weichselian glacial invasion of eastern England, which occurred late in the Upper Pleniglacial (Penny *et al.*, 1969), we analysed the coarse silt fractions from two samples of Hunstanton Till, the only representative of the Weichselian glacial succession in Norfolk. The results (Tables 3 and 4) show that the Weichselian glacial sediment is indeed mineralogically similar to the Norfolk coverloam and the loess of East Kent, but contains slightly less potash felspar. Silts from all pre-Weichselian glacial deposits in Norfolk that we have studied contain different heavy mineral assemblages from the coverloam; many lack abundant garnet, chlorite, and green hornblende, and so cannot have contributed much material to the coverloam. Until more is known about the silt mineralogy of English Pleistocene deposits, we therefore regard the Weichselian glacier as the most probable source of the silt in the coverloam.

The sands giving the subsidiary peaks of the particle size distributions are mineralogically more variable than the coarse silts, and so are probably derived from several sources. They contain less felspar (1–10 per cent) and heavy minerals than the coarse silt but more quartz. The

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[1] Or = orthoclase; Ab = albite; An = anorthite.

TABLE 3

Mineralogical composition of coarse silt (20–50 μm) fractions from the Norfolk coverloam, Kentish loess and the Hunstanton Till

Minerals	1 *Corton*	2 *Sheringham*	3 *Aylmerton*	4 *Burlingham*	5 *Costessey*	*Pegwell Bay, Kent**	*Holkham and Stiffkey†*
(Per cent)							
Quartz	76	76	77	76	78	74	76
Felspar	20	19	18	19	19	22	17
Flint	3	2	2	2	2	2	2
Muscovite	..	1	1	1	1	1	2
Glauconite	..	< 1	< 1	..	..	1	2
Opaque minerals (Magnetite, Leucoxone, Limonite, Haematite)	< 1	1	1	1	< 1	< 1	< 1
Non-opaque heavy minerals	0·6	0·7	0·8	0·4	0·1	0·1	0·6
(parts per thousand in non-opaque minerals)							
Epidote	306	452	431	500	366	367	375
Zircon	111	90	104	109	108	193	140
Garnet	58	53	65	49	90	73	108
Green Hornblende	199	156	154	110	183	129	140
Brown Hornblende	58	25	37	26	33	19	24
Tremolite and Actinolite	55	46	37	40	30	21	32
Chlorite	62	36	33	23	6	28	46
Biotite	3	14	3	5	12	..	5
Yellow Rutile	41	20	32	35	45	64	31
Brown Rutile	12	8	15	19	12	10	12
Red Rutile	2	4	5	3	9	6	5
Anatase	15	22	15	14	15	20	23
Brookite	..	..	2	3	..	4	4
Tourmaline	10	12	25	12	48	13	21
Zoisite	46	34	30	33	15	28	16
Staurolite	3	10	7	3	9	12	5
Kyanite	9	14	3	9	3	5	1
Apatite	..	..	..	..	..	7	5
Augite	7	4	2	7	9	..	7
Hypersthene	3	..	..	..	6	..	..
Monazite	..	..	..	..	..	1	..
Number of non-opaque grains counted	583	495	603	577	333	804	715

* Average of seven samples of decalcified loess, over Thanet Beds.

† Average of two samples of decalcified Hunstanton Till.

heavy sand mineral assemblages of the Corton, Sheringham, and Costessey samples resemble in many ways the heavy fractions of the coarse silt, though the proportions of many minerals are different, but those of the Aylmerton and Burlingham samples contain fewer minerals, and are evidently from deposits other than the coverloam.

TABLE 4

Percentage felspars (in terms of end members) in the coarse and fine silt fractions of the Norfolk coverloam

	1 *Corton*	2 *Sheringham*	3 *Aylmerton*	4 *Burlingham*	5 *Costessey*	*Hunstanton Till*
Coarse Silt (20–50 μm)						
K Felspar	9·8	9·4	9·5	9·6	9·9	7·7
Na Felspar	8·2	8·0	7·3	7·6	7·9	7·8
Ca Felspar	1·6	1·5	1·4	1·6	1·4	1·3
Total	19·6	18·9	18·2	18·8	19·2	16·8
Fine Silt (2–20 μm)						
K Felspar	11·5	11·9	11·2	10·1	11·5	..
Na Felspar	10·3	10·7	10·4	9·1	10·4	..
Ca Felspar	1·7	1·7	1·4	1·0	1·5	..
Total	23·5	24·3	23·0	20·2	23·4	..

The fine silt fractions of the coverloam contain 54–62 per cent quartz, 21–3 per cent felspar (see Table 4) and 17–24 per cent layer silicate minerals (mainly mica with small amounts of kaolinite, chlorite, vermiculite, and interstratified mica-vermiculite). The fine silt of the Pegwell Bay loess is similar in composition (Weir *et al.*, 1971, Table III), but contains slightly more quartz and felspar but less chlorite and vermiculite.

The clay (< 2 μm) fractions are composed mainly of layer silicates with only a little quartz and felspar. In the Corton, Aylmerton, and Costessey samples the layer silicates are composed of about equal amounts of kaolinite, mica, and chlorite. However, the Sheringham and Burlingham samples contain larger amounts of expanding minerals; smectite, vermiculite, and interstratified smectite-vermiculite together form at least 40 per cent of the clay fraction, and the remaining layer silicates are mainly mica and kaolinite with small amounts of chlorite and interstratified chlorite-mica. This difference reflects either various degrees of weathering in the loess or the original inhomogeneity of the clay mixed with the coverloam. However, we need to study several complete soil profiles before deciding the cause of the difference.

Conclusions

The deposits described are all composed mainly of silt that is mineralogically similar to silt in the loess at Pegwell Bay, Kent, and the Hunstanton Till of north Norfolk. We suggest that the silt was derived from Weichselian glacial outwash sediments by deflation, and is part of a thin deposit of Upper Pleniglacial loess in eastern England. Further evidence for the aeolian origin of the silt is provided by its distribution over north-east Norfolk and Suffolk. This shows that it originally formed a cover, about 0·7 m thick, over almost the entire landscape, though somewhat thicker layers accumulated in lee positions or have been built up on valley floors by downslope soil movements since the Upper Pleniglacial. Wind is the only agency capable of spreading such a cover. Some of the silt was probably secondarily transported by streams, because the floodplain alluvium of the major rivers in north Norfolk (the Bure, Ant, Thurn, and Wensum) is very silty.

The coverloam also contains small amounts of sand and clay, both of which are more variable in composition than the silt component. At some places the sand could have come from the same source as the silt, but elsewhere the sand and possibly also some of the clay were incorporated from the subjacent glacial sediments (Norwich Brickearth, Lowestoft Till, and others). Mixing probably accounts also for the stones in the coverloam, which are mainly flints with a few far-travelled erratics. Because it contains these other materials, the coverloam cannot be described simply as loess. The deposit lacks most of the characteristic features of loess listed by Russell (1944) and others, such as the presence of concretionary and disseminated carbonate. However, we are sure that loess, which has lost some characteristics by weathering and other soil-forming processes, is the main constituent of the coverloam.

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POSTGLACIAL SOIL FORMATION IN THE LOESS OF PEGWELL BAY, KENT (ENGLAND)

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ABSTRACT

This paper reports the mineralogy, micromorphology and particle size distribution of seven horizons in a buried soil developed in Weichselian loess at Pegwell Bay in southeast England. The radiocarbon date of the soil organic matter is 6,120 ± 250 years B.P., and the profile was buried by colluvium in late prehistoric times. Most of the profile development probably occurred in a few thousand years, mainly during the Postglacial climatic optimum. The composition of sand ($>50\ \mu$) and silt ($2–50\ \mu$) fractions suggests that only 10–20% of the loess was derived from the local Thanet Beds (Palaeogene). The remainder is mineralogically similar to loess in other parts of south and east England, and is probably far-travelled.

After decalcification of the loess, the main soil-forming process was translocation of fine and medium clay ($<0.5\ \mu$) from the highest 45 cm of the profile into lower horizons. However, the horizons of clay accumulation contain more fine clay ($<0.1\ \mu$) than could have been derived from the upper 45 cm. This apparent gain of fine clay results partly from the weathering of glauconite in the highest 45 cm of the profile.

INTRODUCTION

The cliffs in the northern part of Pegwell Bay (TR 3564)[1] near Ramsgate, Kent, expose approximately 4 m of brickearth overlying the Thanet Beds and Upper Chalk. White (1928, p.66) described the section at Cliffsend, which is still visible behind the hoverport, but Pitcher et al. (1954) were the first to recognise the brickearth as loess. East of the disused brickyard shown in White's cliff section (ibid., p.50), the loess is overlain in places by 1–2 m of silty hillwash containing Neolithic flint flakes. The base of the hillwash is marked by a black organic horizon, which is associated with a soil profile developed in the loess. In this paper we report a detailed petrographic study of this buried profile, and attempt to reconstruct the soil-forming processes that occurred in it. Similar processes probably occurred in many modern surface soils developed in loess, which are common in south and east England. However, their effects in

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[1] National Grid Reference (Great Britain).

these soils have been largely obscured either by the changes resulting from more recent natural processes or by modern agricultural practices. A study of buried soils developed in the same parent material as present-day soils can therefore help the pedologist to reconstruct the often complex history of geological and pedological changes that many modern soils have undergone.

ANALYTICAL METHODS

Samples from each horizon recognised in the buried profile were treated with 2*N* acetic acid to remove calcium carbonate and with 12% hydrogen peroxide to remove organic matter, and were then dispersed in 0.05% w/v sodium hexametaphosphate solution by mild ultrasonic agitation. The samples were suspended in thick glass beakers in a 5-l tank agitator rated at 200 W at 25 kHz. Sand fractions were removed with a 50 μ sieve, and the clays ($<2\ \mu$) and two silt fractions (2–20 μ and 20–50 μ) were separated by repeated sedimentation in dilute suspension. The fine sands (50–250 μ) and coarse silts were separated into light and heavy fractions with bromoform, and analysed mineralogically with a petrological microscope. The clay fractions were further divided by centrifugation into coarse (0.5–2 μ), medium (0.1–0.5 μ) and fine ($<0.1\ \mu$) clays.

The fine silts and three clay fractions were analysed mineralogically by X-ray diffractometry of lightly compressed powders and oriented aggregates, and by chemical methods. Portions of each were fused with sodium bisulphate to remove layer silicate minerals (Kiely and Jackson, 1964), and the amounts of quartz and feldspars (in terms of end members) were estimated by chemical analysis of the residues. Amounts of mica and interstratified mica layers were calculated from the quantities of non-feldspar potassium in the original size fractions, assuming that mica contains 10% K_2O (Jackson, 1956). The composition of feldspars in the coarse silts was determined from the amounts of potassium, sodium and calcium in the light fractions after allowing for the potassium in mica and glauconite. Free iron oxide in fractions $<50\ \mu$ was determined by extraction with sodium dithionite in a citrate buffer, and amounts of amorphous silica and alumina in the fine clays were estimated by sodium hydroxide extraction (Hashimoto and Jackson, 1960). The percentage of layer silicates other than mica in the clay and fine silt fractions was obtained by subtracting amounts of quartz, feldspar, mica, free iron oxide and amorphous silica and alumina from 100%, and their relative proportions were calculated from their basal reflection intensities. Carbonate and organic carbon were determined by a modification of Shaw's (1959) method.

Particle size distribution was determined by separating the sand fractions ($>50\ \mu$) at $\frac{1}{4}\phi$ intervals with sieves, and by taking two staggered sets of measurements at $\frac{1}{2}\phi$ intervals from 5 to 150 μ with the sedimentation apparatus described by Stairmand (1950). The micromorphology of the soil horizons was studied in thin sections, and the morphology of clay particles was examined with an electron microscope. Soil pH was measured with a laboratory meter, using a mixture of 10 g soil and 25 ml distilled water.

FIELD DESCRIPTION OF THE PROFILE AND SITE

The profile studied was exposed beside the sloping pathway to the beach (National Grid reference TR 353643), approximately 100 m east of the viking ship; Fig.1 shows its relationship to the surrounding deposits. The profile is overlain by 1.3 m of hillwash, in which the modern soil is developed. Considerable erosion of the loess occurred before the buried soil developed, because the loess is much thinner here than on the opposite (western) side of the old brickpit. The soil formed in a broad hollow or channel cut in the loess, which was later partly filled with the hillwash. At the profile site the loess is 1.5 m thick, and rests on a thin solifluction gravel composed of angular flint fragments, chalk pellets and Thanet Beds sand, and this in turn rests on disturbed Thanet Beds.

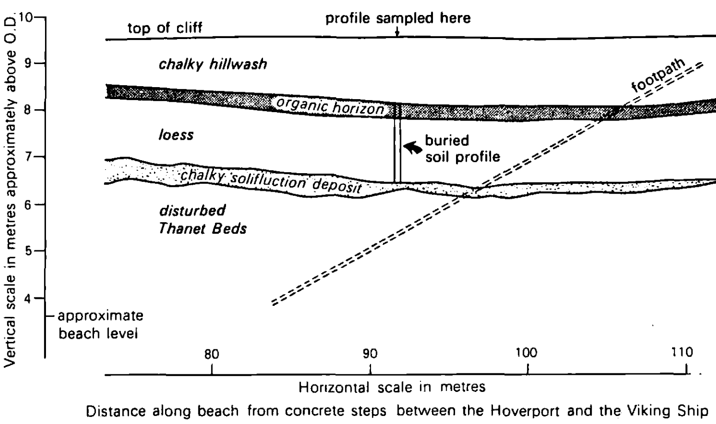

Fig.1. Cliff section near Cliffsend (Kent), showing relationship of the buried soil profile to surrounding deposits.

Seven horizons were recognised in the buried profile:

Depth (cm)	Horizon	Description
0–19	1	Very dark brown (10YR 2/2) to black (10YR 2/1) humose silt loam; organic matter intimate and largely amorphous to the naked eye; structureless; very friable when moist, but brittle when dry; abundant fine and very fine pores; a few locally concentrated fine fibrous living roots; a few calcareous concretions; pH 8.0. A merging boundary with the hillwash above and narrow undulating boundary below.
19–29	2	Very dark brown (10YR 2/2) humose silt loam, with many streaks and patches of light grey (10YR 7/2) silt loam; very weakly developed sub-angular

Depth (cm)	Horizon	Description (continued)
		blocky structure; pores and roots as in horizon 1; pH 8.0. Fairly sharp boundary at base.
29–45	3	Light grey (10YR 7/2) silt loam, with horizontal streaks of light yellowish brown (10YR 6/4) and dark brown (7.5YR 3/2) silt loam, and many distinct very dark brown (10YR 2/2) organic speckles; structureless, but the horizontal laminae give a weak horizontal parting; pores as in horizon 1; fewer roots than above; very friable; pH 7.8. Sharp boundary at base.
45–69	4	Brown (7.5YR 4/4) silt loam, with many yellowish brown (10YR 5/8) and a few greyish brown (10YR 5/2) mottles, and some darker (5YR 2/2) structural faces; organic speckles as in horizon 3; weakly developed coarse prismatic structure, breaking to coarse sub-angular blocks; abundant very fine pores; firm consistence; rare fine fibrous living roots along structural faces; pH 7.4. Merging boundary at base.
69–103	5	Greyish brown (10YR 5/2) silt loam, with many strong brown (7.5YR 5/8) mottles and some darker (5YR 2/2) structural faces; organic speckles as in horizon 3; structure, pores, consistence and roots as in horizon 4; pH 7.5 Merging boundary at base.
103–130	6	Greyish brown (10YR 5/2) silt loam, with many strong brown (7.5YR 4/6) mottles; organic speckles as in horizon 3; very weakly developed coarse prismatic structure; friable consistence; fewer roots than in horizons 4 and 5; pores as in horizon 4; pH 7.5. Merging boundary at base.
130–152	7	Greyish brown (10YR 5/2) silt loam, with many strong brown (7.5YR 4/6), brownish yellow (10YR 5/8) and pale brown (10YR 6/3) mottles; organic speckles as in horizon 3, but slightly less common; structure, consistence and roots as in horizon 6; slightly fewer pores than in horizon 6; pH 7.9. Sharp boundary at base.
152+		Angular flinty gravel.

Unaltered loess does not occur in the profile, because even in the lowest horizon the soil is mottled and decalcified. Loess that is almost completely unaffected by soil-forming processes occurs west of the old brickpit at depth below the modern soil profile (Dalrymple, 1969); this deposit is strongly calcareous and has an almost uniform yellow-brown (10YR 5/4) colour.

RADIOCARBON DATING

A 500 g sample of horizon 1, containing originally 1.2% organic C, was treated with $2N$ hydrochloric acid to remove calcium carbonate, and the residue was washed many times with distilled water. The fibrous roots that penetrate the profile from the modern soil on the hillwash were removed by handpicking and by centrifuging after each water wash. Centrifugation also separated much of the colloidal organic matter from the sample. The carbon in the material submitted for dating therefore occurred almost entirely in relatively inert organic particles ranging from 2 to 100 μ, so that contamination with modern organic matter or calcium carbonate was minimised.

The date obtained was 6,120 ± 250 years B.P. (sample no. I-3538). This does not give the time of burial of the profile, because much of the organic matter in the soil would already be quite old when that happened. The date is equivalent to that of a homogeneous sample of organic matter with the same $\delta\ ^{14}C$ value as the heterogeneous sample analysed, so that the difference between this and the date of burial depends mainly on the rate of renewal of organic matter during soil formation. At present the best estimates of this difference are based on radiocarbon dating of the organic matter in the highest 20–30 cm of modern soil profiles developed wholly or partly in loess. Scharpenseel et al. (1968) reported equivalent ages of 1,210 ± 70 and 1,340 ± 80 years for the organic matter at a depth of 10–20 cm in two chernozems, and Jenkinson (1969) gave 1,280 ± 125 and 1,385 ± 140 years for the equivalent ages of organic matter in the highest 23 cm of two soils from Rothamsted Farm (Harpenden, England). These suggest that the Pegwell Bay profile was buried about 5,000 years B.P., which agrees approximately with Kerney's suggestion (1965) that the overlying colluvium resulted from soil erosion following forest clearance during late prehistoric (i.e.,Subboreal) times. The period of soil formation therefore included the Atlantic period (approximately 5,000–7,000 years B.P.), which was the Postglacial climatic optimum, a time of warm and probably rather wet conditions.

PARTICLE SIZE DISTRIBUTION

The detailed particle size distribution of samples from horizons 1–7 (Table I) shows that there are only a few small textural variations in the profile. Horizon 7 contains slightly more sand than higher horizons, probably because some Thanet Beds sand was incorporated in the basal layers of the loess. The silt and coarse clay fractions show no significant variations through the profile. However, horizon 3 contains rather less fine clay than horizons 1, 2 and 7, and considerably less than horizons 4, 5 and 6; the same is true, but to a lesser extent, of the medium clay fractions. This suggests that some fine and medium clay was eluviated from horizon 3 and redeposited in horizons 4, 5 and 6.

The mean particle size, standard deviation, skewness and kurtosis of the fractions coarser than 7.0ϕ ($8\ \mu$) in each horizon were calculated by moment summation. This eliminated the differences between horizons caused by movement of the finest soil particles through the profile, and allowed a further quantitative granulometric comparison to be made between the skeletal components of each horizon. The lower limit of $7.0\ \phi$ was imposed by the lack of data at $\frac{1}{4}\phi$ intervals in fractions finer than this. The ranges of calculated values for the four moments are extremely small. The

TABLE I

Detailed particle size distribution of samples from horizons 1–7 of buried soil profile in loess at Pegwell Bay, Kent

	ϕ divisions	μ equivalent	1	2	3	4	5	6	7
Sand	> 1.25	> 420	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	1.50–1.25	355–420	0.0	0.0	0.0	0.0	0.0	0.0	0.1
	1.75–1.50	300–355	0.1	0.0	0.0	0.0	0.0	0.1	0.2
	2.00–1.75	250–300	0.1	0.0	0.0	0.0	0.0	0.1	0.3
	2.25–2.00	210–250	0.1	0.1	0.0	0.0	0.0	0.1	0.3
	2.50–2.25	180–210	0.1	0.1	0.1	0.0	0.0	0.1	0.3
	2.75–2.50	150–180	0.1	0.1	0.1	0.1	0.1	0.1	0.3
	3.00–2.75	125–150	0.1	0.1	0.1	0.1	0.1	0.2	0.4
	3.25–3.00	105–125	0.3	0.2	0.3	0.2	0.2	0.2	0.4
	3.50–3.25	90–105	0.5	0.4	0.6	0.4	0.3	0.4	0.6
	3.75–3.50	75– 90	1.2	1.3	2.0	1.4	1.0	1.1	1.2
	4.00–3.75	63– 75	3.0	3.6	5.0	3.1	2.6	2.8	2.7
	4.25–4.00	53– 63	6.5	7.5	9.1	7.8	6.3	6.8	7.1
Silt	4.50–4.25	44– 53	8.5	9.6	10.2	9.7	9.3	9.1	9.2
	4.75–4.50	37– 44	9.3	10.6	11.6	9.9	10.0	10.8	10.6
	5.00–4.75	31– 37	9.2	9.6	10.4	9.5	9.2	9.7	10.2
	5.25–5.00	26– 31	7.8	8.2	8.7	7.8	7.4	7.8	8.4
	5.50–5.25	22– 26	6.0	6.7	7.0	6.3	6.1	6.3	6.8
	5.75–5.50	19– 22	5.1	5.2	5.5	5.0	4.7	5.0	5.3
	6.00–5.75	16– 19	4.2	4.2	4.3	4.0	3.7	3.7	4.0
	6.25–6.00	13– 16	3.4	3.3	3.4	3.2	3.2	2.9	3.0
	6.50–6.25	11– 13	2.7	2.8	2.7	2.6	2.5	2.4	2.3
	6.75–6.50	9– 11	2.2	2.2	2.1	2.1	2.1	1.9	1.7
	7.00–6.75	8– 9	1.8	1.9	1.8	1.8	1.7	1.5	1.5
	9.00–7.00	2– 8	7.0	6.0	5.9	4.4	4.9	4.3	4.7
Clay	11.00–9.00	0.5–2	3.9	4.0	3.5	3.3	2.9	2.5	2.3
	13.00–11.00	0.1–0.5	4.1	3.3	1.3	4.4	5.1	4.9	4.0
	< 13.00	< 0.1	9.4	7.2	2.8	12.7	16.1	15.1	9.9

mean grain size ranges from 4.92 to 5.01 ϕ (31–33 μ), and the range of standard deviation is 0.62–0.75 ϕ, or 0.62–0.70 ϕ if horizon 7 is excluded. There is a slight (but probably insignificant) positive skewness in horizons 1–6 (0.08–0.42), but a small negative skewness (–0.32) in horizon 7. Kurtosis ranges from 2.7 to 3.6 in horizons 1–6, and is 4.3 in horizon 7. These values indicate that no significant differences are detectable by particle size analysis at $\frac{1}{4}$ ϕ intervals between the skeletal components of horizons 1–6, but that horizon 7 differs slightly from these, because it contains a little more fine sand.

MICROMORPHOLOGY

Thin sections of the soil horizons provide further evidence for the eluviation of clay in the profile. All the horizons have a mainly argillasepic porphyroskelic microfabric (using the terminology of Brewer, 1964, chapter

14). In horizons 4 and 5 all the soil voids are thickly lined with oriented, birefringent clay. Similar argillans occur in horizons 6 and 7, but they become thinner and less common downwards, so that in horizon 7 the amounts of redeposited clay are very small. The main horizons of illuvial deposition are therefore 4 and 5. In horizon 4 some masses of oriented clay are embedded in the soil matrix; these probably originated as void argillans, but were later redistributed, possibly by soil fauna.

Argillans do not occur in horizon 3, which is the main eluvial horizon in the profile. However, a few thin cutans do occur in horizons 1 and 2. It is unlikely that these resulted from soil formation in the buried profile, because horizons 1 and 2 are separated from the zone of clay deposition by horizon 3, which has no cutans. As they occur mainly in channels formed by roots penetrating from the present soil, they probably originated during the more recent period of soil formation after the hillwash was deposited. The carbonate concretions, which form 0.53% of the air-dried soil in horizon 1 and 0.14% in horizon 2, also originated from material translocated from the modern soil.

The yellowish brown mottles in horizon 4 and the strong brown ones in horizons 5–7 are seen in thin sections as areas of iron concentration, which are dense in the lowest two horizons and become progressively more diffuse upwards. They result from the local movement of iron in reducing conditions caused by poor drainage in the profile. Mottling is not visible in horizons 1–3 in the field, but poor drainage is indicated in thin sections by diffuse areas of iron concentration. However, evidence of poor drainage is lacking in the overlying hillwash, which has no mottles and shows in thin section an almost even distribution of iron compounds. This suggests that the present site drainage is good, and that the poor drainage in the buried profile occurred before the hillwash was deposited.

SAND MINERALOGY

The sand fractions from all horizons of the buried profile are composed of 85–87% quartz, 6–12% feldspar, 2% flint fragments, 1–4% muscovite, 0–2% glauconite and small amounts of heavy minerals. Pitcher et al. (1954, p.24) and Kerney (1965) noted the mineralogical similarity of coarser fractions in the Pegwell Bay loess to those of the underlying Thanet Beds. Our analyses of the Thanet Beds (Weir and Catt, 1969) and the loess show that the same sand minerals occur in both deposits, but that the relative amounts of some species are significantly different. In particular, the loess contains approximately three times as much feldspar, epidote and amphibole, and at least ten times as much chlorite and muscovite as the Thanet Beds, but has less quartz and flint. This suggests that, although some of the sand in the loess was derived from the Thanet Beds, a large proportion (probably $> 50\%$) came from another source. This source was probably quite distant, because we know of no deposit older than the loess in eastern Kent that contains large amounts of sand-sized feldspar, muscovite, chlorite, epidote and amphiboles. Horizon 7 contains slightly more Thanet Beds sand than the higher horizons of the profile, because its content of far-travelled sand (feldspar etc.) is smaller.

Small amounts of opaline silica occur in horizons 1 and 2; this is mainly in phytoliths derived from the stems of plants that grew in the soil. Almost all the glauconite in the profile is partly altered to iron oxide (limonite), but in horizons 1–3 this alteration has proceeded so far that little or no recognisable glauconite remains. Samples of the least altered glauconite were separated electromagnetically from the fine sand and coarse silt fractions of horizon 7, then disaggregated by violent ultrasonic treatment (the particles were suspended within 10 mm of the top of an ultrasonic probe rated at 60 W at 20 kHz), and examined by X-ray diffractometry of oriented aggregates. Both consisted of mica giving a broadened 10 Å basal reflection, and poorly crystallised interstratified minerals composed of complex mixtures of chloritic, vermiculitic and montmorillonitic layers.

COARSE SILT MINERALOGY

The coarse silt fractions contain 75–77% quartz, 21–23% feldspar, 1–3% flint, 0.6–2% muscovite, 0–2% glauconite and $< 0.3\%$ total heavy minerals. The heavy mineral suite resembles that of sand fractions in the loess, but epidote, amphibole and chlorite are slightly more abundant. The coarse silt of the Thanet Beds yields 5–20 times as large a heavy fraction as the coarse silt of the loess. Both contain the same heavy mineral species (Weir and Catt, 1969, p.21), but the heavy fraction of the loess coarse silt has 2–3 times as much chlorite as that of the Thanet Beds coarse silt, and epidote and amphibole are as much as 20 times more common. This suggests that the amount of Thanet Beds derived coarse silt in the loess is certainly $< 10\%$, and may be $< 5\%$.

The composition of light fractions also indicates that most of the coarse silt in the loess is not derived from the Thanet Beds. The quartz particles in the loess are much more angular than those in the Thanet Beds, and flint is approximately 5 times more abundant in the Thanet Beds than in the loess. Also, feldspar is at least twice as abundant in the loess as in the Thanet Beds, and its overall composition in terms of end members is different; in the loess the ratio Or:Ab:An is approximately 4:4:1 (Table II), whereas the ratio in the Thanet Beds is 13:12:1. The mineralogical composition of far-travelled material in the coarse silt fraction of the loess is similar to that in the fine sand, except that amounts of muscovite are smaller. In both fractions, the far-travelled component contains moderate amounts of feldspar and a little muscovite, epidote, amphibole, and chlorite, but consists mainly of angular quartz. Small amounts of other heavy minerals might also have come from distant sources, but the similarity of these minerals to the heavy fractions of the Thanet Beds suggests that they are mainly local in origin. As in the sand fractions, the glauconite is partly oxidised in lower horizons of the profile, and has been almost completely removed from horizons 1–3.

FINE SILT MINERALOGY

The fine silt fractions contain 58–66% quartz, 23–25% feldspar (Table II), 8–16% layer silicate minerals and 0.6–1.0% iron oxides. The layer

TABLE II

Overall composition (in terms of end members) of feldspar in the coarse silt, fine silt and coarse clay fractions of samples from horizons 1–7 of buried soil profile in loess at Pegwell Bay, Kent

	1	2	3	4	5	6	7
Coarse silt (20–50 μ)							
% K feldspar	9.1	9.1	9.5	8.7	10.0	10.0	10.0
% Na feldspar	9.5	9.5	9.5	9.5	9.5	10.0	10.0
% Ca feldspar	2.3	2.3	2.5	2.5	2.5	2.7	2.8
Total	20.9	20.9	21.5	20.7	22.0	22.7	22.8
Fine silt (2–20 μ)							
% K feldspar	11.8	12.0	11.9	11.5	12.0	12.3	12.9
% Na feldspar	11.6	11.1	10.7	10.3	10.2	10.3	10.7
% Ca feldspar	1.4	1.6	1.5	1.5	1.5	1.6	1.8
Total	24.8	24.7	24.1	23.3	23.7	24.2	25.4
Coarse clay (0.5–2 μ)							
% K feldspar	8.3	7.1	8.0	6.4	6.8	7.3	8.2
% Na feldspar	5.8	5.1	4.3	3.9	3.8	3.8	4.1
% Ca feldspar	0.5	0.5	0.6	0.6	0.5	0.5	0.6
Total	14.6	12.7	12.9	10.9	11.1	11.6	12.9

silicates are mica, vermiculite, chlorite, kaolinite and randomly interstratified mixtures of mica-chlorite, vermiculite-chlorite and vermiculite-montmorillonite. These minerals give sharper and more intense basal X-ray reflections than layer silicates in the clay fractions. Their diffraction intensities are enhanced by differential settling in the oriented aggregates used for diffractometry, in which the layer silicates form well-oriented skins covering the sub-equant quartz and feldspar grains. The sharpness of their diffraction reflections suggests that they occur largely in true silt-sized particles, and not as silt-sized aggregates of clay particles. This is also indicated by the fact that the kaolinite is thermally stable to 550°C, whereas the kaolinite in the clay fractions is stable only to 500°C. Optical examination of the fine silts confirmed the presence of mica-like flakes as large as 15 μ across, but also showed that glauconite-like aggregates occur in horizons 4–7. However, the aggregates probably account for only small amounts of the layer silicates. At least two types of mica flakes were recognised. Some were colourless and slightly birefringent, but others were brownish-green and almost isotropic, with refractive indices in the basal plane ranging from 1.59 to 1.61. Amounts of the first type, which is probably muscovite, seem to be constant through the profile, but there is an evident upward decrease in amounts of the brownish-green mica. This mineral is probably an iron-rich vermiculite, but some of the flakes, which have refractive indices greater than is usual for vermiculite, may contain interstratified chloritic layers.

The fine silt fractions of the Thanet Beds (Weir and Catt, 1969, p.23) differ from those of the loess in containing montmorillonite and more mica, but less quartz and feldspar. As in the coarse silts, the feldspars as a whole (Table II) are slightly more calcic than those of the Thanet Beds. Also, some of the layer silicates in the loess are absent or rare in the Thanet Beds, and clinoptilolite, which occurs abundantly in fine silt fractions of the basal Thanet Beds (Brown et al., 1969), was not detected in the buried profile. These differences suggest that the amount of Thanet Beds derived fine silt in the loess is very small, probably even less than the amount of coarse silt from that source.

The differences in amounts of most layer silicates in the fine silt fractions through the profile are small, and probably reflect only the range of mineralogical composition of the original loess. However, the upward decrease in amounts of expanding minerals (Table III) might have been caused by weathering. This decrease results partly from the smaller amounts of vermiculite in higher horizons, which could be traced by the lessening of the 14 Å basal X-ray reflection as well as by optical examination, and partly from the absence of interstratified vermiculite-montmorillonite from horizon 1.

CLAY MINERALOGY

The coarse clay fractions (0.5–2 µ) contain 23–28% quartz and 11–15% feldspar, and the medium clays (0.1–0.5 µ) 8–13% quartz and 2–5% feldspar, but neither mineral was detected in the fine clay fractions (< 0.1 µ). The amounts of free iron oxides increase with decreasing particle size as far as the medium clay fractions (Table III), and are generally greater in lower horizons, especially 4, 5 and 6, than in higher. Lepidocrocite was detected by X-ray diffraction in the fine silt and all clay fractions of horizons 4–6, and there was a broad, weak goethite reflection in the fine clays of horizons 3–7, but the nature of the remaining iron oxides is unknown.

In the coarse clay fractions the amounts of layer silicate minerals increase from a total of 53% in horizon 1 to 58% in horizon 6. These minerals are fairly well crystallised and orient strongly, giving moderately intense basal X-ray reflections. Most of the potassium in the layer silicates occurs in the phase that has a 10 Å basal spacing, but a little is in interstratified mica-chlorite. Nevertheless, mica is the most abundant layer silicate in the coarse clays.

The expanding minerals in the coarse clays are complex, and change slightly with depth in the profile. Mg-saturated, air-dried specimens from all horizons give an intense X-ray reflection corresponding to a basal spacing of 14.5–14.7 Å and also an area of continuous scattering between 14.5 Å and the mica reflection at 10 Å. Glycollation of the coarse clay from horizon 1 diminishes both the intensity of the 14.5 Å reflection and the scattering between 10 Å and 14.5 Å, and gives a small reflection corresponding to spacings of 15–16 Å (Fig.2). In horizon 2 glycollation produces a small broad reflection corresponding to an 18 Å basal spacing, and also an area of continuous scatter between 18 Å and 14.5 Å. In horizons 3–7 the scattering between 10 Å and 14.5 Å decreases almost to background level after glycollation, and the intensity of the 18 Å reflection in glycollated specimens gradually increases with depth (Fig.2). The expanding minerals in coarse clays from all horizons collapse to a 10 Å interlayer spacing when heated to 335°C. K-saturation also collapses the expanding minerals of horizons 1 and 2 to 10 Å, but in lower horizons this collapse is only

TABLE III

Composition of fine silt and clay fractions from horizons 1–7 of buried soil profile in loess at Pegwell Bay, Kent

	Fine silt (2–20 μ)							Coarse clay (0.5–2 μ)							Medium clay (0.1–0.5 μ)							Fine clay (<0.1 μ)						
Horizon:	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
% fraction in soil	26	25	25	23	23	22	22	3.9	4.0	3.5	3.3	2.9	2.5	2.3	4.1	3.3	1.3	4.4	5.1	4.9	4.0	9.4	7.2	2.8	12.7	16.1	15.1	9.9
% mica and interstratified mica layers	7	6	6	7	7	8	7	25	26	23	23	22	22	23	34	36	31	28	29	31	29	18	18	19	20	20	22	21
% expanding minerals, interstratified expanding layers and chlorite	2	3	4	5	8	7	6	23	25	25	25	26	28	27	29	32	35	40	36	39	40	62	61	59	60	60	61	59
% kaolinite	–	1	1	3	1	1	1	5	5	8	10	9	8	8	13	14	16	10	12	12	11	3	4	4	2	2	3	2
% quartz	66	65	63	60	58	59	60	28	27	27	26	25	23	24	13	11	8	12	10	8	8	–	–	–	–	–	–	–
% feldspar	25	25	24	23	24	24	25	15	13	13	11	11	12	13	5	2	2	3	3	2	4	–	–	–	–	–	–	–
% amorphous SiO_2 (NaOH soluble)	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	6.2	6.5	5.9	6.7	6.3	5.3	5.2
% amorphous Al_2O_3 (NaOH soluble)	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	4.5	4.3	4.5	4.6	4.2	3.8	3.9
% FeO(OH) (dithionite soluble)	0.7	0.6	0.6	0.9	1.0	1.0	0.8	4.1	4.4	4.1	4.5	6.7	7.2	4.9	5.6	5.4	7.6	6.7	9.8	8.1	7.7	5.8	5.8	7.8	6.1	5.7	5.2	7.6
Lepidocrocite (Le)	–	–	–	Le	Le	Le	–	–	–	–	Le	Le	Le	–	–	–	–	Le	Le	Le	–	–	–	–	Le	Le	Le	–
Goethite (Go)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Go	Go	Go	Go	Go

Note: nd = not determined.

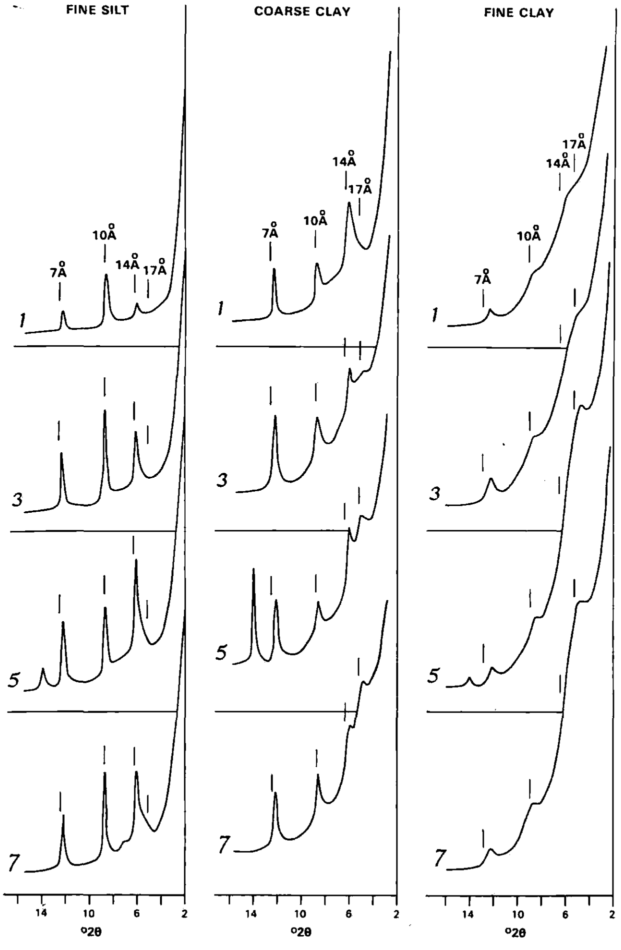

Fig.2. X-ray diffractometer traces of glycollated fine silt, coarse clay and fine clay from horizons 1, 3, 5 and 7 of the buried soil profile.

partial and subsequent glycollation causes a little re-expansion. The expanding minerals in the coarse clay of horizon 1 are therefore vermiculite and interstratified vermiculite-mica and vermiculite-montmorillonite. Lower horizons contain vermiculite and montmorillonite, and the proportion of montmorillonite increases with depth. Horizons 2–4 also contain interstratified vermiculite-montmorillonite, which gives a continuous scatter of X-rays between the 18 Å and 14.5 Å reflections. The expanding minerals in the lowest horizon of the profile are therefore almost entirely freely-expanding, but those in higher horizons become progressively less freely-expanding upwards, and horizon 1 has no freely-expanding coarse clay minerals. Although it is convenient to use different mineral names, all the expanding minerals in this and other size fractions are probably genetically related members of a single series, which extends from freely-expanding montmorillonite through interstratified vermiculite-montmorillonite, vermiculite and interstratified vermiculite-mica towards pure, non-expanding mica.

Layer silicate minerals are more abundant in the medium clay fractions than in the coarse clays (Table III). The expanding minerals in horizons 1 and 2 are vermiculite and interstratified vermiculite-montmorillonite and vermiculite-mica. The interstratified vermiculite-montmorillonite is more freely-expanding than that in the coarse clay from horizon 1, as it expands on glycollation to 16.5 Å. In horizon 3 there is much vermiculite, some interstratified vermiculite-mica, and a montmorillonite that expands to 17 Å, but no interstratified vermiculite-montmorillonite. In lower horizons the amounts of vermiculite and interstratified vermiculite-mica decrease downwards, and montmorillonite increases. As in the coarse clays, the expanding minerals thus expand less freely in higher horizons than in lower.

In the fine clay fractions kaolinite gives a small broad reflection corresponding to a basal spacing of 7.2 Å, and mica gives a small 10 Å reflection, which is broader in higher horizons than in lower. The only expanding mineral in the fine clay of horizons 4–7 is montmorillonite, but in higher horizons there is also some interstratified vermiculite-montmorillonite, which has a basal spacing after glycollation of approximately 15 Å. In horizon 3 the reflection from this interstratified mineral is a prominent shoulder on the main montmorillonite diffraction peak (Fig.2); in horizon 2 it is a smaller shoulder, and in horizon 1 the two merge into a single broad reflection covering spacings of 15–17 Å. The montmorillonite in horizon 7 expands to almost 18 Å, and that in horizons 5 and 6 expands to 18.5 Å (**Fig.2**). The expanding minerals from all horizons collapse to a 10 Å basal spacing at 335°C and to 9.7 Å at 525°C. K-saturation collapses the layers to 10 Å and 12.5 Å; subsequent glycollation causes little or no re-expansion in the fine clay of horizon 1, but gives increasing amounts of re-expansion to 15 Å in horizons 2–4. The montmorillonite in horizon 5 re-expands to almost 17 Å, but that in horizons 6 and 7 re-expands to only 15 Å. The most freely-expanding fine clay minerals therefore occur in horizon 5, where there is the maximum accumulation of translocated clay, and not, as in the medium and coarse clay fractions, in the lowest horizon.

Table III gives the amounts of amorphous SiO_2 and Al_2O_3 in the fine clay fractions. These decrease slightly with depth in the profile, but the SiO_2/Al_2O_3 ratio is approximately 1.4 throughout. This suggests that small amounts of amorphous material were formed by breakdown of aluminosilicate minerals in the higher horizons of the profile.

DISCUSSION AND CONCLUSIONS

The soil parent material

Mineralogical comparison of different size fractions $> 2\,\mu$ from the buried profile and the Thanet Beds (Weir and Catt, 1969) shows that only a small part of the soil material was derived from the Thanet Beds. A large proportion of the sand is mineralogically similar to the Thanet Beds sand, but sand comprises only 10–14% of the total soil. In finer fractions (2–50 μ) the amount of material derived from the local Thanet Beds is much less, and we estimate that only 10–20% of the total soil material was so derived. The source of the remainder is unknown, but is probably distant from southeast England.

The difference in amounts of material derived from Thanet Beds in the sand and silt fractions suggests wind transportation, because sand is rarely carried far by wind and therefore should be mainly local in origin, whereas silt can be carried much further. Also, the mineralogical composition of the material not derived from the Thanet Beds is similar to that of a silty deposit found in soils of the Chilterns (Avery et al., 1959; Weir et al., 1969) and the South Downs (Hodgson et al., 1967), and the petrographic uniformity of such widespread superficial deposits occurring in various geomorphic situations is consistent only with wind transportation. We therefore agree with Pitcher et al. (1954) and Tilley (1961) that the brickearth deposits in northeast Kent are part of the European Pleistocene loess cover.

The clay (< 2 μ) in the loess is probably derived from the same sources as the silt. There are small differences between size fractions, but they are gradational. For example, the ratio of layer silicate minerals to quartz and feldspar increases with decreasing particle size, and the assemblage of layer silicates also changes slightly from fraction to fraction; however, these changes are gradual and result partly from weathering in the profile and partly from the natural inclination of some minerals to occur in particles of a limited size range determined by their physical and chemical stabilities. There are no sharp discontinuities between size fractions that would indicate different source materials. However, it is not clear whether the clay was carried by the wind as discrete particles, as silt-sized aggregates, or as coatings on silt particles.

The radiocarbon date of the soil organic matter defines the age of the loess merely as older than the Postglacial climatic optimum. However, the unweathered nature of most of the loess west of the old brickpit suggests it is not pre-Weichselian, and Kerney's suggestion (1965) of a late Middle Weichselian age (approximately 14,000–30,000 years B.P.), based on a comparison with the aeolian deposits of continental Europe, seems the most likely.

Profile development

The profile was buried approximately 5,000 years B.P., and this event probably caused most of the soil-forming processes in it to cease. However, the start of soil formation in the buried profile is more difficult to date. At least 2–3 m of loess were removed before the profile developed to its present form, but some soil-forming processes affecting the lowest 1.5 m of loess might have started before erosion ceased. The earliest phases of profile development could therefore be as old as Middle Weichselian. However, it is extremely unlikely that such a well-developed and undisturbed profile could either attain anything like its present form during the Middle or Late Weichselian cold periods, or survive unaltered the periglacial soil activity of those times. Also, as there are no impervious deposits near the buried soil and the site is now well-drained, the poor drainage conditions indicated by mottling must have occurred during a much wetter period than the present. The rapid growth and decay of plants leading to formation of a thick organic horizon also depended on a wet and relatively warm climate. Taken together, these features suggest that most of the profile development occurred during the 5,000–6,000 years after the younger Dryas period (Late Glacial zone III), and that some of the soil-forming processes depended largely on the more oceanic climate of the Atlantic period (Postglacial zone VIIa).

Although decalcification was an important soil-forming process, no evidence of it remains in the buried profile, because it was fully decalcified. Early in the development of the profile, carbonate was probably redeposited in lower parts of the loess, but later the dissolved bicarbonate was carried into the underlying deposits. The present pH is no indication of the pH during soil formation, because the rate of leaching would have diminished greatly after the profile was buried, and because horizons 1 and 2 are now within the zone of carbonate redeposition of the modern soil.

Translocation of fine and medium clay from horizons 1–3 to lower horizons is indicated by the differences in particle size distribution of these horizons and by the cutans of oriented clay in horizons 4–7. This process could not occur until at least the higher parts of the profile were decalcified, because the deflocculation necessary to move the finer clay particles (Soil Survey Staff, 1967, p.11) is inhibited by calcium ions. The exact amount of clay removed from horizons 1–3 cannot be determined, because horizons 1 and 2 have received some clay from the modern soil profile developed in the hillwash, and because a little clay was lost from the profile as a whole by eluviation into the underlying solifluction gravel and Thanet Beds. However, these gains and losses were quite small, and the magnitude of clay translocation can be estimated approximately by comparing the total amounts of fine and medium clay in the illuvial and eluvial horizons with those in unaltered loess. No unaltered loess is present in the profile, but the composition of horizon 7 is close enough to that of unaltered loess for this calculation, because it contains only small amounts of redeposited clay.

Assuming that the original loess was similar to horizon 7, the eluvial horizons of the profile (1–3), which are together 45 cm thick, would have contained approximately $9.9 \cdot 45 = 445$ cm% fine clay before soil formation began. These horizons now contain $(9.4 \cdot 19) + (7.2 \cdot 10) + (2.8 \cdot 16) =$ 295 cm% fine clay, and have therefore lost 150 cm%, or 35% of their assumed original fine clay content. Before soil formation began, horizons 4–6 (the main illuvial horizons) would have contained $9.9 \times 85 = 840$ cm% fine clay, but they now contain $(12.7 \cdot 24) + (16.1 \cdot 34) + (15.1 \cdot 27) =$ 1,260 cm%. Horizons 4–6 have therefore gained 420 cm%; as only 150 cm% could have been derived by translocation from horizons 1–3, approximately 270 cm% is evidently from other sources. A similar calculation for the medium clay fractions shows that the amount removed from horizons 1–3 (25% of the original) is approximately the same as the excess in horizons 4–6, so that there is no gain of medium clay comparable to that of fine clay.

The large gain of fine clay could be attributed to: (1) clay forming within the profile by weathering of minerals in coarser fractions; (2)

vertical translocation of clay from horizons originally much thicker than 45 cm, the upper layers of which were subsequently removed by erosion; (3) horizontal translocation of clay from decalcified loess at slightly higher levels near the edge of the hollow in which the profile is situated; and (4) inhomogeneity of the original loess. Horizontal translocation was probably unimportant, because the profile occurs on a very gentle slope, and there is no impermeable horizon in or beneath the loess to encourage lateral movement of groundwater. Inhomogeneity of the loess is also unlikely, because we detected no differences between horizons in the particle size distribution of fractions not normally translocated, and because there are no sharp mineralogical discontinuities in the profile.

Excessively large amounts of clay occur also in the illuvial horizons of some modern soils (e.g. Soil Survey Staff, 1960, p.76), but explanations for the phenomenon are rarely offered. However, Glenn et al. (1960) attributed a clay gain in a loess soil of Wisconsin to the formation of montmorillonite by weathering of silt-sized ferromagnesian mica and other minerals, and Bouma et al. (1968) suggested that a similar increase of clay in a loess soil profile in southern Limburg (The Netherlands) resulted from weathering. We have therefore examined the evidence for weathering of silicate minerals in the Pegwell Bay profile to see if this can account for the observed gain of fine clay.

As weathering begins in the highest horizons of the soil and gradually proceeds downwards, it usually results in an upward decrease in the amounts of weatherable minerals. The only minerals in the buried profile that show this effect are glauconite in the sand and silt fractions and vermiculite and interstratified vermiculite-montmorillonite in the fine silts. The first visible stage in the alteration of glauconite pellets is the formation of abundant iron oxide granules, which change the pellets from green to yellow-brown and render them opaque. This has already occurred in much of the glauconite in horizons 4–7. Further alteration disaggregates the pellets, and probably releases the constituent mica and expanding mineral particles into finer size fractions. These may remain unaltered in the same horizon, or may be further modified by weathering, or may be translocated to lower horizons.

Assuming that the percentage of silt (2–50 μ) plus sand ($> 50\,\mu$) in the unaltered loess was similar to that of horizon 7 (81.6%), and that the fine silt contained as much glauconite as the coarse silt and sand fractions of horizon 7 (approximately 2 %), then the total amount of glauconite in horizons 1–3 would have been $81.6 \cdot 45 \cdot 2/100 = 73.4$ cm%. Making similar assumptions, the total amount of vermiculite in the fine silt of horizons 1–3 would have been $17.2 \cdot 45 \cdot 6/100 = 46.4$ cm%. Thus, even if all the glauconite and vermiculite in horizons 1–3 (totalling approximately 120 cm%) had been converted to fine clay, which was then either translocated to horizons 4–6 or remained in horizons 1–3 to replace fine clay previously translocated, it would account for less than half the estimated gain of fine clay (270 cm%). The actual amount of fine clay so produced was probably much less than 120 cm%, because only part of the vermiculite has been removed from horizons 1–3, and it is unlikely that either mineral was altered entirely to fine clay. We therefore conclude that only a small part (probably < 30%) of the fine clay gained by the profile as a whole was formed by weathering of these minerals in horizons 1–3. The remainder was probably derived by vertical translocation from an overlying layer of loess, which was later removed by erosion. Before this erosional phase in the history of profile development, the horizons now forming the highest 45 cm were within the zone of clay redeposition.

The main mineralogical difference between the clay fractions of different horizons in the profile is in the expanding minerals, which are freely-expanding at depth but less freely-expanding in higher horizons. St. Arnaud and Mortland (1963) described a similar change with depth in the clay fractions of soils developed on till, and attributed it to the formation of mica from expanding minerals by the fixation of potassium derived from decaying plant material. However, this cannot account for the upward decrease in amounts of freely-expanding layers in the clay fractions of the Pegwell Bay soil, because the plants in turn would have obtained their potassium only from the soil clays. More probably, the poorly-expanding minerals in the higher horizons were obtained at least partly from the weathering of glauconite, because they are similar to the complex interstratified minerals in the glauconite. Also, the slight upward increase in amounts of amorphous silica and alumina in the profile suggests that small quantities of alumino-silicate minerals were broken down during weathering. The aluminium released in this way is commonly redeposited as complex hydrated ions in the interlayer spaces of expanding minerals to form pedogenic chlorite (Tamura et al., 1956; Glenn et al., 1960; Jackson, 1963; Pawluk, 1963), and in the higher horizons of the buried profile this would help to make the clays less freely-expanding.

None of the less freely-expanding minerals typical of higher horizons were detected in either the fine or medium clay fractions of the main horizons of clay accumulation (4–6), and the fine clay minerals in horizon 5 are even more freely-expanding than those of horizon 7. However, horizons 1–3, in which chemical weathering made the clay minerals less freely-expanding, were the main source of the translocated clay. This suggests that most of the clay translocation occurred before the breakdown of alumino-silicate minerals.

We summarise below the sequence of events at Pegwell Bay; the dating is tentative (see Table IV).

Classification of the profile

In the system of classification currently used by the Soil Survey of England and Wales (Avery, 1965), the buried soil would be classified as a gleyed brown earth (*sol lessivé*). Distinct mottles caused by gleying occur in horizons below 450 mm, and the ratio of % clay ($< 2\ \mu$) in the main horizon of clay accumulation (5) to that in the horizon which has lost most clay (3) is $24.1/7.6 = 3.2$. In the French system of classification (Aubert, 1965), which is similar to the English in soils affected by clay eluviation, the profile would therefore be described as a *sol lessivé faiblement podzolique hydromorphe*.

TABLE IV

Sequence of events at Pegwell Bay

	Event	Time (years)
1	deposition of loess	Late Middle Weichselian (30,000–14,000 B.P.)
2	erosion of 2–3 m of loess	Late Middle Weichselian or Late Weichselian (14,000–10,000 B.P.)
3	decalcification of remaining loess, and eluviation of some clay	Late Weichselian or early Postglacial (10,000–7,000 B.P.)
4	further erosion of loess	Late Weichselian or early Postglacial
5	further eluviation of clay and development of the present organic horizons	early Postglacial and Atlantic period (7,000–5,000 B.P.)
6	weathering of glauconite and alumino-silicate clay minerals; less eluviation of clay; poor drainage conditions	Atlantic period
7	burial of profile by deposition of overlying hillwash	Subboreal period (5,000–2,500 B.P.)
8	modern soil development in the hillwash; some clay and carbonate deposited in horizons 1 and 2 of the buried profile	Subboreal to the present

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A SIMPLE DIFFRACTOMETER HEATING STAGE

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ABSTRACT: The construction is described of a heating stage for examining oriented clay specimens in a Philips' diffractometer. The stage, which is simple and cheap to make, is interchangeable with standard specimen holders, operates over the range 20–265°C and does not require the diffractometer to be specially modified. The maximum temperature attained at the surface of the specimen collapses freely-expanding Mg-saturated vermiculite and prevents re-expansion of layer silicate minerals once they have been collapsed.

INTRODUCTION

Changes in X-ray diffraction patterns produced by chemical and thermal treatments are often used as diagnostic tests for identification of clay minerals. Rehydration after heating, which can occur rapidly, may lead to errors. Milne & Warshaw (1956) recommended the use of dry air in the specimen chamber of a diffractometer to prevent rehydration. We have used a heated specimen stage for the same purpose.

Many devices have been described that allow specimens to be examined by X-ray diffractometry at temperatures above ambient (for examples, see Goldschmidt, 1964) but none satisfied our requirements. We needed a device that: (i) would allow the examination of specimens at temperatures ranging from room temperature to about 250°C; (ii) could be used interchangeably with conventional specimen holders without realignment of the diffractometer; (iii) incorporated the excellent radiation protection shielding provided in the Philips' instrument; this set a maximum size of about 5 × 5 × 1 cm for the whole stage. For routine identification of clay minerals in our laboratory, oriented films of clay are prepared on the surface of glass slips 3·8 × 1·27 × 0·12 cm (see Appendix) that are laid on the stepped surface of a duralumin specimen holder to align the clay surface with the reference surface of the diffractometer. The heating stage described below supplements the duralumin holder by holding similar clay-coated glass slips in the diffractometer for examination at elevated temperature. The dimensions of the completed heated stage are

$4{\cdot}0 \times 3{\cdot}2 \times 0{\cdot}6$ cm. It uses a small electrical heater set in a duralumin block, which is in contact with the glass slip, but otherwise supported by asbestolite. Thus, for a given temperature at the clay specimen surface, heat reaching the stage and transferred to the goniometer is minimized and special modifications for cooling are unnecessary.

Although the heating stage described is specifically made for clay mineral studies using a Philips' PW 1050/25 diffractometer, little modification in design would be needed to make a stage for use with other diffractometers or with other kinds of specimens.

DESCRIPTION

Figure 1 shows the components of the heating stage*.

The insulating block, (1) is formed from Asbestolite†. Its reference face (S), which is held against the reference surface of the goniometer shaft, is ribbed to minimize heat transfer to the shaft.

The metal block, (2) is made of duralumin. When components 1 and 2 have been permanently fixed together, surface (S) is machined parallel to, and 0·050 in. (1·27 mm) above, surface (P). The specimen slips are prevented from sliding on surface (P) by the small phosphor–bronze bracket (9).

The heating coil, (14) is positioned in the cylindrical hole in block 2 inside a double insulating sleeve of woven glass fibre (12) and protected by a steel outer cover (11). This cover is held in position by two screws that also attach the mica-filled P.T.F.E. insulating block (4) to block (2).

The heating coil is formed from a soldering iron element, 15 W, 240 V, Type CN manufactured by A.N.T.E.X. Ltd‡.

As supplied, the ceramic tube former of the heater is too long to fit the sample holder. It is therefore removed from its stainless steel sheathing tube and woven glass fibre cover and shortened to give a total length of 4·3 cm. The leads connecting the heating coil to the supply have to be re-attached following this operation. The ends of the wire of the heating coil are twisted on to 0·25 mm-diameter nichrome wires and then welded using an electric arc from a pointed carbon electrode and a 40–50 V battery. The modified heating coil is then resleeved in its glass fibre and steel covers, secured in block (2), and the leads, cut to about 3 cm and insulated with silicone rubber sleeving, are soldered to the terminal pins (6), in block (4). A *control unit* conveniently supplies power from the 240 V mains supply through a small auto-transformer to give 0–270 V to the heating coil. Figure 2 shows a suitable circuit. Thin insulated flexible leads from XY (Fig. 1) connect the heating stage to the transformer unit. The heating stage leads are brought into the specimen chamber of the diffractometer through the removable cover. We have modified a *replacement*

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* Working drawings for construction may be obtained from the authors.

† Asbestolite is a composite of asbestos and cement.

‡ A.N.T.E.X. Ltd., Mayflower House, Plymouth, Devon.

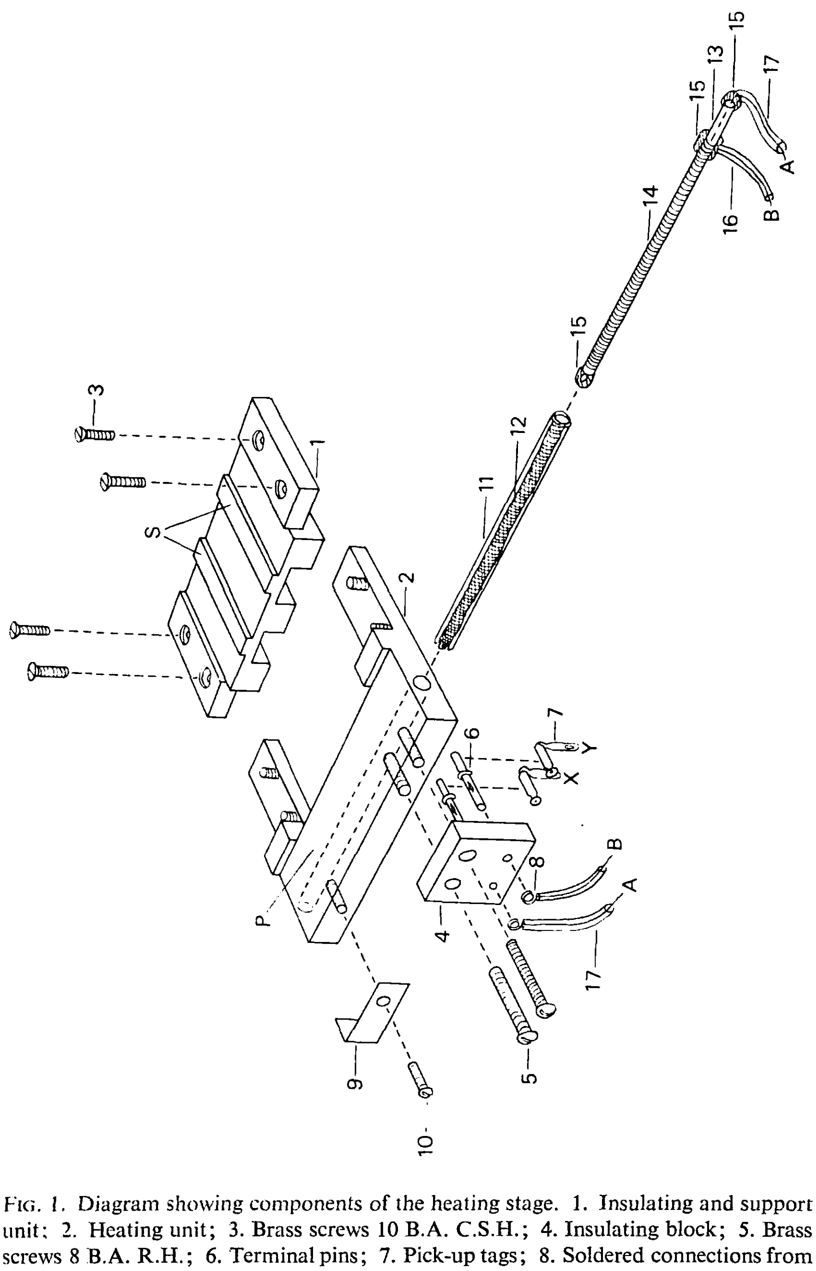


FIG. 1. Diagram showing components of the heating stage. 1. Insulating and support unit; 2. Heating unit; 3. Brass screws 10 B.A. C.S.H.; 4. Insulating block; 5. Brass screws 8 B.A. R.H.; 6. Terminal pins; 7. Pick-up tags; 8. Soldered connections from heater; 9. Slide retaining bracket; 10. Brass screw 10 B.A. R.H.; 11. Steel outer cover; 12. Woven glass-fibre insulation (2 layers); 13. Ceramic tubular heater support; 14. Heater winding (0·003 mm diam.); 15. Ceramic cement; 16. Nichrome connecting wires (0·254 mm diam.); 17. Silicone rubber sleeving.

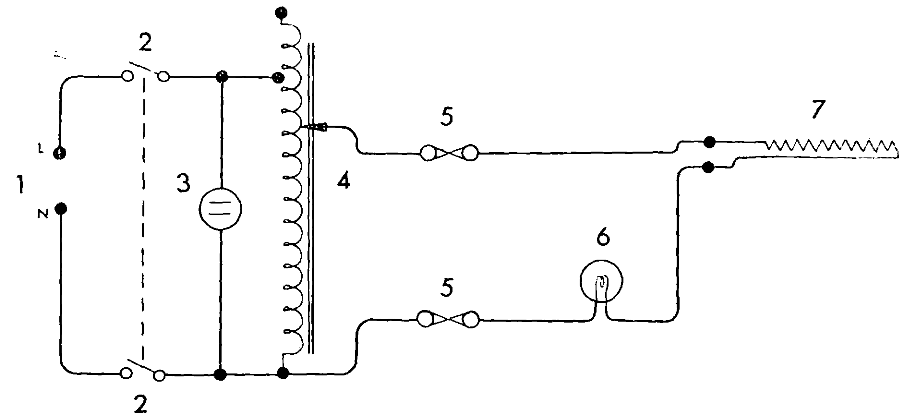


FIG. 2. Circuit diagram for the control unit of the heating stage. 1. Mains, 240 V; 2. ON/OFF switch; 3. Mains ON, neon; 4. Autotransformer, 2 A rating, input 240 V, output 0–270 V; 5. Fuse, 200 mA; 6. Heater ON, filament lamp, 6 V, 0·1 A; 7. Stage heating element.

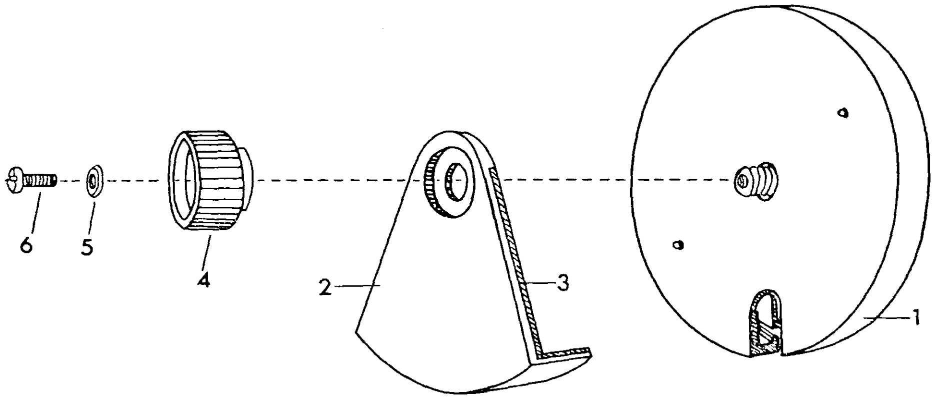


FIG. 3. Diagram showing components of the modified specimen chamber cover. 1. Modified cover plate; 2. Movable sector; 3. Lead lining; 4. Knurled securing knob; 5. Brass washer 6 B.A.; 6 Brass screw 6 B.A. C.H.

cover by cutting a 12 × 6 mm slot through the periphery of its inner and outer components (Fig. 3). To prevent scattered radiation escaping through this slot, a 55° sector of lead-lined duralumin is added, pivoted about the central locking screw. When the cover is in position the sector is rotated to cover the slot and is then clamped. The leads emerge from the radiation shielding via the 12 × 6 mm slot and the 3 mm gap between the perimeter of the cover and the flange of the sector. With the sector in position scattered radiation could not be detected outside the radiation shielding.

TEMPERATURE CALIBRATION

The temperature of the specimen is controlled by varying the voltage applied to the heating coil. Equilibrium at each temperature is attained in about 10 min and a calibration curve of temperature versus applied voltage is given in Fig. 4. The temperature of the clay specimens was determined by observing the melting of powdered crystals of pure substances of known melting points in contact with the clay surface. The temperature range over the surface of the specimen does not exceed the error in measurement, estimated to be about ±2°C.

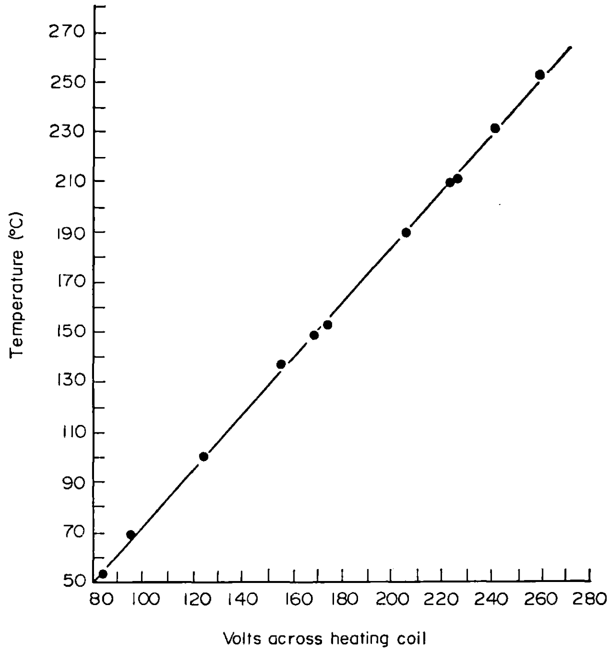


Fig. 4. Calibration curve of specimen; surface temperature against applied voltage.

	M.P.°C		M.P.°C
p-dichlorobenzene	53	citric acid (anhyd.)	153
stearic acid	68·5	salophene	190
citric acid	100	dicyandiamide	210
phenacetin	135	silver nitrate	212
cholesterol	149	tin	232
		phenolphthalein	254

MEASUREMENT OF 2θ

Because the heated stage is a composite of different materials, tests were made to discover whether heating caused the position of the specimen surface to change. Measurements of 2θ from a specimen of diamond powder, which has a very small coefficient of thermal expansion (Skinner, 1957), showed that over the temperature range 20–250°C changes in 2θ caused by thermal expansion of the instrument do not exceed 0·01° 2θ.

The only aberration introduced by replacing conventional specimens with those we use for examination of clay films occurs because the glass slips, which are cut from 7·62 × 3·81 cm microscope slides, may range in thickness between 1.17 mm and 1·35 mm. The surface of the clay film is therefore usually displaced from the reference plane of the goniometer causing shifts in the position of reflections, to larger angles if the specimen surface is inside the focussing circle and to smaller angles if the surface is outside, by

$$\Delta 2\theta = 2S \cos \theta / R \text{ radians,}$$

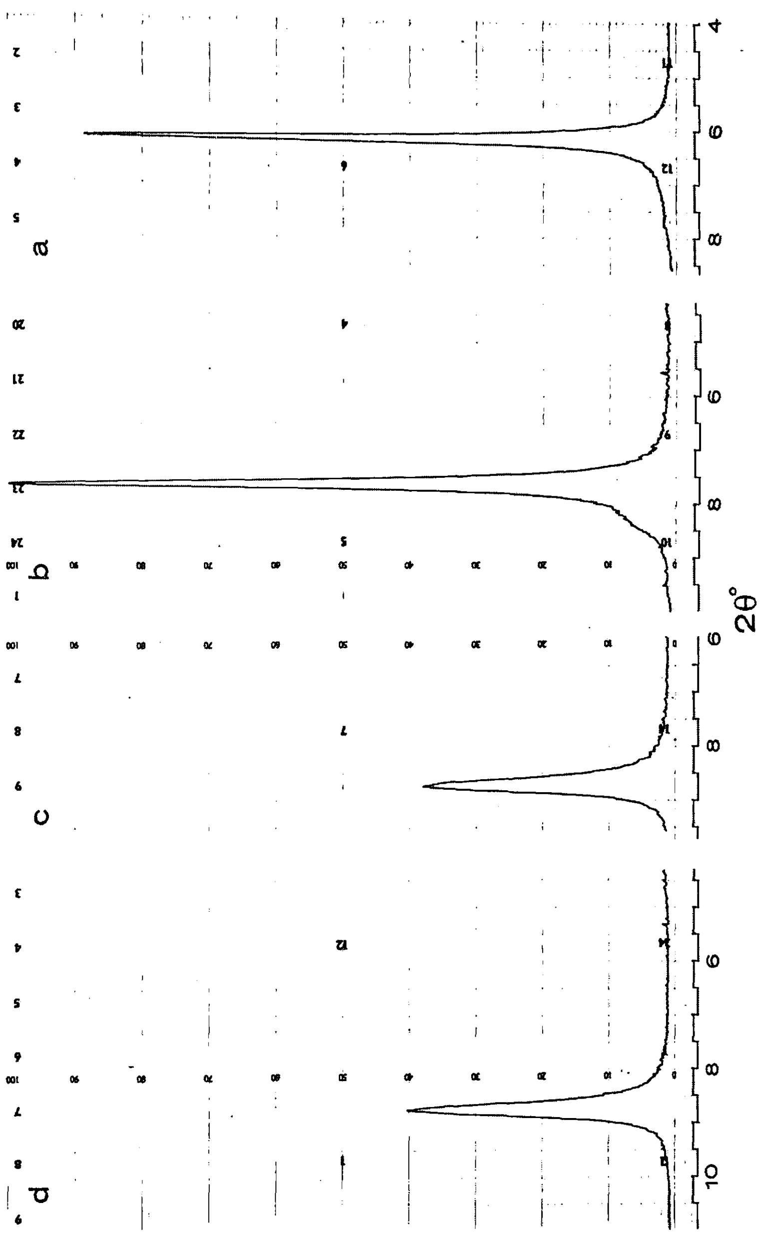
where S is the distance between the specimen surface plane and the reference plane, and R is the radius of the goniometer (Wilson, 1950). For unheated specimens an internal standard can be used for correction, but because of changes in spacings caused by thermal expansion, it is difficult to use internal standards to correct the observed 2θ values of heated specimens. For both unheated and heated specimens of the kind described here, a correction can be made conveniently for routine work by measuring the thickness of the slip + clay film with a micrometer and reading the corresponding $\Delta 2\theta$ from a graph or table.

USE FOR CLAY STUDIES

Plate 1 gives examples of diffractometer patterns made using the heating stage. The sample was a Mg-vermiculite, AP3, c.e.c. = 190 meq/100 g, prepared by Newman (1967) by removing potassium from phlogopite. The sample was heated to various temperatures on the heating stage and chart recordings made of the first order basal reflection at each temperature. At room temperature (Plate 1a), the reflection has $2\theta = 6{\cdot}17°$, $d = 14{\cdot}3$ Å corresponding to the two-layer water 14·36 Å phase of Walker (1961). Heating at 100°C for 20 min produces the one-layer water phase $d = 11{\cdot}59$ Å (Plate 1b) and heating to 265°C, the maximum attainable temperature, for 30 min gives a spacing of 10·1 Å (Plate 1c). Further heating at 265°C for 2·5 hr causes little change in the position of the reflection (Plate 1d). Heating the same sample at 700°C for 4 hr in an electric furnace followed by cooling to almost 250°C and transfer to the heating stage at 265°C, produced a further small collapse giving a spacing of 9·9 Å.

In routine analysis of clays, samples are heated on the glass slips in an electric furnace at 300°C and 500°C to collapse expanding minerals and destroy kaolinite. The heating stage is then used to prevent rehydration during X-ray examination.

PLATE 1



Diffractometer traces of basal reflections of Mg-saturated vermiculite AP3 held at various temperatures on the heated stage. (a) specimen at 20°C; (b) specimen at 100°C for 20 min; (c) specimen at 265°C for 30 min; (d) specimen at 265°C for 2·5 hr.

General conditions. Specimen: a slurry of vermiculite in water was dried to give a very thin oriented film, which with the glass slip measured 40 × 10 × 1·27 mm. Tube: CuK radiation, 40 kV, 20 mA. Goniometer: scan speed 1°/min, divergence slit 1/4°, receiving slit 0·1 mm, anti-scatter slit 1°, 0·178 mm Ni filter. Proportional counter: full scale deflection (a) 1 × 10^4 c.p.s., (b), (c), (d) 4 × 10^3 c.p.s. Chart speed: 1200 mm/hr.

(*Facing p.* 412)

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APPENDIX

A JIG FOR CUTTING GLASS SLIPS USED IN X-RAY DIFFRACTOMETRY OF CLAYS

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As noted above, the specimens for X-ray diffractometry were formed by drying a slurry on 3·81 × 1·27 × 0·12 cm (1·5 × 0·5 × 0·5 in.) glass slips. These slips are conveniently made by cutting standard 7·62 × 3·81 cm (3 × 1·5 in.) microscope slides in the jig in Fig. A5. Slides 0·127 cm (0·05 in.) thick are selected, placed in the jig, and scored with a standard laboratory tungsten carbide glass knife which has had its point sharpened to subtend an angle of not more than 30°. A laboratory diamond glass knife is unsatisfactory for this purpose as slivers of glass catch under the diamond mount and give a jagged cut that breaks unevenly.

The slide is placed in the slot (Fig. A5) in the body (A) and under the bridge (B), and pushed against the stop of the head (C) which has first been adjusted to give the correct breadth of slip. The glass is scored using B as a straight edge and the slip broken along the score by depressing C.

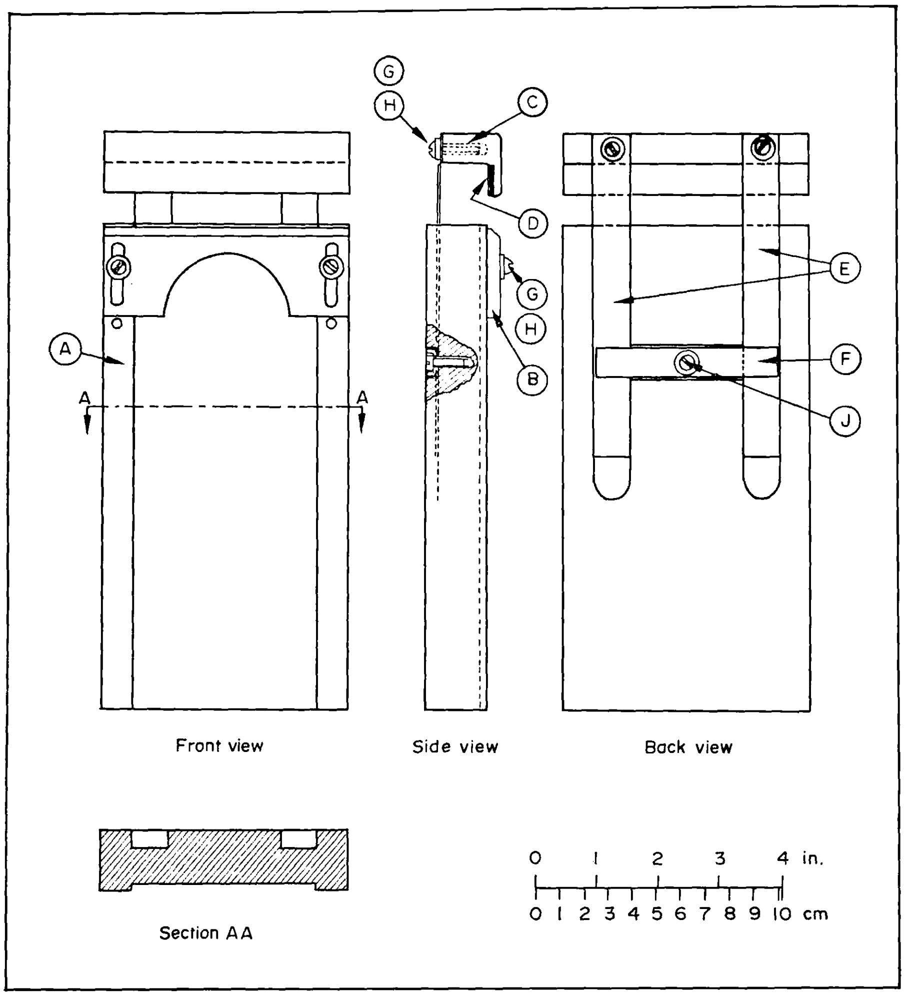

FIG. A5. Details of construction. A. Body, aluminium; B. Bridge, mild steel, cadmium plated; C. Head, aluminium; D. Pad, rubber; E. Springs, 0·290″ × 0·012″ tempered spring steel; F. Clamp, $\frac{1}{4}''$ × $\frac{1}{8}''$ mild steel, cadmium plated; G. Screws, 6 BA × $\frac{3}{8}''$ RD. HD., brass; H. Washers, 6 BA brass; J. Screw, 6 BA × $\frac{3}{8}''$ CH. HD., brass.

All the samples contain a large proportion of coarse silt (6–4ϕ, 16–63μm), and most of them resemble loess in overall particle size distribution (Table 1). However, the amounts of clay and coarse sand in some samples are slightly greater than in typical loess, suggesting that small quantities of other detritus are mixed with the windblown silt. The Sewerby sample also contains some fine sand, which may result from contamination with the blown sand that underlies the chalk head there.

IV. Mineralogy

Coarse silt fractions (6–4ϕ), separated from the samples by repeated settling in water, were divided into heavy (specific gravity greater than 2·9) and light components by centrifuging in bromoform, and then analysed mineralogically with a petrological microscope. All are composed mainly of quartz and feldspar, with small amounts of flint, muscovite, glauconite, iron ores and non-opaque heavy minerals. The amounts of iron ores are small but variable (between 0·05 and 0·4 per cent of total coarse silt), and are probably determined mainly by weathering and changing drainage conditions within the deposits. The remaining assemblage of silt minerals (Table 2) is the same in each sample, which suggests that the silt has a common origin, despite its widespread occurrence. Also, as in the Norfolk coverloams (Catt *et al.*, 1971), the 6–4ϕ silt is mineralogically similar to the same size fraction of the Devensian till (represented in Table 2 by the means of twelve samples from Lincolnshire and seven from Yorkshire), so that the debris brought by this glacial advance was probably the main source of the windblown silt. In the till, epidote is more abundant and chlorite less so in Norfolk than in Lincolnshire and Yorkshire. A similar change in mineralogy also occurs in the loess of these counties, suggesting that much of the silt was carried a relatively short distance by winds blowing from approximately north or north-east off the ice sheet.

Almost all the coarse sand (greater than 500μm) in the samples from Kirkburn, Huggate and Callis Wold is composed of flint fragments, which have been derived either from frost cracking of flint nodules or from the residue left on dissolution of chalk within or beneath the deposits. Similarly, the coarse sand in the Murton Common sample consists mainly of chalcedony, which is probably derived from the underlying Corallian oolitic limestone, because the acetic acid insoluble residue of a sample of the limestone contained similar microcrystalline silica.

V. Discussion and Conclusions

The uniformity of both particle size distribution and silt mineralogy of the drift deposits under consideration strongly suggests that they are all derived from the same source by the same means of transport. The widespread occurrence as a thin layer in various physiographical situations is consistent with aeolian deposition, and the similarity in particle size distribution and silt mineralogy to known loess deposits supports this conclusion. Glacial outwash plains have been recognized as sources of loess in many parts of the world. Their braided streams sort the glacial debris and spread the finer components over large areas, where they are subject to wind erosion in drier periods (Rutten, 1954). Further sorting of silt from sand and clay is achieved during this aeolian phase, as sand cannot be carried far even by the strongest winds, and clay particles are easily lifted into the upper atmosphere. Clouds of mainly silt particles are blown tens or hundreds of kilometres from the outwash plain, and are deposited where air currents weaken or rain falls. This type of origin for the deposits we have studied is indicated by their strong similarity in silt mineralogy to the Late Devensian glacial deposits in Yorkshire and Lincolnshire. In the Late Devensian (i.e. after approximately 25,000 years B.P.) the North Sea basin, left dry by eustatic fall of sea level, would certainly have contained the extensive outwash deposits that are a potential source of loess.

A Late Devensian age for the silty drifts would explain why they seem to be older than the Devensian till on the Yorkshire Wolds, yet still form an almost continuous cover. The actual arrival of the ice sheet at Dimlington in south-east Holderness was in the later part of the Late Devensian, shortly after 18,500 B.P. (Penny *et al.*, 1969), but the North Sea basin would have been largely above sea level and partly covered by the slowly advancing glacier for a long period before this date. Loess derived from the proglacial outwash would therefore have been deposited mainly before the ice surmounted the abandoned Ipswichian cliff at the foot of the Chalk dip-slope. Once the ice reached its limit, the supply of outwash and of loess could have been diminished by stagnation and slow melting *in situ.* Preservation of the thin but almost continuous cover on the Wolds may be attributable to the lack of any prolonged cold period since Late Devensian deposition of the loess. During long cold periods the chalk becomes impervious because of deep permafrost, and superficial layers are then extensively removed even from gently sloping surfaces by gelifluction, and by mudflows and streams during periods of temporary thaw. In contrast, during warmer periods, such as the post-Devensian, the chalk is more permeable and surface erosion is less widespread.

After weathering in the Ipswichian Interglacial, the older glacial and other drifts on the Yorkshire Wolds were probably removed by gelifluction, mudflows and temporary surface streams during earlier Devensian cold periods, so that only a few erratic stones and deposits preserved in solution pipes and hollows were left. During the Late Devensian the loess was consequently deposited on a bare chalk surface, virtually devoid of drifts other than *remanié* stones, and exposed to frost shattering and disturbance. The resulting mixture of silt and broken chalk and flint fragments has been weathered and decalcified in post-Devensian times, leaving the flinty silty drifts as a residue. Some of the mixture moved downslope during the Late Devensian, and accumulated in small hollows and on the floors and lower side slopes of valleys as a chalky head or coombe deposit. Also, before the ice arrived considerable quantities had accumulated in the lee of the Ipswichian cliff. Within the Devensian glacial limit, the head has been protected from post-Devensian weathering by the subsequent till cover, and thus retains its chalk component. Some post-Devensian erosion from steeper slopes is suggested by the relatively thick accumulations of less stony colluvial debris on foot-slopes.

The residue from dissolution of chalk within and beneath the silty deposits is perhaps partly responsible for their large clay content compared with typical loess, as the insoluble residue from chalk is clay-rich. However, the increased clay content may also result from subsoil concentration beneath an eluvial surface horizon later removed by erosion. The fact that the silty drift on the Hambleton Hills is restricted to the outcrop of the Corallian limestones could be taken as evidence for its purely residual origin. However, the particle size distribution and mineralogy of the acetic acid insoluble residue from samples of the limestones show this cannot be so. It contains mainly fine sand (4–2ϕ) and fine silt (9–6ϕ), fractions which are only minor constituents of the drift, and its coarse silt fraction (6–4ϕ) is mineralogically unlike that of the drift, as it contains approximately 50 per cent chalcedony, only 4 per cent feldspar, and few of the non-opaque heavy minerals found in the drift.

An aeolian origin does not explain why the silty drifts seem to be restricted to limestone outcrops, because windborne material would surely have been deposited to some extent in other areas as well. Apart from the small areas of thin aeolian silt on the Bunter Sandstone of Nottinghamshire (Robson and George, 1971), the association with limestone surfaces seems to be true throughout northern England, for loess-like drifts have otherwise been reported only on the Carboniferous Limestone of Derbyshire (Pigott, 1962), West Yorkshire (Bullock, 1971) and Westmorland (Furness and King, 1972), and the loess of the Durham coast described by Trechmann (1920) partly overlies Magnesian Limestone. Clearly, the loess that fell on deposits other than limestones was (a) never stabilized at the time, or (b) removed by subsequent widespread surface erosion, or (c) so deeply intermingled with those deposits by cryoturbation or other soil mixing processes that it has been diluted beyond recognition. Surface run-off may have removed the loess deposited on substrata less permeable than limestone (e.g. clays), but this does not explain the absence of loess on other permeable rocks, such as sandstone. For a large part of post-Devensian time, complete removal of the loess over limestones was possibly prevented by partial cementation of the head deposits with secondary carbonate. However, the loess deposited on other substrata would have been incorporated in a head containing insufficient carbonate for significant cementation, and this would have been eroded more easily.

The loess in County Durham (Trechmann, 1920) could be coeval with the silty superficial deposits in Yorkshire, as it lies between the Warren House Till and the Blackhall Till, which Francis (1970) has correlated with the Wolstonian and Late Devensian glacial phases respectively. However, he suggested the loess there is Wolstonian because its upper layers contain crystalline boulders, which seem to have been weathered in a warm, possibly interglacial period, before deposition of the Blackhall Till. Unfortunately, the deposit is no longer exposed, and we have not been able to compare its composition with that of the Yorkshire deposits, so its exact age must remain a matter of conjecture.

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THE LOESS OF EASTERN YORKSHIRE AND LINCOLNSHIRE

BY J. A. CATT, A. H. WEIR AND P. A. MADGETT

(*Read at Hull*, 10*th November*, 1973)

CONTENTS

SUMMARY

Thin, silty, superficial deposits cover parts of the Yorkshire and Lincolnshire Wolds outside the Late Devensian glacial limit, and also occur on the Hambleton Hills. Their particle size distribution and mineralogy suggest that they are composed mainly of loess derived from the Devensian glacial debris. On the Yorkshire Wolds the loess was deposited before the ice reached its extreme limit, as it is incorporated in a chalky, flinty head beneath the till. The silty deposits are probably the decalcified residues of similar head deposits formed extensively in Late Devensian times.

I. INTRODUCTION

Loess with many of the characteristics listed by Russell (1944) and others occurs only locally in eastern England (Trechmann, 1920; Pitcher *et al.*, 1954). However, soil mapping and profile studies in the last twenty-five years have shown that a thin silty drift is widespread in south and east England, and many workers have suggested this is loess that has been weathered and partly mixed with subjacent deposits. In particular, it occurs on the Cornish serpentine (Coombe *et al.*, 1956); the Carboniferous Limestone of Somerset (Findlay, 1965), Derbyshire (Pigott, 1962) and other areas; the Upper Chalk and Clay-with-flints of the Chiltern Hills (Avery *et al.*, 1959, 1969, 1972) and South Downs (Hodgson *et al.*, 1967); the tills and glacial gravels of north Norfolk (Catt *et al.*, 1971); the Bunter Sandstone of Nottinghamshire (Robson and George, 1971), and probably many other deposits.

Beyond the western limit of the Devensian glacial deposits (Fig. 1), the Chalk in Yorkshire and Lincolnshire is covered by several thin superficial deposits. Some are remnants of older glacial drifts (Bisat, 1939; Straw, 1957, 1969) or Tertiary Beds

(Versey, 1938), but others seem to be more recent. For example, patches of windblown sand on the north Lincolnshire Wolds are probably Devensian or younger (Straw, 1963), and many of the flinty valley gravels may be similar in age. On the Yorkshire Wolds the most widespread of these younger drifts is very silty, and resembles some of the loess-containing deposits on the Chalk of southern England. Reid (1885, p. 119) suggested that this material is wind-blown dust derived from the Holderness plain. In this paper we report the distribution and petrography of the silty deposits in eastern Yorkshire and Lincolnshire, and discuss their age and origin.

II. Geographical Distribution

The largest single area of silty drift is on the Yorkshire Wolds (Fig. 1), where it is 0·3 to 1·5 metres thick on most of the flat or gently sloping upland surfaces, locally thicker over solution and other irregular hollows in the chalk surface, but generally less than 0·3 metre thick on steeper slopes, such as valley sides. The thicker deposits are brown or yellowish-brown beneath dark brown ploughed topsoil, and a slightly more clay-rich yellowish-red horizon frequently occurs immediately above the chalk. Angular flint fragments are common throughout, especially where the deposit is thin. Less stony colluvial accumulations of brown or yellowish-brown silty material, commonly more than 1·5 metres thick, occur on the less steep footslopes and on the floors of some valleys. This type of blanket distribution on the Wolds suggests deposition by wind, as this is the transporting agent most likely to leave a thin deposit over almost the entire landscape.

The thickest of these deposits were once worked locally for brickearth, as at High Hunsley (SE 955353) and Huggate (SE 889551). The deposit at High Hunsley is shown as a boulder clay outlier on Sheet 72 (Beverley) of the Institute of Geological Sciences, and J. L. Rome suggested that the Huggate deposit is an outlier of the "Purple Clay of Holderness" (in Bisat, 1939, p. 145). However, both are lithologically unlike any of the Yorkshire boulder clays; a glacial origin was perhaps inferred from the presence of occasional far-travelled erratic stones, but these could have been derived from a *remanié* of pre-Devensian glacial drift.

On the dip-slope spurs of the Yorkshire Wolds the silty drift is continuous down to the feather edge of the Devensian till, and commonly extends eastwards beneath it as a discontinuous layer of silty, chalk and flint gravel. In the area between the Devensian limit and the buried Ipswichian cliff (Fig. 1), this gravel can often

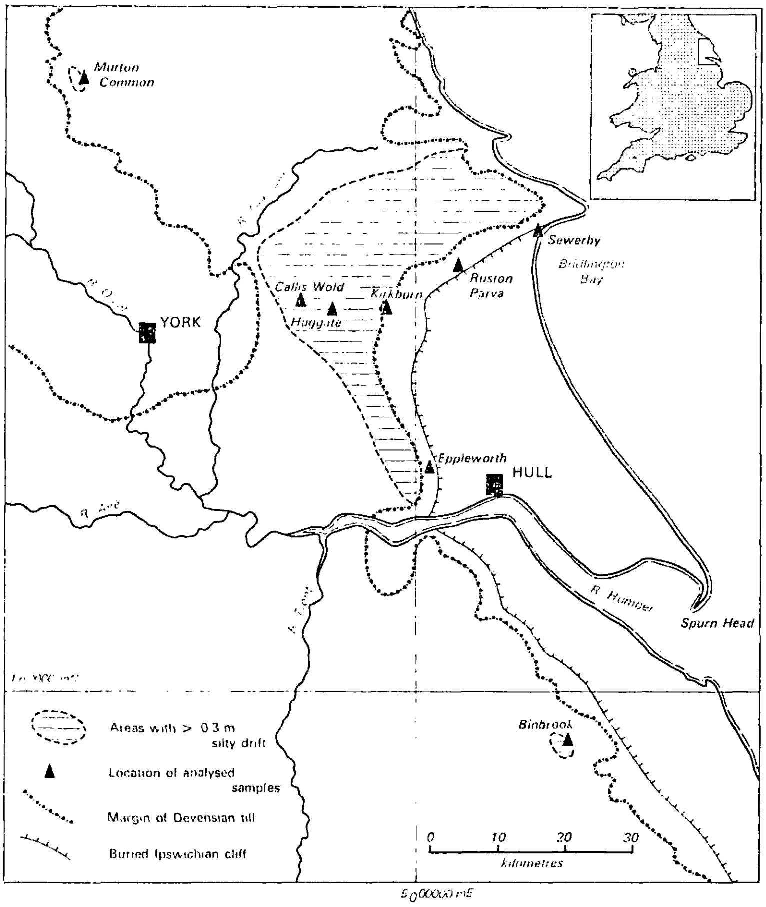

FIG. 1.—Distribution of loess-containing superficial deposits in eastern Yorkshire and Lincolnshire.

be found by augering through the till, and sections showing pockets of the gravel up to 0·8 metre deep penetrating disturbed chalk beneath one to two metres of till are exposed in quarries at Eppleworth (TA 021324) and Ruston Parva (TA 069617). The silty material was therefore deposited before the Devensian ice reached its extreme limit in Yorkshire, but its almost ubiquitous occurrence on the Yorkshire Wolds suggests that it is not older than the last major phase of valley formation and landscape development.

The chalk "rubble" or head, which buries the Ipswichian

Interglacial cliff and beach deposits at Sewerby (Catt and Penny, 1966, fig. 2) and is overlain by Devensian till, also contains abundant yellowish-brown silty material, both dispersed throughout and locally concentrated in lenticular inclusions. On the seaward side of the buried cliff, this bed is often exposed either in the present cliff (TA 198684) above the Late Ipswichian–Early Devensian blown sand, or nearby on the foreshore, where it is up to 8 metres thick. The silty lenses contain terrestrial molluscs (Lamplugh, 1903) indicative of an open habitat, and a similar head deposit at Hessle, also between the buried cliff and the Devensian till, has yielded remains of horse and possibly other mammals (Boylan, 1967). An Early Devensian age was suggested by Catt and Penny (1966), but the head could have been deposited at any time between the Ipswichian Interglacial and the arrival of the Devensian glacier.

Silty drifts up to one metre thick also occur over Upper Jurassic Corallian oolitic limestone on Murton and Dale Town commons, which are parts of the plateau surface of the Hambleton Hills north-east of Thirsk. In some areas a podzol profile is developed in the silty sediment beneath a thin (0·10 to 0·15 m) peaty layer. The drift thins rapidly and disappears at the edge of the plateau; it is also absent from the plateau surface farther north, where grits and sandstones rather than limestones crop out.

On the Lincolnshire Wolds the silty drift is less widespread than in Yorkshire. We found 0·5 to 0·8 metre of silty clay loam on flat and gently sloping surfaces near Binbrook, but elsewhere very thin, flinty, and usually sandy soils predominate in the areas not covered by till. The Lincolnshire Limestone outcrop is also free of silty drift.

III. Particle Size Distribution

Samples for laboratory study were taken from suitable exposures or soil profile pits near Binbrook (Lincolnshire); at two localities (Huggate and Callis Wold) on the Yorkshire Wolds outside (west of) the Devensian limit; at four sites (Eppleworth, Kirkburn, Ruston Parva and Sewerby) where silty chalk gravel or head underlies Devensian till, and at Murton Common on the Hambleton Hills. The samples were decalcified where necessary by treatment with acetic acid buffered at pH5 with sodium acetate, and were dispersed by overnight shaking in a 0·5 per cent solution of sodium hexametaphosphate. Their particle size distribution at ϕ intervals ($\phi = -\log_2 d$, where d is the equivalent spherical diameter of particles in millimetres) was then determined by sieving and the pipette sampling technique.

Table 1

Particle size distribution of silty drifts from Yorkshire and Lincolnshire (weight percentages of oven-dry, non-calcareous soil, less than 2 millimetres), compared with typical loess.

ϕ Divisions	μm Equivalent		Binbrook, Lincs. (TA 178956) 0·6–0·7m depth	Huggate, Yorks. (SE 875548) 0·4–0·5m depth	Callis Wold, Yorks. (SE 828560) 0·25–0·30m depth	Eppleworth, Yorks. (TA 021324) below till	Kirkburn, Yorks. (SE 975566) below till	Ruston Parva, Yorks. (TA 069617) below till	Sewerby, Yorks. (TA 198684) between inter-glacial blown sand and Devensian till	Murton Common, Yorks. (SE 505887) 0·25–0·50m depth	Loess, Ford, Kent	Loess, Tongrinne, Belgium
			%	%	%	%	%	%	%	%	%	%
0– —1	1000–2000		0·2	0·3	1·1	0·1	1·4	0·1	0·2	0·9	0·2	0·0
1 – 0	500–1000	SAND	0·3	0·1	0·2	0·2	1·1	0·1	0·4	0·3	0·3	0·0
2 – 1	250–500		0·4	0·1	0·2	0·4	1·4	0·0	2·4	0·3	1·0	0·0
3 – 2	125–250		0·8	0·7	0·6	1·2	3·6	0·1	16·5	4·7	2·9	0·1
4 – 3	63–125		8·7	8·1	10·8	8·4	6·8	1·9	12·2	7·5	7·1	0·8
5 – 4	31–63		25·4	22·6	25·2	31·2	16·6	32·1	16·1	23·1	26·5	27·2
6 – 5	16–31		16·4	17·1	18·9	24·6	14·1	29·0	10·1	21·1	21·6	30·9
7 – 6	8–16	SILT	8·6	7·4	10·2	10·2	7·9	10·0	6·7	12·9	10·0	11·7
8 – 7	4–8		4·6	7·0	5·1	4·8	5·9	4·5	4·0	7·9	5·4	4·7
9 – 8	2–4		4·3	5·3	3·9	3·0	5·6	2·2	3·4	5·3	2·6	1·9
>9	<2	CLAY	30·3	31·3	23·8	16·0	35·6	20·0	28·0	16·0	22·4	22·7

TABLE 2

Mineralogical composition of 6-4ϕ fractions (excluding opaque heavy minerals) from silty drifts in eastern Yorkshire and Lincolnshire, compared with the same size fractions of Norfolk coverloams, Kentish loess and Devensian till (light minerals given as percentages of total coarse silt, heavy minerals as parts per thousand of non-opaque heavy fraction).

Minerals	Binbrook, Lincs. (TA 178956) 0·6–0·7m depth	Huggate, Yorks. (SE 875548) 0·45–0·50m depth	Callis Wold, Yorks. (SE 828560) 0·25–0·30m depth	Eppleworth, Yorks. (TA 021324) below till	Kirkburn, Yorks. (SE 975566) below till	Ruston Parva, Yorks. (TA 069617) below till	Sewerby, Yorks. (TA 198684) between inter-glacial blown sand and Devensian till	Murton Common, Yorks. (SE 505887) 0·25–0·50m depth	Mean of 5 Norfolk Cover-loams (Catt *et al.*, 1971, table 3)	Mean of 7 Kentish loess samples	Mean of 12 Devensian till samples, Lincs.	Mean of 7 Devensian till samples, western Holderness, Yorks.
A LIGHT FRACTION	%	%	%	%	%	%	%	%	%	%	%	%
Quartz	79	77	78	78	78	76	79	81	77	74	75	74
Feldspar	18	21	18	19	18	20	18	16	19	22	19	20
Flint	2	1	2	1	2	2	1	1	2	2	3	3
Muscovite	<1	1	1	2	1	2	1	1	1	1	2	1
Glauconite	<1	<1	<1	<1	<1	<1	1	<1	<1	1	1	1

B NON-OPAQUE HEAVY FRACTION	°/oo	°/oo	°/oo	°/oo	°/oo	°/oo	°/oo	°/oo	°/oo	°/oo	°/oo	°/oo
Epidote	298	298	346	270	325	234	306	312	411	367	216	240
Zoisite	26	20	17	26	25	23	13	16	32	28	19	19
Zircon	108	131	99	112	100	72	93	130	104	193	116	140
Tourmaline	41	63	55	23	21	22	34	43	21	13	31	33
Chlorite	180	89	156	284	190	169	118	152	32	28	206	154
Biotite	13	15	11	15	26	8	22	15	7	—	55	30
Garnet	54	50	40	39	66	71	92	45	63	73	70	83
Green hornblende	166	180	145	119	125	287	205	155	160	129	152	163
Brown hornblende	21	17	25	9	17	15	12	18	36	19	14	11
Tremolite	32	27	32	23	30	38	37	34	41	21	29	28
Yellow rutile	15	31	18	26	11	11	24	16	35	64	18	21
Red rutile	3	2	2	2	7	1	1	5	5	6	3	3
Brown rutile	4	14	13	7	7	9	8	5	13	10	6	9
Anatase	19	24	24	20	17	6	11	26	16	20	13	14
Brookite	4	12	3	4	4	4	3	9	2	4	4	7
Staurolite	4	5	8	6	13	2	8	10	6	12	6	6
Kyanite	6	3	6	3	4	4	3	5	8	5	3	2
Augite	3	14	—	4	3	6	3	3	6	—	16	24
Apatite	2	5	—	8	9	18	7	—	—	7	23	13
Monazite	1	—	—	—	—	—	—	1	—	1	—	—
Hypersthene	—	—	—	—	—	—	—	—	2	—	—	—