Penny, L. F. and Catt, J. A. 1967. Stone orientation and other structural features of tills in east Yorkshire. *Geological Magazine.* 104 (4), pp. 344-360.

Stone Orientation and Other Structural Features of Tills in East Yorkshire

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ABSTRACT

Macrofabric (stone orientation) and microfabric studies of the four tills exposed in the coastal areas of East Yorkshire indicate that the regional direction of ice movement during both the Saale and Weichsel Glaciations was from north-east to south-west. The Saale (Basement) Till was considerably modified by the advance of ice during the Weichsel Glaciation; in particular, the stones in the Basement were reorientated so that their long axes now lie at right angles to the direction of movement of the Weichsel ice sheet. The fabrics of the three Weichsel tills (Drab, Purple and Hessle) are alike, and it is suggested that all three were deposited from one composite ice sheet. The relationship of vertical joints in the Basement and Drab Tills to directions of ice movement is discussed; those in the Basement possibly originated as *ac* tension joints inherited from the parent ice, whereas some of those in the Drab are probably conjugate shear joints formed during post-depositional deformation of the till.

I. INTRODUCTION

ALTHOUGH the preferred orientation of stones in till was noticed by a few nineteenth-century geologists, such as Hind (1859, *vide* Elson, 1966) and Miller (1884), statistical methods have only recently been applied to the study of this phenomenon. Richter (1932, 1933) and Holmes (1941) both showed that the direction of preferred orientation of the long axes of till stones corresponds to the direction of movement of the ice that deposited the till. This has been confirmed by work on modern glaciers and their tills by Richter (1936), Hoppe (1953) and Donner and West (1957). Subsequent studies by many workers in Europe and North America have proved that investigation of fabric is an important part of the examination of glacial drifts. In addition to the fabric determined by the preferred orientation of stones (macrofabric), tills also possess a microfabric, which is conveniently studied in thin sections by measuring the directions of long axes of sand and silt particles (Seifert, 1954; Sitler and Chapman, 1955; Harrison, 1957; Ostry and Deane, 1963). The macrofabric of the Elster and Saale tills in East Anglia was described by West and Donner (1956), Stevens (1960), Norris (1962) and Banham and Ranson (1965); Suggate and West (1959) extended this work to the Weichsel till in north Norfolk and Lincolnshire. The present paper describes the fabric of Saale and Weichsel tills in East Yorkshire, an important area of Pleistocene deposition lying immediately north of the districts already investigated by these workers.

Wood and Rome (1868) suggested a three-fold subdivision of the glacial deposits exposed in the coastal cliffs of East Yorkshire, but Lamplugh (1879, 1882) showed that in fact four separate tills can be distinguished. In current nomenclature (Catt and Penny, 1966) these are, in ascending order, the Basement, Drab, Purple and Hessle Tills. Although many beds of stratified gravel, sand and silt occur between or within these four tills, most are englacial or subglacial in origin, and do not represent warm periods of interglacial or even interstadial status. However, the Drab and higher tills overlie a buried cliff, the beach deposits of which rest on an eroded and weathered surface of Basement Till (Catt and Penny, 1966) and contain a mammalian fauna that is almost certainly of Last Interglacial (Eemian) age. This indicates that the Basement Till was deposited during the Saale Glaciation or earlier, and that the Drab, Purple and Hessle Tills are all referable to the Weichsel. The Hessle Till is correlated by most authors with the Hunstanton Till, which is the sole representative of the Weichsel in Norfolk. The Basement Till is visible at only a few localities on the Yorkshire coast, and contains partially digested masses of marine clay (the Sub-Basement of Bisat, 1940) and sand (the Bridlington Crag of Lamplugh, 1878, 1881, 1884), which were incorporated from the floor of the North Sea by the ice that deposited the Basement.

The method of determining the direction of preferred stone orientation in the Yorkshire tills was similar to that described by West and Donner (1956). The directions of the long axes of 100 stones were measured at each locality with a compass; the compass readings were then converted to grid bearings and grouped into 10-degree groups, from which rose diagrams were constructed. Maxima were determined from these diagrams by visual inspection; it was not necessary to treat the rose diagrams statistically to find the maxima, and no useful additional information was obtained by measuring the dip of the long axes. Although it is impossible to distinguish on the basis of stone orientation alone between, for example, ice moving NE–SW and ice moving SW–NE, the erratics in all the tills clearly indicate that the ice came from a generally northerly direction rather than a southerly direction.

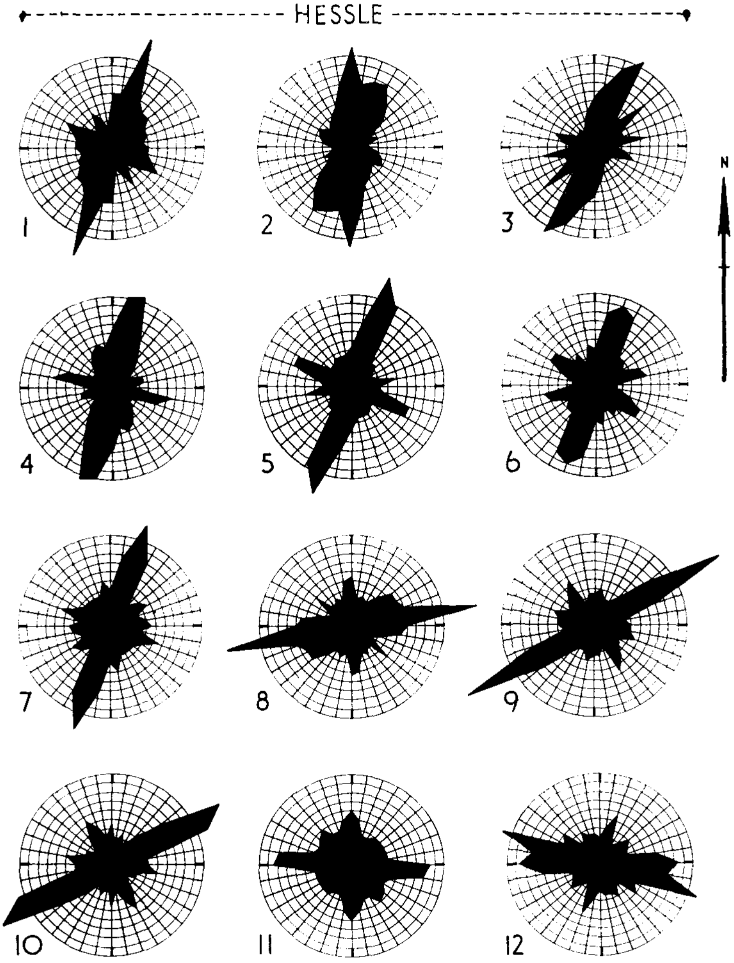
II. Macrofabric of the Weichsel Tills

The cliff sections of Holderness and Filey Bay provide almost continuous exposures of two of the tills (Drab and Hessle) deposited during the Last Glaciation, but the intervening Purple Till is absent from northern and extreme southern Holderness. Horizontal surfaces of undisturbed till were available for most of the stone orientation measurements of the Drab and Purple Tills, but as the Hessle is usually exposed only in an almost vertical face at the clifftop it was necessary to modify slightly the technique described by West and Donner to allow the use of vertical surfaces. This is because most of the stones selected for measurement on a vertical surface are inevitably those whose long axes project from the surface, so that the true direction of preferred orientation may be obscured by a false preferred orientation approximately normal to the exposed surface. The effect of this was reduced as much as possible when working on a vertical surface by ignoring all the exposed stones, and digging back behind the surface to measure the long axes as stones were uncovered. Although the Hessle Till is commonly exposed at inland sites, particularly in Chalk quarries on the eastern margin of the Yorkshire Wolds, the only exposure of underlying deposits available at the time of working was that of the Drab Till on the north bank of the Humber at Red Cliff (SE 979249).

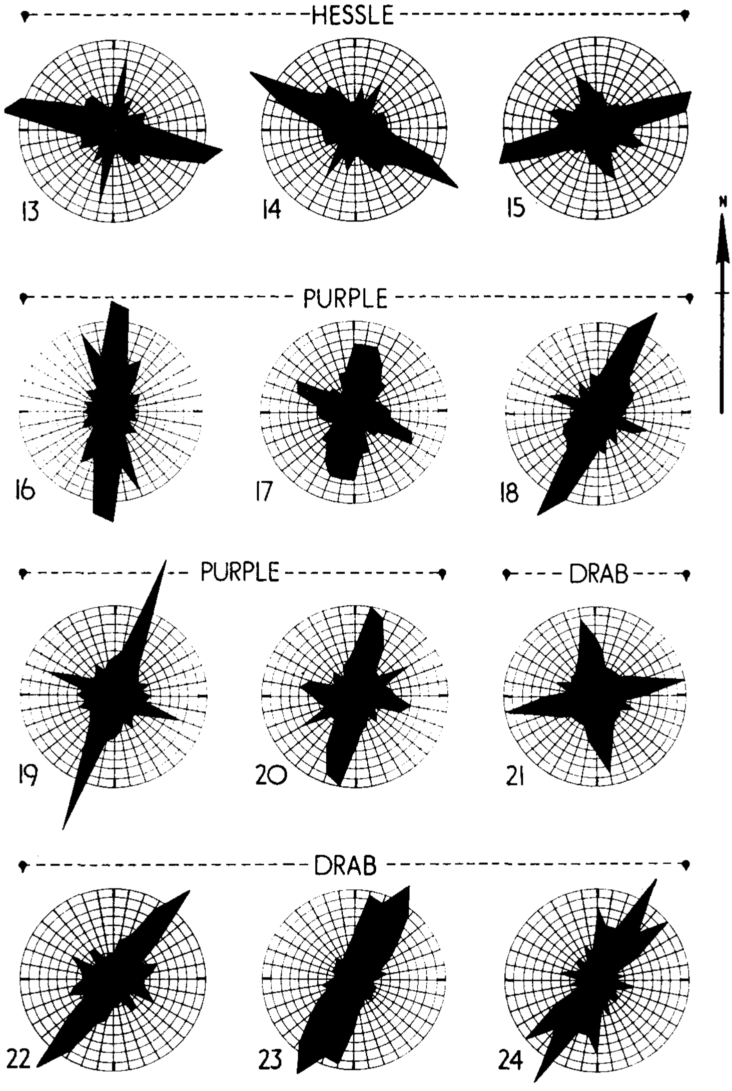
The rose diagrams for the Drab, Purple and Hessle Tills are given in Text-figs. 1, 2 and 3, and the ice movement directions deduced from these are shown as arrows in Text-fig. 4, the head of each arrow being placed on the locality where stone orientation was measured. The direction of preferred stone orientation of all three Weichsel tills in the coastal regions of Filey Bay and of central and southern Holderness is approximately NNE–SSW. This probably indicates the regional direction of ice movement in eastern Yorkshire during the Last Glaciation, as it agrees with the direction of glacial striae on the bedrock surface beneath Drab Till at Filey Brigg (Stather, 1898) and with the direction of ice advance suggested by Kendall (1902) and other workers. However, on the southern flank of Flamborough Head and in western parts of Holderness the direction of preferred stone orientation in the Hessle and Drab Tills is approximately E–W, indicating that the ice changed direction by 45 to 60 degrees both in crossing Holderness and in circumventing Flamborough Head. The high ground formed by the Chalk outcrop in Yorkshire must have been such a severe obstacle to the ice that it was forced to flow mainly to the east of Flamborough Head. In the lee of the headland the ice was able to fan out westwards over the low-lying ground of Holderness, though in the coastal areas of southern Holderness the regional direction of movement was maintained.

Many of the rose diagrams in Text-figs. 1, 2 and 3 show subsidiary stone orientation peaks at right angles to the inferred direction of ice movement. The direction of glacial transport can be referred to as the " *a* " direction by analogy with the direction of " tectonic transport " in structural geology; the direction at right angles to ice movement is then the " *b* " direction. Some of the *b* stone orientation peaks noted by previous workers exceeded the peaks parallel to the known direction of ice movement, but those in the Drab, Purple and Hessle Tills are all smaller than the *a* maxima.

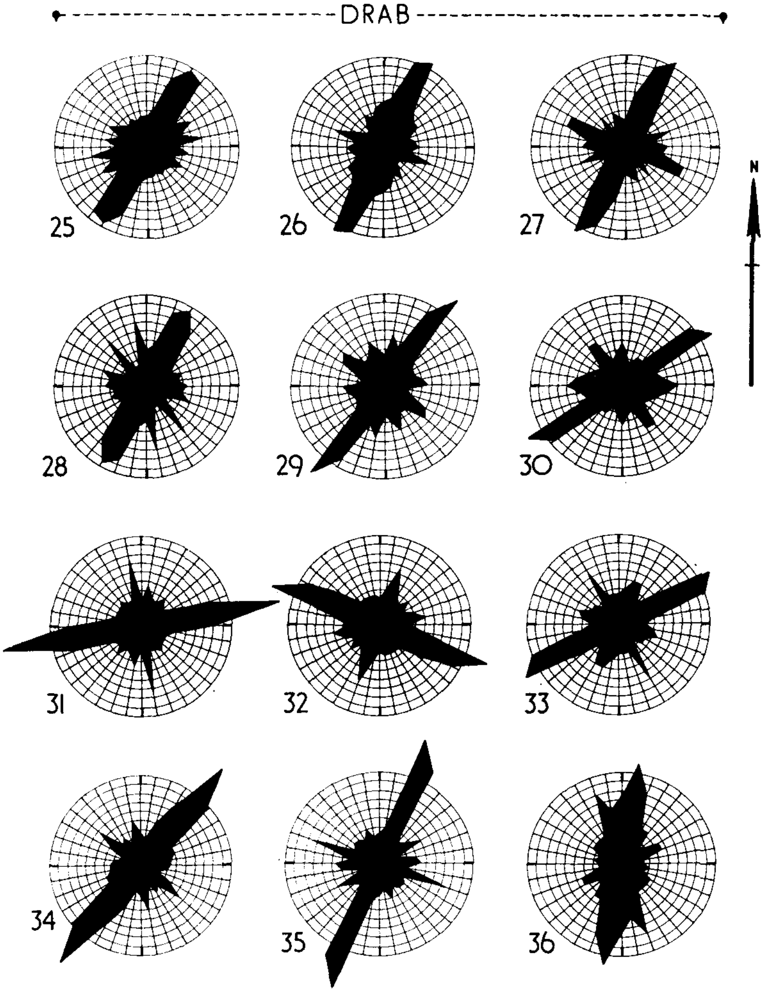
There are no detectable differences in the directions of movement of the ice that deposited the Drab, Purple and Hessle Tills. This indicates either that the three tills were deposited from the same ice sheet, or that



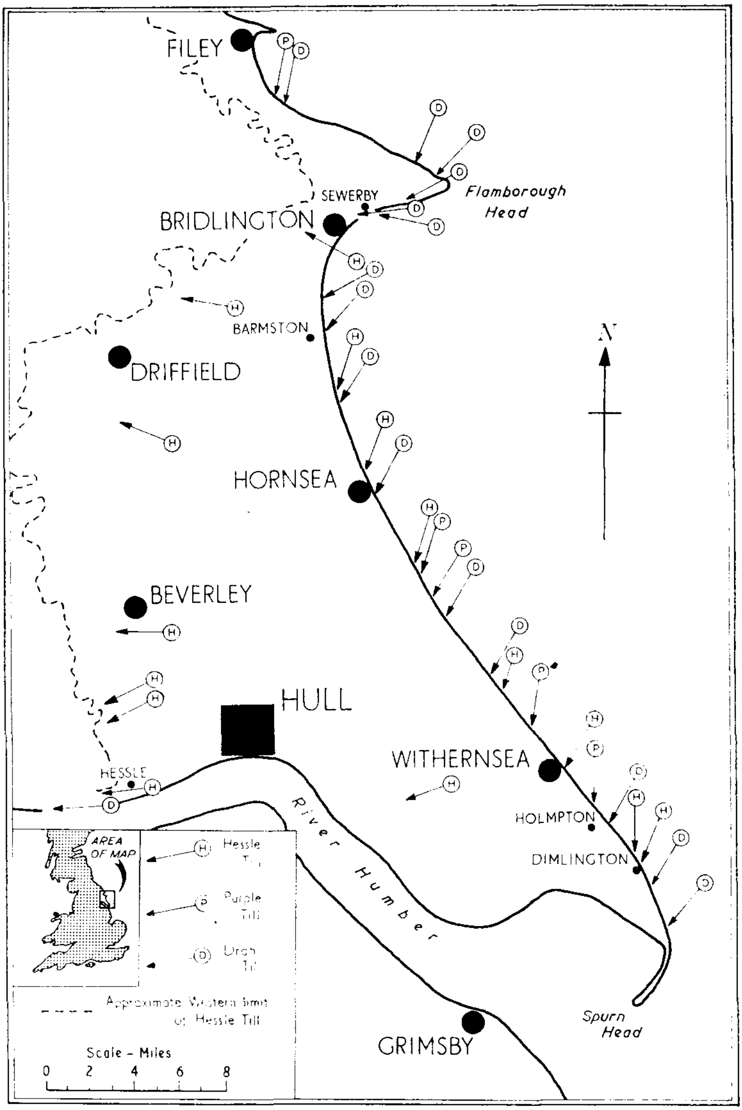
TEXT-FIG. 1.—Macrofabric of Weichsel tills in East Yorkshire: the Hessle Till at 1. Dimlington (TA 399206), 2. Dimlington (TA 397209), 3. Withernsea (TA 348272), 4. Hilston (TA 296343), 5. Cowden (TA 238427), 6. Hornsea (TA 206489), 7. Skipsea (TA 182551), 8. Hessle (TA 012259), 9. Willerby (TA 014313), 10. Eppleworth (TA 020323) 11. Beverley (TA 025374), 12. Hutton Cranswick (TA 024530).



TEXT-FIG. 2.—Macrofabric of Weichsel tills in East Yorkshire (continued): the Hessle Till at 13. Ruston Parva (TA 069617), 14. Bridlington (TA 163667), 15. Keyingham (TA 236253); the Purple Till at 16. Withernsea (TA 365253), 17. Tunstall (TA 321310), 18. Aldbrough (TA 252406), 19. Cowden (TA 243418), 20. Reighton (TA 140765); the Drab Till at 21. North Ferriby (SE 979249), 22. Kilnsea (TA 418161), 23. Easington (TA 405196), 24. Holmpton (TA 376237).



TEXT-FIG. 3.—Macrofabric of Weichsel tills in East Yorkshire (continued): the Drab Till at 25. Hilston (TA 291349), 26. Aldbrough (TA 261392), 27. Hornsea (TA 212472), 28. Skipsea (TA 186543), 29. Barmston (TA 172595), 30. Fraisthorpe (TA 170629), 31. Sewerby (TA 197683), 32. Sewerby (TA 198685), 33. South Landing (TA 231692), 34. Flamborough Head (TA 258705), 35. North Landing (TA 238722), 36. Reighton (TA 143763).



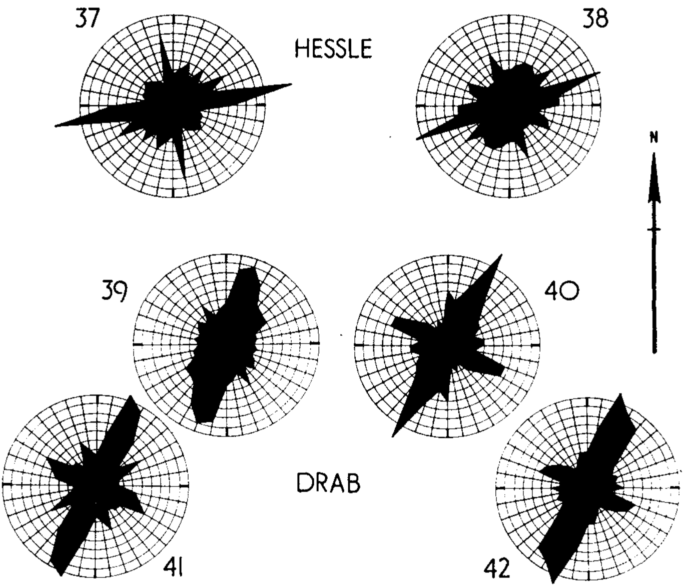
TEXT-FIG. 4.—Directions of ice movement in East Yorkshire during the Last (Weichsel) Glaciation, based upon stone orientation measurements of the Drab, Purple and Hessle Tills.

the topographical configuration of East Yorkshire was such that successive ice sheets invading the area from the north-east all followed the same pattern of movement. The latter demands the rather unlikely coincidence of all three ice sheets having just sufficient power to surmount the Chalk escarpment on the southern side of Filey Bay but not enough to drive completely over it, so that they were all forced to flow mainly to the east of Flamborough Head. Also, the repeated retreat and readvance of ice usually results in features such as the incorporation of masses of one till in another, the contortion and weathering of the surface layers of older tills, and the deposition of intercalated deposits containing indigenous fossils; the series of deposits comprising the Drab, Purple and Hessle Tills have none of these features. A variety of evidence therefore favours the deposition of these tills from a single composite ice sheet. Details of the origin, composition and melting processes of the type of glacier envisaged were discussed by Carruthers (1953); he also suggested that the Basement was deposited from the same ice sheet, but it is clear that at least an interglacial period separated deposition of the Drab, Purple and Hessle Tills from that of the Basement.

III. Microfabric of the Drab and Hessle Tills

Following their thin section examination of Wisconsin (Würm, Weichsel) tills from Ohio and Pennsylvania, Sitler and Chapman (1955) described three types of microfabric unit: (a) microfoliation due to roughly parallel alignment of silt flakes, (b) preferred orientation of long axes of sand grains and coal fragments, and (c) veining caused by thin bands of silt lying parallel to the microfoliation, which originated through shearing of the till. Ostry and Deane (1963) also used the preferred orientation of elongate sand grains to determine the direction of ice movement.

Thin sections of two of the Weichsel tills of East Yorkshire (the Drab and Hessle) were cut in the horizontal plane from orientated blocks of undisturbed till, using the methods of impregnation described by Catt and Robinson (1961). These were used for the measurement of preferred orientation of sand grains; they showed no signs of the veining described by Sitler and Chapman, but some showed weakly developed microfoliation. A quick method of measuring the orientation of elongate sand grains was developed by projecting the thin section, much enlarged, on to high contrast photographic paper; after development the resulting negative was used for making direct measurements of the long axes of sand grains with a protractor. Rose diagrams were then constructed from these measurements (Text-fig. 5). The directions of ice movement indicated by the maxima in these diagrams are the same as those suggested by the macrofabric study of till at the same localities



TEXT-FIG. 5.—Microfabric of Weichsel tills in East Yorkshire: the Hessle Till at 37. Hessle (TA 012259), 38. Eppleworth (TA 020323); the Drab Till at 39. Dimlington (TA 397211), 40. Atwick (TA 197511), 41. Skipsea (TA 184546), 42. Flamborough Head (TA 258705).

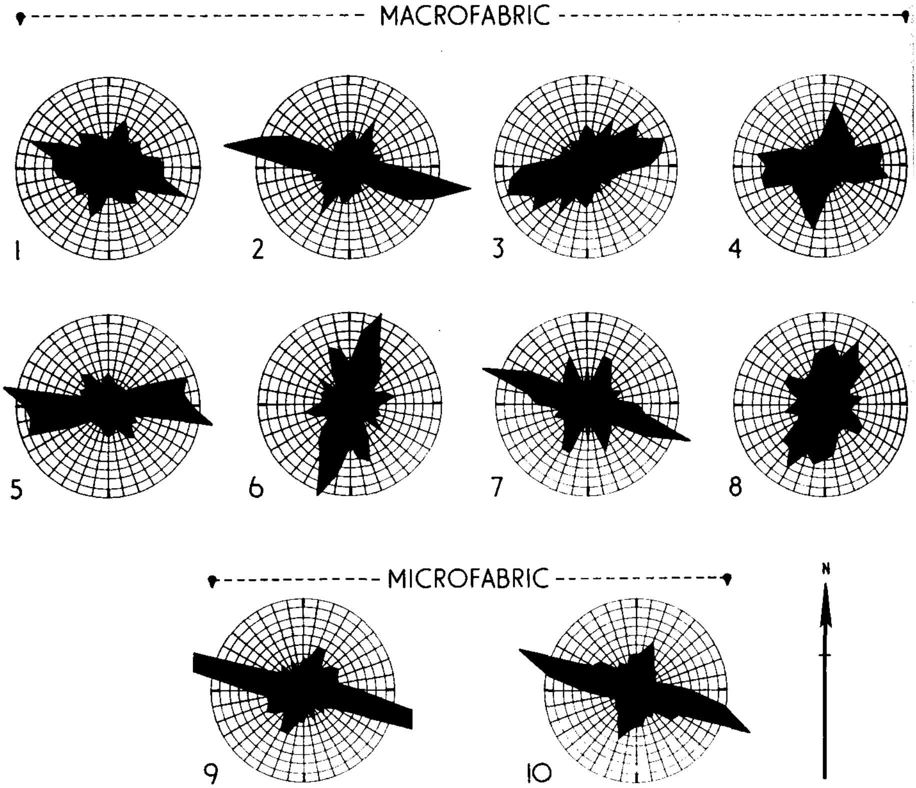
and horizons. The microfoliation of the Hessle and Drab is not as strongly developed as that described by Sitler and Chapman, possibly because micaceous minerals constitute a comparatively small part of the silt fraction, particularly of the Hessle Till. It was most easily detected with the help of a sensitive tint microscope accessory plate, as suggested by Sitler and Chapman. The directions of microfoliation in the Drab agree closely with the directions of ice movement determined by the other methods of fabric analysis.

IV. Fabric of the Basement Till

In comparison with the Weichsel tills of East Yorkshire, the Basement Till is poorly exposed. Throughout most of Holderness and Filey Bay its surface lies well below sea level, but it rises to form broad low ridges at Dimlington (Text-fig. 4) and at Bridlington. The Basement at Bridlington was carefully described by Lamplugh (1882, 1883), but it is rarely exposed nowadays. However, it is frequently visible in the foreshore and cliff base (to approximately 10 feet O.D.) between Holmpton (TA 376237) and Kilnsea Beacon (TA 413175), particularly at the foot of Dimlington Cliff (TA 392217). At Sewerby (TA 198685) an eroded surface of Basement Till is overlain by beach deposits of the buried Eemian cliff, the sea level at the time of formation of which was 3 to 5 feet above O.D. (Catt and Penny, 1966). This suggests that the surface of the Basement Till declining away from the buried cliff is a marine erosion surface, but as the Basement rises again at Bridlington and Dimlington this erosion surface must have been subsequently modified.

The stone orientation of the Basement Till was measured at eight localities in the Dimlington area. Two of the corresponding rose diagrams (Text-fig. 6, Nos. 6 and 8) show NNE–SSW maxima, a direction similar to the preferred stone orientation of the Weichsel tills at Dimlington; but many of the others have maxima almost perpendicular to this direction. Two thin sections of Basement from Dimlington also indicate a strong WNW–ESE preferred orientation of sand grains (Text-fig. 6, Nos. 9 and 10) and a weakly developed microfoliation in the same direction. Over a short distance the ice cannot have changed direction by as much as 90 degrees, and one of the two directions of strongly preferred orientation therefore represents an enlarged transverse (*b*) maximum. As the Basement Till contains erratics of shelly sand and clay derived from the sea bed and of many Jurassic and Cretaceous rocks exposed on the north-east Yorkshire coast, the ice that deposited it must have come from the north-east, and the strong WNW–ESE stone and sand grain orientation is therefore the *b* maximum.

The origin of the *b* maxima in till macrofabric has been discussed by many authors. Small subsidiary peaks at right angles to the direction of ice movement appear to be an almost universal feature of normal till fabric, but *b* maxima exceeding those in *a* are comparatively rare, and probably indicate abnormal depositional or post-depositional conditions. Donner and West (1957) and Glen, Donner and West (1957) suggested that strong shearing of the ice, which produces narrow band tills, causes stones to roll so that their long axes lie perpendicular to the direction of glacial transport. However, it is unlikely that this process alone is responsible for the strong *b* maxima of the Basement Till, because it is a very uniform till and shows fewer signs of the banding caused by shearing than, for example, the Drab. MacClintock and Dreimanis (1964) showed that stones in the highest 35 feet of the Malone Till in the St. Lawrence Valley were reorientated by the subsequent Fort Covington advance. As an ice-free interval followed deposition of the Basement, it was perhaps similarly modified by the later advance during the Weichsel. However, the fabric of the deformed Malone Till differs from that of the Basement at Dimlington in that the reorientated stones are parallel to the direction of the subsequent readvance, whereas the enlarged *b* maxima of the Basement are approximately perpendicular to the direction of movement of the Drab ice.



TEXT-FIG. 6.—Macrofabric and microfabric of the Basement (Saale) Till at Dimlington, East Yorkshire. The localities represented are: 1. Foreshore near Dimlington Farm (TA 398208), 2. Foreshore approx. 50 yds. NW. of locality 1, 3. Foreshore approx. 80 yds. NW. of locality 1, 4. Foreshore at TA 398209, 5. Foreshore approx. 30 yds. NW of locality 4, 6. Foreshore at TA 394215, 7. Base of cliff near locality 6, 8. Foreshore near Out Newton (TA 388223), 9. Foreshore at TA 389221, 10. Foreshore at TA 400205.

Although most of the rose diagrams for the macrofabric of the Basement Till at Dimlington show either *a* or *b* maxima, a few show either a combination of these two maxima (e.g. Text-fig. 6, No. 4) or a single strong peak at an intermediate (ENE–WSW) position (e.g. Text-fig. 6, No. 3). These probably represent an intermediate stage in the transformation of the original *a* lineation to the *b*, and are therefore similar to the intermediate types of macrofabric recognized by MacClintock and Dreimanis (1964, pp. 136–138). In one diagram (Text-fig. 6, No. 4) the longest axes of most stones lying between the two peaks occur in the NE/SW sectors and not the NW/SE sectors; this suggests that the reorientation of stones at that locality was accomplished by rotation in a clockwise direction.

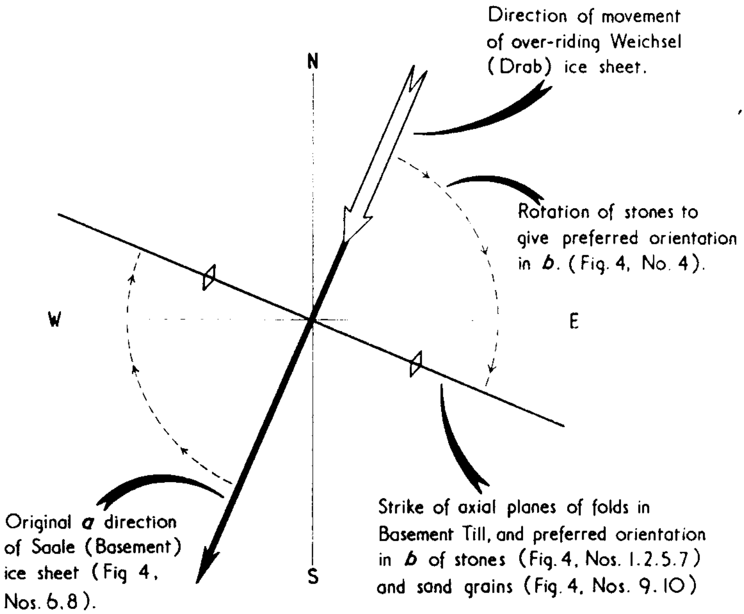
The mechanism by which the stones in the Basement Till were reorientated is suggested by the structural features of small overfolds occasionally revealed in the surface layers of the Basement immediately beneath the junction with the overlying Drab. These folds were clearly caused by the advance of the ice that deposited the Drab, because the strike of their axial planes is WNW–ESE. The stones in these contorted parts of the till are visibly orientated, especially in the fold crests, so that their long axes lie parallel to the *b* axes of the folds, thus providing an extreme example of well developed *b* lineation. At least some of the stones in the Basement were therefore reorientated by the subsequent advance of the Drab ice, but recognizable folds are not sufficiently numerous in the Basement at Dimlington to account for all the *b* stone orientation maxima. However, the recognizable folds are only visible because they are small and tight, and because they usually involve layers of till that are slightly dissimilar in colour or texture. Larger and less tight folds could easily remain invisible in till of generally uniform colour and texture, and within such folds the *b* lineation would probably be weaker than in the small tight folds, because the stones were possibly reorientated by rolling about their long axes—a movement controlled by the amount of shearing between successive layers in the fold limbs. The inferred relationship between directions of ice movement, stone orientation maxima and fold axes in the Basement Till is shown diagrammatically in Text-fig. 7.

If the Basement at Dimlington is so extensively contorted as the commonly occurring WNW–ESE maxima suggest, the force of the advancing Drab ice, which formed the folds, was probably sufficient also to modify the surface relief of the Basement. The heaping of contorted masses of Basement Till as a push moraine rising above the Eemian marine erosion surface (Catt and Penny, 1966) would account for the anomalous rise of the Basement into the foot of Dimlington Cliff. The ridge of Basement at Bridlington possibly originated in a similar way, but exposures there have never been good enough to allow stone orientation measurements to be made.

V. Joints in the Holderness Tills

During the structural investigation of the Pleistocene deposits in East Yorkshire a variety of vertical or subvertical cracks in the tills were observed. Some of these result from the decalcification, desiccation and consequent shrinkage of deposits, such as the Hessle Till, which have been subjected to postglacial weathering. Others are apparently inherent structural features of the deposits, because they have a definite relationship to the fabrics already discussed, and occur well below the depth to which weathering could possibly have penetrated.

At Dimlington the Basement Till is commonly exposed on the foreshore in a wavecut platform, which is dissected by numerous parallel grooves or troughs ranging from 6 to 12 inches in both depth and width. Although these are eroded and enlarged by the movement



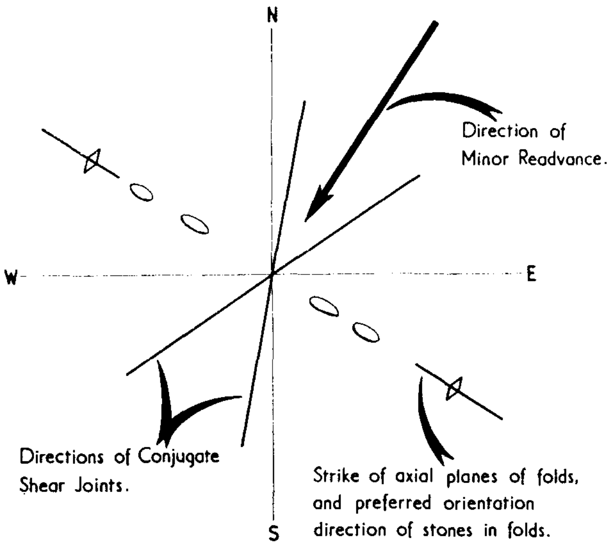
TEXT-FIG. 7.—The relationship between structural features in the Basement (Saale) Till at Dimlington, East Yorkshire, and ice movement directions during the Saale and Weichsel Glaciations.

of water on the shore, their marked straightness and parallelism suggest that their position was originally determined by a series of parallel, vertical joints in the till, and this is confirmed by the observation that most of the grooves pass down into barely perceptible subvertical cracks. Measurements taken in the field and from aerial photographs show that more than 95 per cent of the grooves are orientated between 30 and 40 degrees E of N. This direction cannot have been determined by the flow of water across the shore at low tide, because the direction of maximum slope of the boulder clay surface is more variable than this and usually near N 80° E. However, it is similar to the direction of ice movement at Dimlington during both the Saale and Weichsel Glaciations, and the joints are thus parallel to the *ac* plane of both glaciers. They were therefore either inherited as tension joints from the parent (Basement) ice, which, by analogy with modern glaciers, probably developed radial (*ac*) crevasses as it spread into the Holderness embayment; or they may be tension joints induced by the overriding Drab ice, which compressed the Basement Till parallel to the *a* direction and thus subjected it to tension normal to the *ac* plane.

Present knowledge of depositional and deformational processes in glaciers is too slight for a definite choice to be made between the two possible modes of origin of the *ac* joints. However, similarly orientated joints occur also in the Drab Till exposed in the cliff sections near Easington (TA 408187). If the three Weichsel tills were deposited from one composite ice sheet, as previously suggested, the Drab Till at this locality was not deformed by a later ice advance, and the *ac* joints in it are therefore probably inherited from the parent ice. If the joints in the Basement Till originated as radial crevasses in the parent ice, they would not necessarily have been destroyed or even appreciably deformed during the subsequent contortion by the advancing Weichsel glacier. Indeed, much of the movement in the till during formation of the push moraine at Dimlington might have been accomplished simply by lateral displacement along these planes of weakness. It is therefore tentatively suggested that the joints were initiated during deposition of the Basement Till as tension cracks inherited from the parent ice, and that they were possibly accentuated by differential movement of adjacent masses of till and perhaps also by stretching in *b* during the period of deformation caused by the advance of the Weichsel glacier. However, not every joint represents a crevasse in the Saale ice sheet. Expansion of the glacier in the *b* direction would have produced many parallel planes of weakness in the ice, but to relieve the tension the ice probably crevassed along only a few of these planes. The joints in the Basement are probably sufficiently numerous to account for most of the planes of weakness in the ice, but the exact mechanism by which they were preserved during melting is difficult to visualize.

A second type of jointing occurs in the Drab Till exposed in the cliffs near Barmston (TA 174579). This consists of two intersecting sets of joints orientated N 10° E and N 55° E, which are most clearly visible at the foot of the cliff where it is washed by the sea. The joints at this level form smaller grooves than those in the Basement at Dimlington, and pass upwards into extremely narrow cracks in the till. Englacial gravels overlying the Drab at this place are strongly contorted, and many of the folds extend down into the till. The strike of the axial plane was measured in six of these folds, and gave a mean direction of N 122° E; the stones in the folded parts of the till are visibly orientated in the same direction. A line at right angles to this direction coincides with the acute bisectrix of the two sets of joints (i.e. N 32° E), which suggests that both folds and joints were formed under the same stress conditions, and that the latter are conjugate shear joints. The relationship of these structural elements is shown in Text-fig. 8.

The folds and joints in the Barmston cliff section clearly indicate that the Drab Till was contorted after deposition, presumably by a subsequent readvance of ice. However, this does not invalidate the earlier



TEXT-FIG. 8.—The relationship between joints, folds and stone orientation in the contorted Drab Till of the Barmston push moraine, East Yorkshire.

conclusion that the Drab, Purple and Hessle Tills were all deposited during one major ice advance. The cliffs here provide an oblique section of a small arcuate ridge, which has already been interpreted as a push moraine (Valentin, 1957, p.43), and the folds and shear joints occur only within the limits of this ridge. The readvance was therefore only a minor local oscillation of the ice front, and probably occurred at a fairly late stage during the melting of the Weichsel glacier in Holderness.

Although the Basement at Dimlington and the Drab at Barmston suffered similar glacial-tectonic histories, their joint patterns are markedly different. However, these differences are no greater than the bewildering variety of joints commonly encountered in deformed consolidated rocks, and are probably due to differences in texture and strength of the tills and in the forces applied to them.

VI. Conclusions

The mechanism by which till stones assume a preferred orientation is still not fully understood, and it is important that an observed stone orientation should be related to the complete structural history of the till. A preferred orientation may represent any of the following:

(i) the direction of movement (*a*) of the parent ice (Richter, 1932);
(ii) an abnormally enlarged transverse (*b*) lineation derived from the parent ice (Donner and West, 1957; Glen, Donner and West, 1957);
(iii) the *a* direction of a later readvance (MacClintock and Dreimanis, 1964);
(iv) the *b* direction of a later readvance (this paper).

Further, this list does not even take into account the possible effects of other post-depositional processes, such as rearrangement by solifluction. In glacial deposits, as in metamorphic rocks, there is a causal connection between transport direction and a variety of structural features, of which stone orientation is only one. The amount of information obtained from stone orientation studies alone is limited, and fabric studies of glacial drifts should be expanded to include other investigations, thereby allowing a synthesis of the complete structural framework of the deposits to be made.

We thank Mr. E. M. Thomson and the staff of the Cartography section of the Soil Survey of England and Wales for drawing the diagrams.

REFERENCES

Banham, P. H., and C. E. Ranson, 1965. Structural Study of the Contorted Drift and Disturbed Chalk at Weybourne, North Norfolk. *Geol. Mag.*, **102**, 164–174.
Bisat, W. S., 1940. Older and Newer Drift in East Yorkshire. *Proc. Yorks. geol. Soc.*, **24**, 137–151.
Carruthers, R. G., 1953. *Glacial Drifts and the Undermelt Theory*. H. Hill & Sons Ltd., Newcastle upon Tyne. vi + 42 pp.
Catt, J. A., and L. F. Penny, 1966. The Pleistocene deposits of Holderness, East Yorkshire. *Proc. Yorks. geol. Soc.*, **35**, 375–420.
—— and P. C. Robinson, 1961. The Preparation of Thin Sections of Clays. *Geol. Mag.*, **98**, 511–4.
Donner, J. J., and R. G. West, 1957. The Quaternary Geology of Braganeset, Nordaustlandet, Spitsbergen. *Skr. norsk Polarinst.*, **109**, 1–29.
Elson, J. A., 1966. Early Discoverers XXIII. Till Stone Orientation. Henry Youle Hind (1823–1908). *J. Glaciol.*, **6**, 303–6.
Glen, J. W., J. J. Donner, and R. G. West, 1957. On the mechanism by which stones in till become oriented. *Am. J. Sci.*, **255**, 194–205.
Harrison, P. W., 1957. A clay-till fabric; its character and origin. *J. Geol.*, **65**, 275–308.
Hind, H. Y., 1859. A preliminary and general report on the Assiniboine and Saskatchewan exploring expedition. *J. legisl. Assembl. Can.*, **19**, App. 36.
Holmes, C. D., 1941. Till Fabric. *Bull. geol. Soc. Am.*, **52**, 1299–1354.
Hoppe, G., 1953. Några iakttagelser vid Isländska jöklar sommaren 1952. *Ymer*, **73**, 241–265.

KENDALL, P. F., 1902. A System of Glacier-Lakes in the Cleveland Hills. *Q. Jl geol. Soc. Lond.*, **58**, 471–571.

LAMPLUGH, G. W., 1878. On the occurrence of marine shells in the boulder clay of Bridlington and elsewhere on the Yorkshire coast. *Geol. Mag.*, II, **5**, 509–517.

—— 1879. On the divisions of the glacial beds in Filey Bay. *Proc. Yorks. geol. Soc.*, **7**, 167–177.

—— 1881. On the Bridlington and Dimlington Glacial Shell-Beds. *Geol. Mag.*, II, **8**, 535–546.

—— 1882. Glacial Sections near Bridlington. *Proc. Yorks. geol. Soc.*, **7**, 383–397.

—— 1883. Glacial Sections near Bridlington. Part II Cliff Section extending 900 yards south of the Harbour. *Proc. Yorks. geol. Soc.*, **8**, 27–38.

—— 1884. On a recent exposure of the shelly patches in the boulder clay at Bridlington Quay. *Q. Jl geol. Soc. Lond.*, **40**, 312–328.

MACCLINTOCK, P., and A. DREIMANIS, 1964. Reorientation of till fabric by overriding glacier in the St. Lawrence Valley. *Am. J. Sci.*, **262**, 133–142.

MILLER, H., 1884. On Boulder Glaciation. *Proc. R. phys. Soc. Edinb.*, **8**, 156–189.

NORRIS, G., 1962. Some Glacial Deposits and their Relation to the Hippopotamus-bearing Beds at Barrington, Cambridgeshire. *Geol. Mag.*, **99**, 97–118.

OSTRY, R. C., and R. E. DEANE, 1963. Microfabric Analyses of Till. *Bull. geol. Soc. Am.*, **74**, 165–8.

RICHTER, K., 1932. Die Bewegungsrichtung des Inlandeises reconstruiert aus den Kritzen und Längsachsen der Geschiebe. *Z. Geschiebeforsch. Flachldgeol.*, **8**, 62–6.

—— 1933. Gefüge und Zusammensetzung von dem norddeutschen Jungmorängebietes. *Abh. geol.-palaeont. Inst. Greifswald*, **11**, 1–63.

—— 1936. Gefügestudien im Engebrae, Fondalsbrae und ihren Vorlandsedimenten. *Z. Gletscherk. Eiszeitforsch. Gesch. Klimas*, **24**, 22–30.

SEIFERT, G., 1954. Das mikroskopische Korngefüge des Geschiebemergels als Abbild der Eisbewegung, zugleich Geschichte des Eisabbaues in Fehmarn, Ost-Wagrien und dem Dänischen Wohld: Meyniana. *Veröff. geol. Inst. Univ. Kiel.*, **2**, 124–190.

SITLER, R. E., and C. A. CHAPMAN, 1955. Microfabrics of till from Ohio and Pennsylvania. *J. sedim. Petrol.*, **25**, 262–9.

STATHER, J. W., 1898. A glaciated surface at Filey. *Proc. Yorks. geol. Soc.*, **13**, 346–9.

STEVENS, L. A., 1960. The Interglacial of the Nar Valley, Norfolk. *Q. Jl geol. Soc. Lond.*, **115**, 291–312.

SUGGATE, R. P., and R. G. WEST, 1959. On the extent of the Last Glaciation in Eastern England. *Proc. R. Soc.*, B, **150**, 263–283.

VALENTIN, H., 1957. Glazialmorphologische Untersuchungen in Ostengland. *Abh. geogr. Inst. frei. Univ.*, **4**, 1–86.

WEST, R. G., and J. J. DONNER, 1956. The Glaciations of East Anglia and the East Midlands: a differentiation based on stone orientation measurements of the tills. *Q. Jl geol. Soc. Lond.*, **112**, 69–91.

WOOD, S. V., and J. L. ROME, 1868. On the Glacial and Postglacial Structure of Lincolnshire and South-east Yorkshire. *Q. Jl geol. Soc. Lond.*, **24**, 146–184.

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