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THE IRISH SEA GLACIATION OF NORTH SHROPSHIRE—SOME ENVIRONMENTAL RECONSTRUCTIONS

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This paper is concerned with the effects of an advance of Irish Sea ice into the north Shropshire area. Observations of the sedimentary record reveal the presence of a lower till, below sands and gravels, and an upper till which is intimately associated with sands and gravels. Detailed interpretation based on stratigraphic relationships, external shape, and internal structure of these lithostratigraphic units is used to develop a hypothesis that the sediments are derived from a single ice-sheet. The lower till is believed to have been transported in a basal position within the ice, whereas the upper till is thought to have been transported along englacial shear planes. Associations of sedimentary structure, morphology and collapse structures are used to differentiate ice-contact fluvio-glacial and deltaic sediments. The total view of the sedimentary features and the physiographic situation is used to illustrate the early stagnation of parts of the Irish Sea ice-sheet. Although small ice-marginal lakes are illustrated, there is evidence against the presence of a large lake in the area during the waning of the ice-sheet being considered. Much of the evidence for Lake Lapworth therefore requires re-interpretation. Finally, by reference to findings in adjacent areas, the ice advance under discussion is tentatively proposed to be of late Weichselian age.

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INTRODUCTION

THE Shropshire plain and adjacent areas have undergone considerable landscape changes during the Quaternary. Radical changes in the courses of the major streams are indicated by the presence of deep, abandoned valleys. Fall in sea level, a consequence of abstraction of water by vast continental ice sheets, enabled ancestral

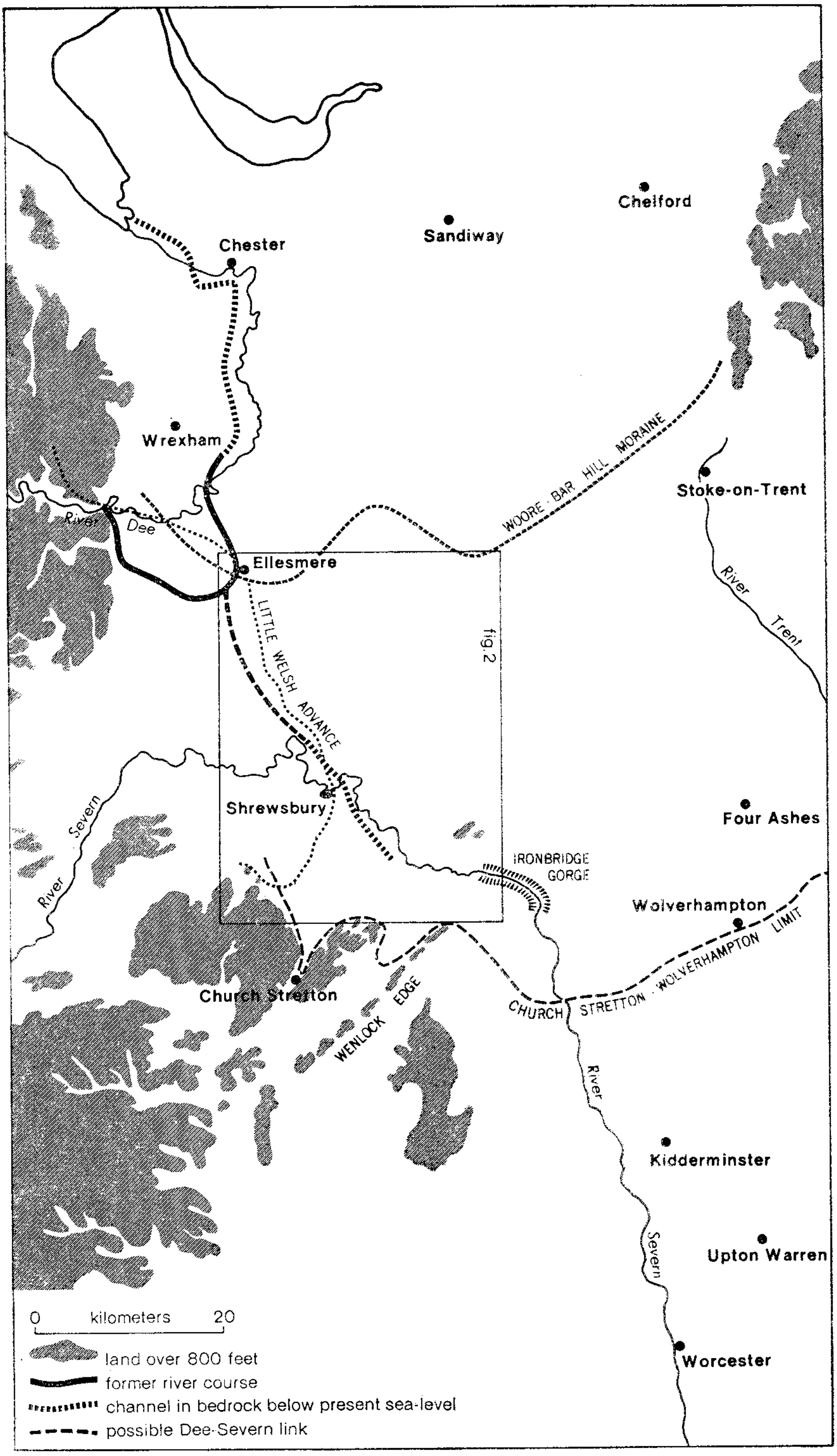


FIG. 1.

Physiographic setting, major drainage changes and ice limits.

streams to cut valleys below present sea level (Fig. 1). Wills (1912) used geomorphological argument and borehole records of the depth to bedrock to support his suggestion that the River Dee previously flowed south of its present course in a broad arc extending to the vicinity of Ellesmere (Fig. 1). In the northern part of the former course several borehole records show the valley floor to have been below present day sea level. On less convincing evidence Wills also proposed that the Upper Severn drainage system extended northwards, from Wenlock-Pennine watershed, and was tributary to the Dee. However, certain difficulties are met with in this hypothesis. The valley floor of the early Severn in the Shrewsbury area is found to be as much as —28·2 m (60 ft.) O.D., which is lower than the values obtained for the early Dee east of Wrexham. Although it is unreasonable to admit upstream segments of an ancient river system at lower levels than downstream reaches, we must be aware of the limitations of the evidence. It may be that borehole records in the Wrexham area strike the sides of the buried valley without indicating the maximum valley depths; whereas maximum depths may have been obtained in the Shrewsbury area. The problem of a previously integrated Upper Severn-Dee drainage system can probably be resolved by further sub-surface investigations, particularly in the area between Ruyton and Myddle, where there may be an extension (C. A. Sinker, pers. comm.) of the deep trough which occurs below the Severn valley near Shrewsbury (Fig. 2).

The direct influence of glacier ice on the changes of drainage is difficult to establish. However, many other lines of evidence illustrate past incursions of ice into the north Shropshire plain. Large volumes of till are found at many localities. Deposits which have accumulated by sedimentation from streams draining glaciers are widepsread. Channels cut into hillsides are believed to have originated as a result of erosion by streams flowing between the hill and an ice margin. Examination of glacial sediments in the area reveal that two types can be differentiated on the basis of lithologic content. Ice advance from a generally northern direction brought granites, flints and marine shells from Scotland, the Lake District and the Irish Sea basin. Large quantities of material derived from the Trias in the Cheshire and Shropshire lowland are also incorporated in this drift. Glacial deposits which are predominantly northern in provenance were deposited by ice advances which are referred to as Irish Sea. Welsh ice moving east or south-east, down valleys extending from the Welsh hills, carried with it fragments of mudstone and sandstone, and volcanics from the Lower Palaeozoic formations. In some cases the matrix of the Welsh till is dominated by Triassic detritus and the till appears bright red. Elsewhere comminuted Palaeozoic mudstones dominate and buff-coloured sediments result. Although some intermixing of the Welsh and Irish Sea drifts occur the provenance of a given deposit is usually distinctive as a result of domination by rocks of one lithological association.

This paper is concerned with a single advance of Irish Sea ice. By limiting the discussion to a single advance it is possible to concentrate on detailed observations which allow confident interpretation of environmental conditions and glacial processes. However, the advance under discussion is just one episode within a complex sequence, and it would be helpful at this stage to place this advance into a regional and chronological context.

Wills (1950) subdivides the glacial deposits of the English Midlands into Older and Newer Drifts. Glaciers from Wales, the Irish Sea, and Eastern England deposited the older drift, and extended further south than the Newer Drift limits. Knowledge

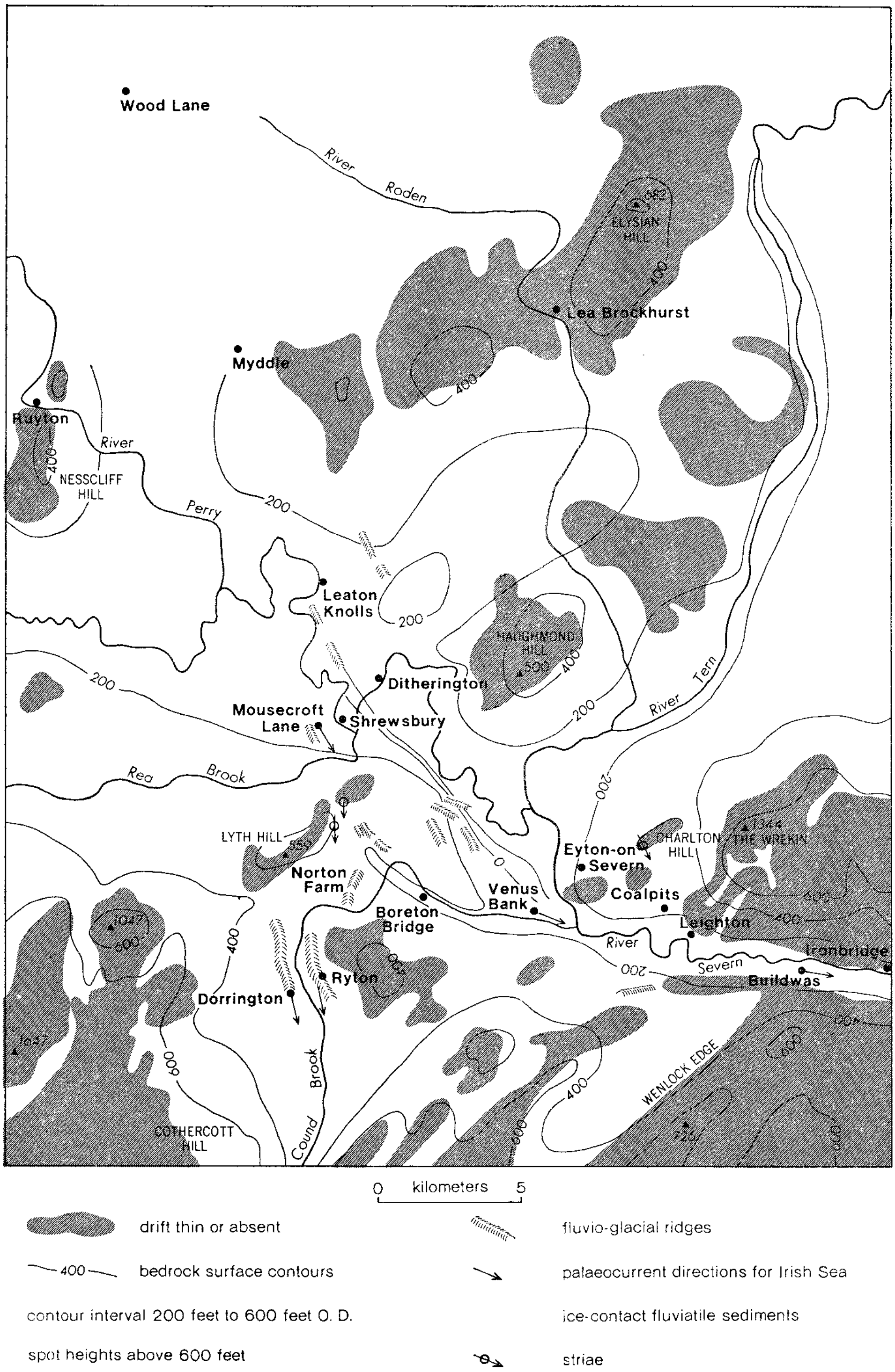


FIG. 2.

The study area. Bedrock contours and selected glacial features are illustrated.

of the timing of Older Drift events is sparse and in this paper attention will be confined to the Newer Drifts. Following the last interglacial, the Riss/Würm or Eemian Interglacial, broad-leaved deciduous trees were absent from the British landscape and a cold period, the Würm or Weichselian, ensued. C^{14} dating of coniferous wood, from sands which occur at Chelford (Fig. 1), below the Irish Sea advance to be discussed, shows that the trees were growing at about 57,000 years B.P. This date corresponds with an interstadial (i.e. a slightly warmer event within a cold period), the Brørup Interstadial in continental Europe. Organic deposits at Upton Warren were dated at about 42,000 B.P. by the C^{14} method. Although tree remains were not found at Upton Warren their absence is attributed to control by herbivorous animals rather than climate (Coope *et al.*, 1961). The date of 42,000 B.P. lies within the age range of the Gottweig Interstadial in Europe. By means of morphological and stratigraphic correlation attempts have been made to place Newer Drift glacial advances into the dating framework of the interstadials. A pronounced morainic system passing through Ellesmere and Whitchurch (Fig. 1) was thought to represent a post Gottweig Irish Sea glaciation limit. An ice limit through Church Stretton and Wolverhampton (Fig. 1) represents the maximum extent of the Main Irish Sea glaciation. The retreat of this advance has been correlated in time with the development of the Severn Main Terrace, which occurs 30 m above the present river at Bridgnorth (Wills, 1950). Coope *et al.* (1961) have related the Upton Warren deposits to the Severn Main Terrace, and suggest that the Main Irish Sea glaciation reached a maximum before 42,000 B.P. According to Wills (1924, 1950) retreat of the Main Irish Sea glaciation to a position north of the Pennine-Wenlock watershed resulted in the formation of Lake Lapworth. Drainage of the lake across the watershed was believed to have initiated the Ironbridge gorge. The deposits described in this work are those of the Main Irish Sea advance. Recently acquired C^{14} dates and detailed sedimentological observations require that both the suggested timing and environmental conditions of this advance be considerably revised.

In the area to the west of Shrewsbury the surface glacial deposits are of Welsh provenance. In the Shrewsbury area these surface deposits are seen to overlie Main Irish Sea glaciation deposits and, therefore, represent a post Main Irish Sea advance of Welsh ice. Wills (1950) has referred to this late advance of local ice as the "Little Welsh Advance". The approximate limits of this advance are illustrated in Figure 1.

The Physiographic Situation

This paper aims to illustrate the development of glacigenic landforms and sediments. In the area of study considerable influence is believed to have been exerted on ice movement by the bedrock physiography. The physiographic controls can be recorded by tracing the sub-drift surface. Although advancing glaciers may move over previously deposited surficial sediments, sub-drift contours give a useful estimate of the amplitude and trend of relief elements encountered by ice entering a region.

The sub-drift surface is seen in Figure 2. The important features are the generally southerly rise of the sub-drift surface from about 76·2 m (250 ft.) O.D. to over 304·8 m (1,000 ft.), the presence of a series of north-east to south-west trending ridges of drift-free higher land, and the deep buried valley corresponding to the present Severn Valley. The most northerly ridge depicted on Figure 2 is of Triassic Sandstone; this ridge rises some 121·9 m (400 ft.) above the sub-drift surface to the north. Southward the sub-drift surface falls rapidly to the proto-Severn valley floor. A north-east to south-westerly grain to the topography is again shown in the Haughmond-Lyth Hill ridge which is largely composed of Longmyndian sedimentary rocks. A further rise of the sub-drift surface occurs along a line from the Wrekin extending in a south-westerly direction to Caer Caradoc and the Lawley. South-eastwards from the Wreklin-Lawley ridge the successive escarpments of Hoar Edge, Kenley ridge, and Wenlock Edge parallel the north-east to south-westerly topographic grain and also mark a general south-easterly rise in the level of the sub-drift surface.

SEDIMENTS OF THE IRISH SEA ICE SHEET

Glacial deposits containing derived marine shells, granites, flints and other erratics of northern provenance are believed to have been transported into the study area by an ice-sheet referred to as the Irish Sea ice. Striations and evidence from particle orientation in tills confirm ice movement from the north or north-west. The stratigraphy, lithology and landforms associated with the Irish Sea ice are especially interesting as their interpretation, in terms of mode and sequence of deposition, has been the subject of considerable controversy. Unfortunately most of the evidence is to be found in limited exposures between which correlation is particularly hazardous. The aim of this section will be to group the deposits according to their genesis. The environmental reconstructions and sequence of events are dependent on the significance of the grouped properties. If the meaning of the grouped properties is misunderstood then the interpretations will be invalid. Generalized successions based on borehole logs and records from exposures are presented in Figure 3. Three major lithostratigraphic units are proposed: (a) lower till, (b) sands and gravels, (c) till-stratified drift association. The remainder of this section will be given to establishing the rationality of this division. The proposed genesis of the lithostratigraphic units will then be used to discuss the transport and deposition of the Irish Sea deposits.

Lower till

The lower till is not associated with commercially exploitable deposits and, therefore, it tends to be exposed only in stream banks. However, one major civil engineering excavation provided a good exposure. The stratigraphic position of this till is the initial factor by which it is identified. At Leighton Village (611056), and in the Coalpits Brook (558067), till of Irish Sea provenance is to be seen overlying blue-black Cambrian shales. At Ditherington (503135) excavations for a sewage pipeline in 1968 exposed till directly above shattered Keele sandstone (Plate I). Irish Sea till at Leaton Knolls (472175) overlies bedded sands and gravels which rest on Bunter sandstone (Pocock and Wray, 1925, p. 74). Shotton (1962) reports a till overlying sands and gravels which in turn overlie Keele sandstone at Mousecroft Lane (475109). Otherwise limited boreholes to bedrock (Fig. 3) illustrate that the sands and gravels are not underlain by till. However, Irish Sea till is noted below the fluvial sands at Boreton Bridge (516068), and sheet 152 of the Geological Survey of England and Wales illustrates that the till is widespread in positions lateral to the sands and gravels. The important feature of the tills in this section is that they lie directly above or close to bedrock, hence the term lower till.

The limited exposure and borehole data cause difficulty in estimating the extent and thickness of the lower till. Excavations at Ditherington revealed the till to be

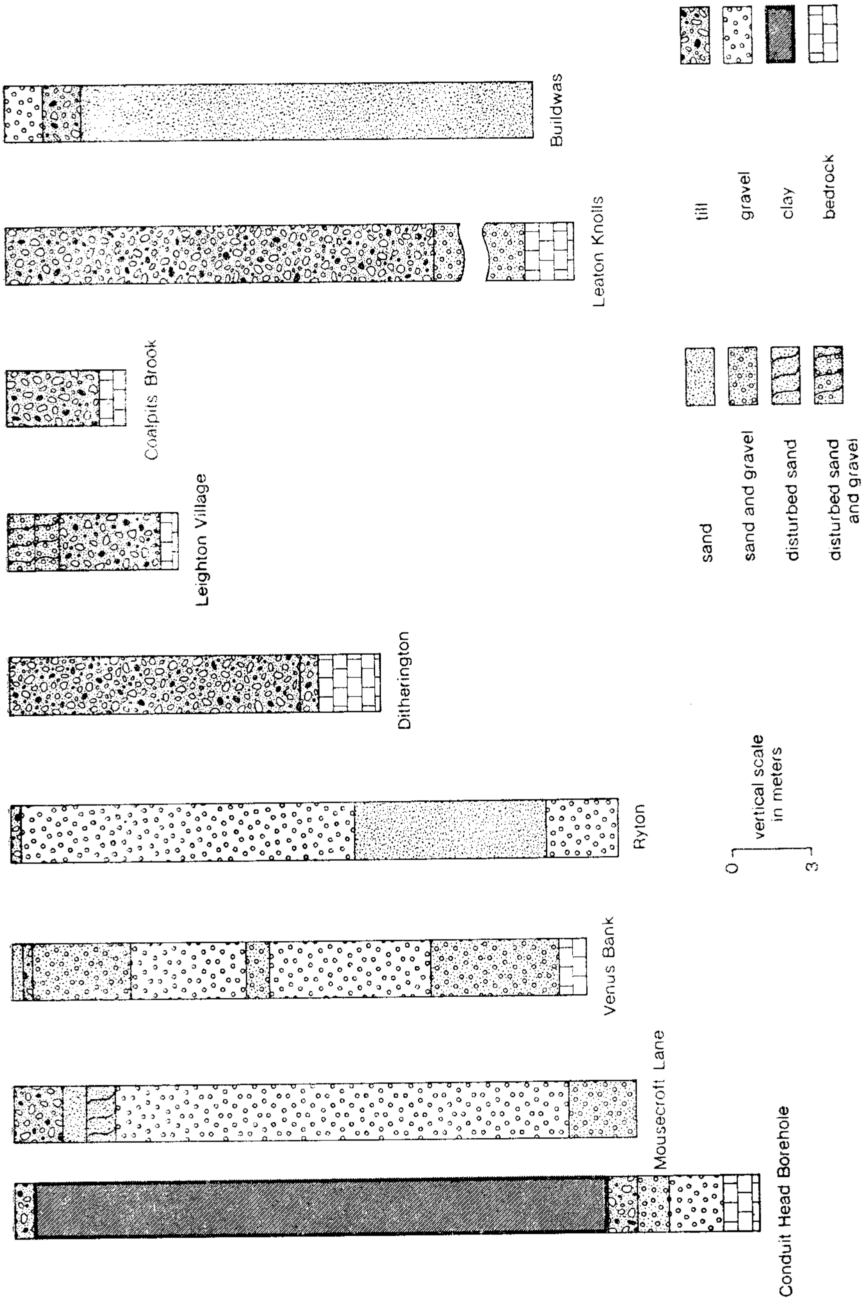


FIG. 3.
Generalized sedimentary successions.

approximately 10 m thick over a distance of 400 m. Elsewhere the till thicknesses vary between 20 m at Leaton Knolls to 3–4 m at Leighton. However, in most cases the upper surface of the till has been eroded and the thicknesses given are consequently minimum values.

The contacts between a till and underlying or overlying materials are often useful indicators of its mode of deposition. At those sites where the lower till rests directly on bedrock, the basal parts incorporate a high proportion of the country rock. Evidently erosional activity by the ice continued until shortly before the till was deposited. At both Ditherington and Leighton contorted fluvio-glacial sands and gravels dip at steep angles to the horizontal although the underlying till is undisturbed. It is probable that the sands and gravels were deposited on ice, and were disturbed during melting, whereas the undisturbed till was deposited beneath this ice.

The internal structures of the lower till are particularly instructive. At each site approximately horizontal fracture planes and foliation occur. Fracture planes at Leaton Knolls cause the till to break up into lens-shaped sections about 0·1 m thick and up to 2 m. long. The till at Coalpits Brook also shows horizontal fracture planes such that layers, 6–10 cm thick, may be lifted with a spade. Foliation is best developed at Ditherington where the micro-foliation shows clearly developed augen type structures around pebbles. Again the foliation is horizontal.

Occasional stringers and lenses of sand and gravel occur within the unsorted till. Detailed observations of these were made at Ditherington. The sand stringers are approximately horizontal and are usually between 2–4 cm thick. The stringers are discontinuous and show a maximum length of 1 m. Stratified sediments also occur in horizontal channels of lens-shaped cross-section. Erosional boundaries occur at both the upper and lower contacts between the channel sediments and the till. Stratification within the channels is conformable with the lower surface and generally the infill is gravel below horizontally stratified sand.

Measurements of till particle long axis orientation were carried out on pebble-sized particles in the field and also on sand and silt particles from microscope thin sections. The thin sections were prepared from till blocks impregnated with "araldite" cement. A clear north-west to south-east preferred orientation pattern, at both the macro and micro scales, emerged from the measurements (Fig. 4). The few striae measurements (Fig. 2) show that there is a parallelism between the preferred pattern and the striae. There can be little doubt that the till particles are arranged with long axes parallel to the ice movement direction.

Diagrams a, b, and c (Fig. 4) are particularly significant with respect to dip. In each case there is a pronounced preferred up-glacier dip of long axes. The two sites of these observations are up-glacier from the Haughmond-Lyth Hill ridge (Fig. 2). The significance of these observations will be referred to later.

As the tills of Irish Sea provenance were being studied under the microscope it became apparent that there were two populations of till in terms of grain size. The relative proportion of sand to silt and matrix was determined for each slide, using a point count method and an eyepiece micrometer. The results of this analysis were expressed in a sand/silt-matrix ratio and plotted on the dispersion diagram (Fig. 5). The diagram shows that tills from the three sites Ditherington, Leaton Knolls and Coalpits Brook are much coarser than those tills to be considered later.

Interpretation

The similarity of stratigraphic position, texture, particle orientation, and internal structural features shown by the tills described is thought to illustrate the validity of combining them into a single group. Furthermore, these similarities are believed to occur as a result of distinct processes during transport and deposition of the debris

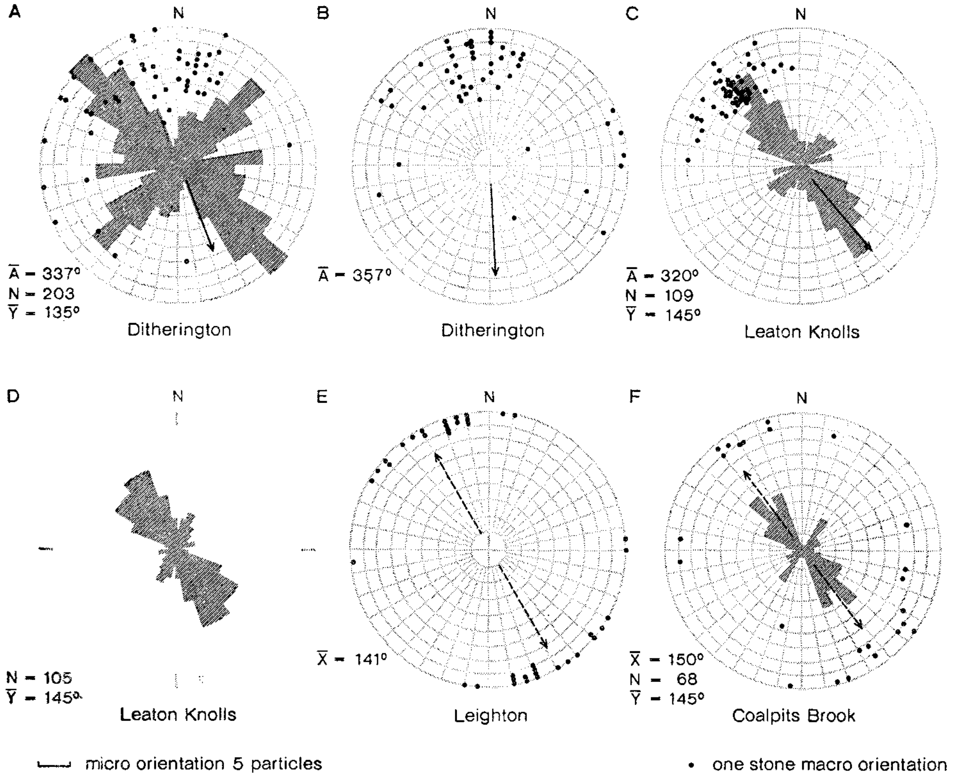


FIG. 4.

Till particle long axis orientation from macro and micro analysis of the lower tills.
$\bar{A}$ = Vector mean direction from the macro-fabric three dimensional 360° distribution.
$\bar{X}$ = Vector mean direction for the macro-fabric two-dimensional 180° distribution.
N = Number of micro-fabric particles.
$\bar{Y}$ = Mid-point of the 30° micro-fabric mode.

of the Irish Sea ice sheet. By interpreting the properties it is possible to begin a reconstruction of past conditions and events.

The stratigraphic position and presence of locally derived material imply that the till was carried close to the base of the ice mass. Certain properties are to be expected of tills carried in this position and it will be seen that the lower tills exhibit many of the expected properties.

Confirmation of high debris content at the base of continental ice sheets has occurred only recently. Behrendt (1963), using seismic evidence, suggested 13 per cent moraine content for the basal part of The West Antarctic ice sheet. Lliboutry (1966) disputed these findings, but Gow *et al.* (1968) obtained borehole evidence of 4–5 m of debris charged ice, beneath 2,164 m of Antarctic ice. Furthermore, Gow observed that the till occurs in ice, at pressure melting point, overlying free water. Gow also reports that ice plasticity and preferred ice crystal orientation do not occur in the upper 900 m of the ice.

The above observations suggest a high probability that the basal parts of a continental ice cap will be more or less continually charged with debris and, therefore, with till release, a sheet like till body is expected. The sheet like distribution of the

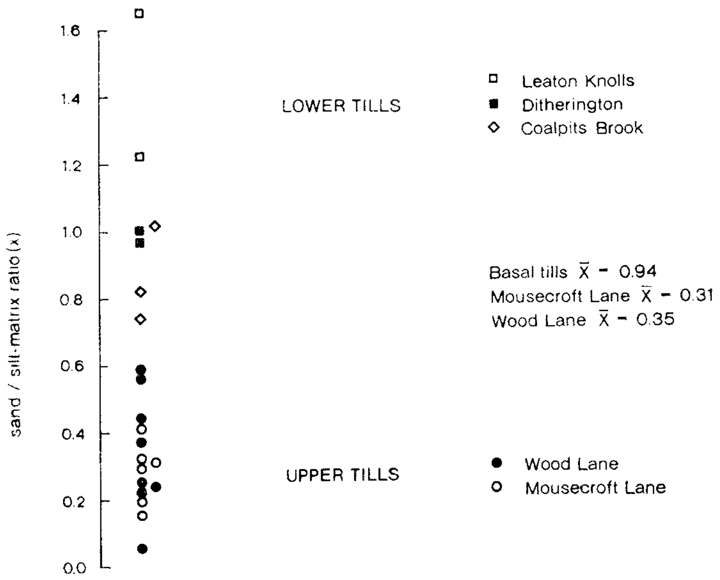


FIG. 5.
Sand/silt-matrix ratio for lower and upper tills.

lower till, U.K. Geological Survey Sheet 152, confirms the expected form. In areas where glacifluvial sediments rest directly on bedrock (Fig. 3), fluvial erosion of the till has probably occurred. In other areas fluvial sediments resting on lower till are contorted whereas the till is not. Evidently the fluvial material was deposited either above, or laterally supported by, the ice from which the till was basally released.

Gow *et al.* (1968) have reported the presence of meltwater at the base of thick continental ice. Hoppe (1963, p. 41) has noted that sorted lenses of material frequently occur within till. He suggests that the sorted material is deposited in small pockets beneath the ice. H. Johansson (1968) quotes G. Lundqvist (1951) who stated that sorted lenses within till were formed ". . . just when an ice layer had melted away and short open channels were open for a short time before the main mass settled". The above mentioned observations and conclusions are particularly relevant to an interpretation of the lower till in the study area. The presence of water at the base of the ice is necessary to produce erosion of the till. The upper erosional surface shows that the upper part of the till was held within the ice at the time of erosion. The stringers and channels of sand are also explained by Lundqvist's (1951) arguments. Therefore, the presence of sorted material is compatible with a basal origin for the lower till. Furthermore, the presence of fissile structure and relatively undisturbed particle orientation requires that the water is able to drain freely from the till. Free drainage permits the compaction necessary for the formation of fissile structure, and also restricts fluid deformation which would disturb primary particle orientation. The channels with stratified infill indicate that sub-glacial drainage was developed. The fissile structure illustrates that till release occurred under the pressure of a considerable thickness of ice and with the presence of interstitial water (Sitler and Chapman, 1955, p. 267).

Basal tills are expected to show regional parallelism of fabric. Harrison (1957) reports such a regional trend for supposed basal tills in the Chicago area. Observations on recently deposited ground-moraine (Richter, 1932; Hoppe, 1953; Okko, 1955; Donner and West, 1957) show a very strong parallelism between the preferred orientation of stones in the till and the direction of ice movement. The agreement between the preferred orientation of the lower tills and ice movement inferred from striae suggests that these tills were deposited basally. Till stones at the two sites up-glacier from the Haughmond—Lyth Hill ridge (Fig. 2) exhibit a pronounced up-glacier dip. Active ice behind this obstacle must have developed compressive flow with pronounced shear planes. It is though that the dip of the till particles is a manifestation of the shearing flow.

The dispersion diagram illustrating textural characteristics of the lower and upper tills (Fig. 5) shows the lower tills to be coarser. Two possible reasons may be put forward to explain this. First Lister (1958) has indicated that the further a till has travelled the finer its particles become. The large amounts of local bedrock in the basal till indicate relatively local derivation, therefore, coarser material is to be expected. However, textural characteristics of the rocks from which the till is derived must be considered together with the distance of transport. The country rock in the study area is predominantly sand and therefore a sandy till is likely to occur. To the north finer textured bedrock (Keuper Marl) predominates. Therefore, both the character of the local bedrock and the limited distance of transport may have been responsible for the relatively coarse nature of the lower till. The textural character supports the contention that the lower tills were confined to the basal parts of the ice.

The above discussion illustrates similarities in the properties of the lower tills which permit their being grouped together. A summary of the properties is given below:

(a) Stratigraphic position toward the base of the Irish Sea suite of deposits.
(b) Sheet form and widespread distribution.
(c) Containing locally derived materials.
(d) Parallel micro and macro particle orientation on a regional scale.
(e) Foliation at both the micro and macro scales.
(f) Incorporation of undisturbed lenses of sorted material which show erosional contacts on both upper and lower surfaces.
(g) Texture closely related to the country rock.

Sands and Gravels

The sands and gravels in the study area are being constantly quarried and are consquently very well exposed at certain sites. Because of the great variability of water lain glacial sediment, a few large exposures are more informative than are numerous smaller ones. Detailed mapping of such large exposures can be used to reconstruct the conditions in the palaeo-environment. The interpretation of water-lain sediments has been aided by relatively recent progress in the understanding of a systematic relationship between the form of a sand bed and stream power (mean velocity of the stream × the force per unit area exerted at the bed by the stream). The general relationship is shown in Figure 6, but some explanation of the bedform terms used is required. Furthermore, individual bed forms give rise to certain types of stratification. As it is the stratification which is available for study in ancient sediments, stream power is inferred from our knowledge of the relationship between stratification and bedform, and the dependence of bedform upon stream power. This is explained in the following paragraphs.

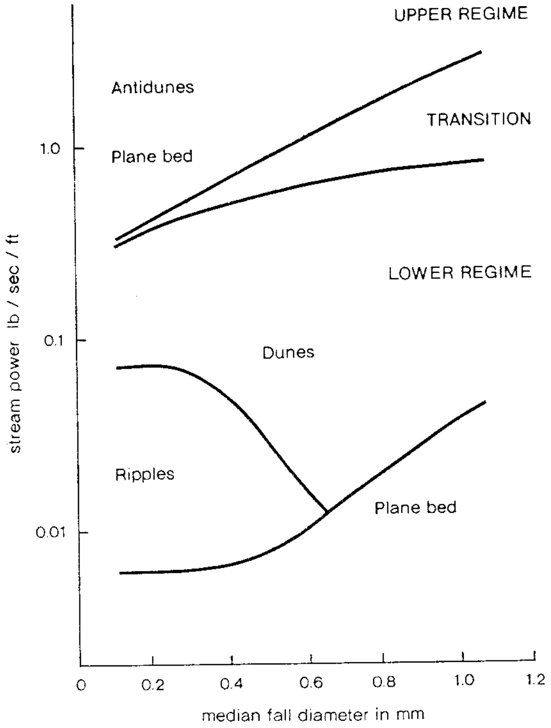


FIG. 6.
The relationship between stream power, bed grain size and bedform (after Simons *et al.*, 1965).

Ripples

Ripples are triangular in cross-section parallel to the flow. They show a gentle upstream or stoss side and a steeper downstream or lee side (Fig. 7a). In plan view they may take on a number of forms although straight or curved long crested ripples or short crested ripples are the most common. Ripples have crest to crest distances measured in the downstream direction of about 30 cm and are generally less than 4 cm in height (Allen, 1968, p. 34; Simons *et al.*, 1965, p. 38). Although the stratification of ripples varies according to the three dimensional geometry of the individual ripples in the bed, generally the stratification is made up of inclined strata deposited on the lee face. Figure 7b illustrates a simple case; readers interested in a more thorough treatment of stratification are referred to Chapter 5 of Allen (1968).

Dunes

Dunes are commonly referred to as large scale ripples or sand waves. As can be seen from Figure 6, for a given grain size dunes will occur on a stream bed with an increase in stream power from that producing ripples. Dunes may have similar forms

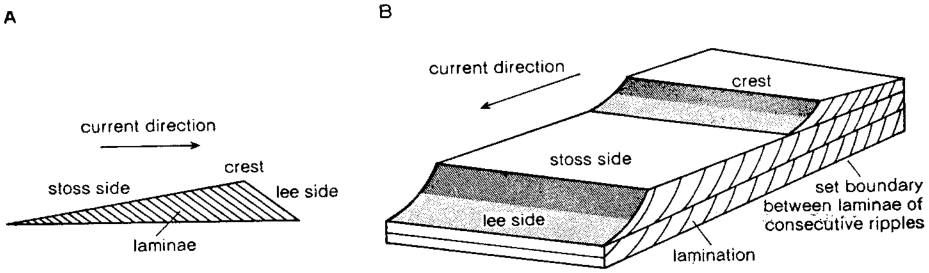
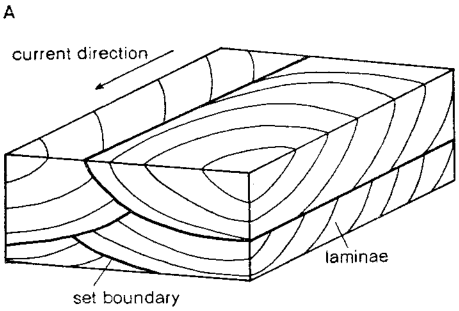


FIG. 7.
The form and internal structure associated with a simple ripple bedform.

to ripples but their height ranges from 4 cm to several metres. The mode of propagation of dunes and ripples is similar and the shapes of the two bedforms are approximately the same: thus the stratification associated with dunes is similar to that for ripples, allowing, of course, for the difference in scale. Two major stratification types are noted to be associated with large scale asymmetric ripples, or dunes, tabular and trough. These are illustrated in Figure 8a, b.



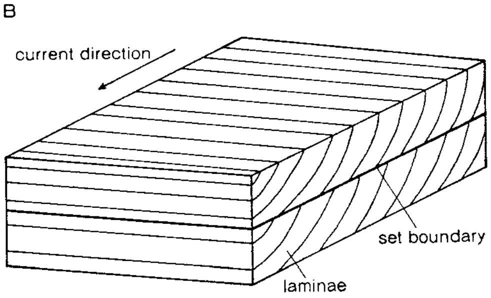


FIG. 8a.
Large scale trough cross-stratification.
FIG. 8b.
Large scale tabular cross-stratification.

Plane Beds

With an increase in stream power dunes become washed out and are replaced by plane beds. Simons *et al.* (1965) define the plane beds as beds without elevations or depressions larger than the maximum size of bed material. The plane bed gives rise to horizontal stratification. Examination of Figure 6 reveals that plane beds are observed at low flow power. However, wherever horizontal stratification is referred to in this paper, set contacts and structural associations indicate accumulation in the upper flow regime.

Antidunes

Antidunes are long crested bed waves in phase with surface waves. Unlike ripples and dunes the longitudinal profile of antidunes is symmetrical and sinusoidal. The stratification associated with antidunes may be upstream dipping cross-strata with dip generally less than 10°. The strata are very poorly developed (Harms and Fahnestock, 1965, p. 108).

Flow Regime

Many important geomorphic and hydraulic properties of a stream cannot be determined from stratification alone. Stratification makes possible the reconstruction of bedform and bedform is a response to stream power; on this basis bedforms are grouped into flow regimes. Ripples and dunes are placed in the lower flow regime, whereas plane beds and antidunes are placed in the upper flow regime. The distinction between upper and lower regimes is to some extent an arbitrary one, although the nature of sediment motion over ripples and dunes is distinct from that over plane and antidune beds, and average flow velocity over the lower flow regime beds is lower than that over plane and antidune beds. There need not necessarily be a distinct, step-like increase in velocity at the transition from dune to plane bed forms (Harms and Fahnestock, 1965, p. 107). Two additions may be made to the flow regime discrimination. (1) Sedimentation below the level of bed load transport will be from suspension, producing fine-grained laminae with parallel stratification. (2) Pebbles with a specific gravity greater than 2, and with diameters greater than about 2.5 cm, are transported in the upper flow regime only (Fahnestock and Haushild, 1962).

Palaeocurrent Estimates

The palaeocurrent flow direction may be estimated from the direction of dip of tabular cross-strata or the direction of dip along the axes of troughs in trough cross-strata. Each measurement gives a point estimate, and by combining estimates at each exposure an overall flow direction estimate is established. Flattened stones on stream beds are often noted to dip upstream. By measuring the direction of dip in imbricated gravel beds a second estimate of palaeocurrent direction may be made. The palaeocurrent estimates made in this study assist in environmental interpretations.

Fluvio-glacial Deposits

At several sites the properties of the sands and gravels occurring between the two tills can be closely related to the expected characteristics of stream deposited sediments. Certain deviations from the "normal" fluvial sedimentation model occur and these are particularly instructive in environmental interpretation (Shaw, in press). Fluvial sedimentary associations are shown at Mousecroft Lane (475109), Norton Farm (495071), Ryton (485045), Dorrington (474042), Venus Bank (553057) and Buildwas (643041). In each case the topography is hummocky with the topographic highs occurring as well orientated ridges (Fig. 2). These conclusions will now be illustrated by reference to selected sequences.

Figure 9 illustrates the sedimentary associations at several sites. The sequences have been drawn up from field measurement and photographs. Irish Sea till is to be found overlying the sands and gravels at Venus Bank, Ryton, Mousecroft Lane and Buildwas. The sediments at Norton Farm and Dorrington are included in this section on account of their association with ridge topography and faulted margins. The lowermost depositional units at Norton Farm and Venus Bank are not included in this section on fluvial sediments, but are discussed, with the sediments at Eyton (570067), under the heading of deltas.

In each case the area beneath the ridge crest is occupied by gravels and sands. At Mousecroft Lane, Dorrington, Norton Farm and Ryton the gravels dominate this

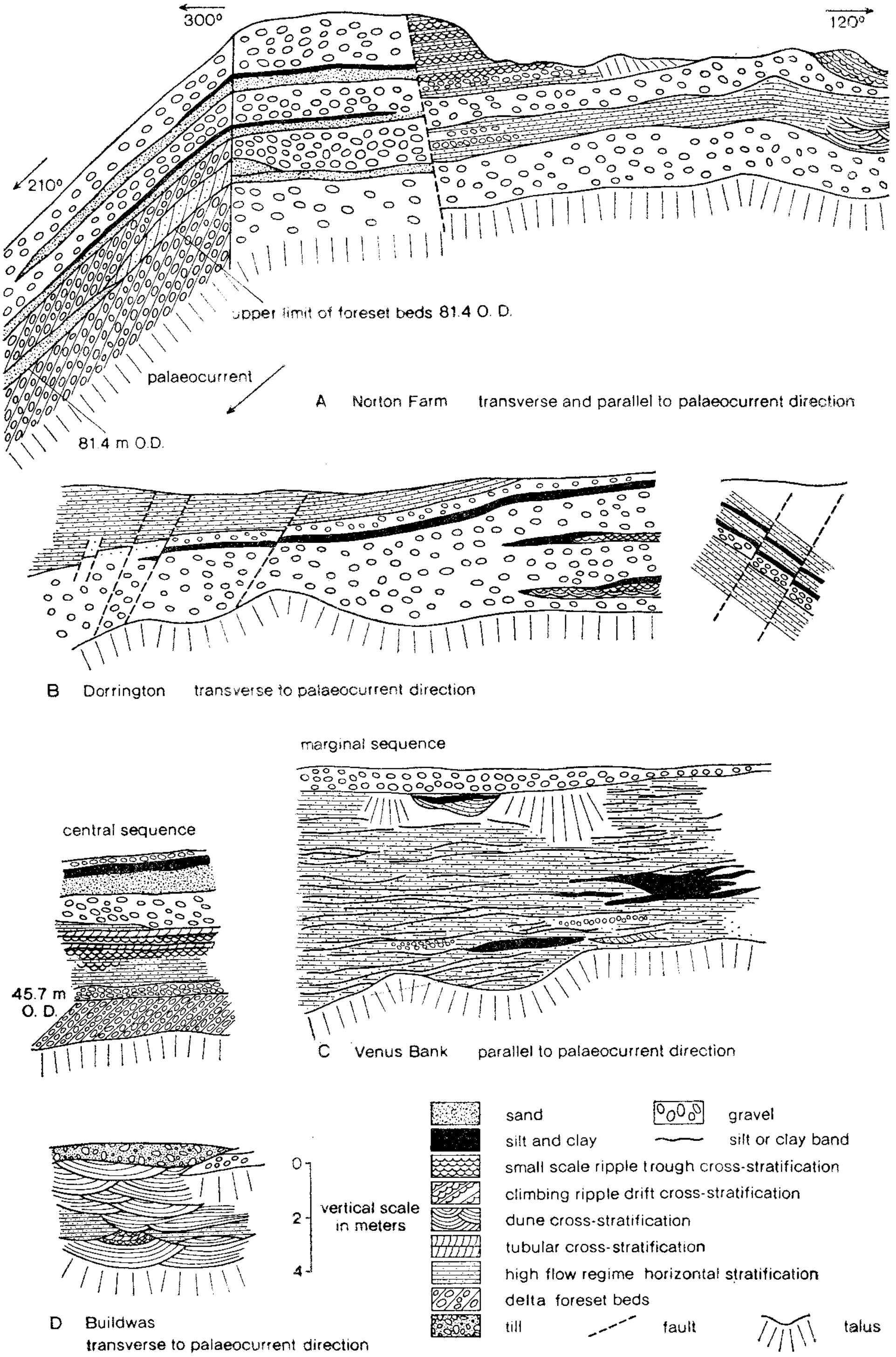


FIG. 9.

Sedimentary associations based on photographs and field observations of exposures in the sands and gravels. The direction of the section relative to the palaeocurrent at each site is given.

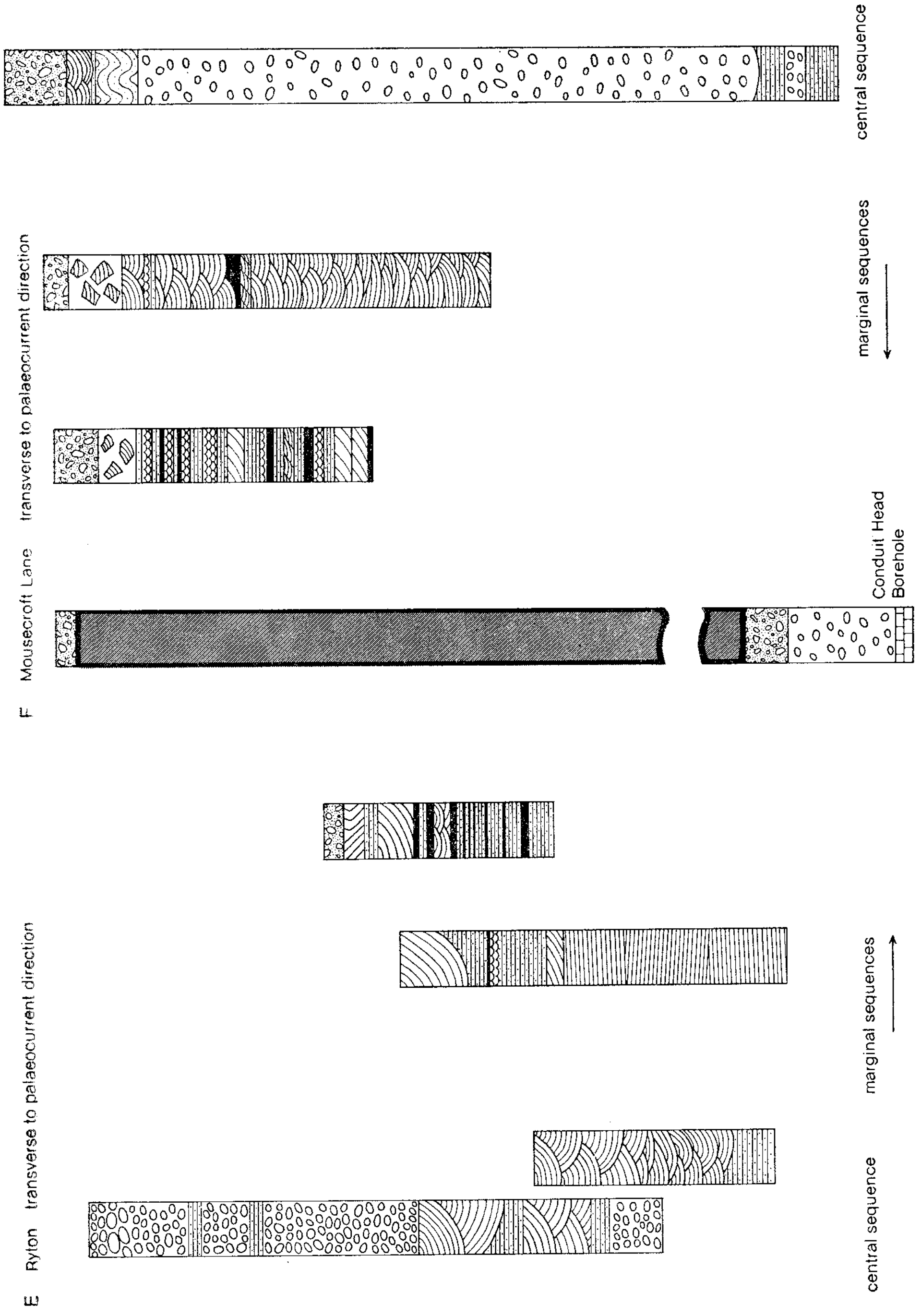


FIG. 9 (cont.)

section (Plate II). At Venus Bank the gravels are associated with a higher proportion of sand in the exposed section, but at depth boreholes reveal the dominance of gravels in a central area (Shaw, in press). The gravels are either cross-bedded or imbricate and show numerous scour surfaces.

Outwards from the central gravel area the sedimentary sequence is dominated by sands. There is also an outward succession of sedimentary structure. At Ryton and Mousecroft Lane the gravels pass laterally into dominantly trough cross-stratified sands (Plate III), which in turn pass into alternating sediments exhibiting horizontal stratification, small scale ripple cross-stratification and parallel stratified silts and clays (Plate IV). At Dorrington and Norton Farm the gravel zone passes laterally into a zone of horizontally stratified sands with gravel beds and occasional silt layers. At Venus Bank the central area is occupied by relatively thick gravel deposits interbedded with sand beds showing a general upward decline in texture and indicating deposition under a generally falling flow regime. Laterally there occurs an extremely rapidly alternating succession of horizontally stratified sands and parallel or ripple bedded fine sand and silt. Very occasional lenses of fine gravel are also noted in the lateral deposits at Venus Bank. Although only a limited record is presented from Buildwas it is highly significant that the sequence at this site is dominated by large scale trough cross-stratification.

Allen (1964) and Visher (1965) have presented idealized models of fluviatile sedimentation. In each model the deepest part of the channel is occupied by the coarsest material deposited under the highest flow regime. In the case of a stream transporting gravel, a gravel facies is to be expected in the high flow position. Laterally the stream bed passes through facies of trough cross-stratification into a facies of alternating horizontal stratification and ripple stratification and finally into an area of overbank sedimentation of predominantly fine-textured sediments. The distribution of sediment types in combination with the lateral migration of the stream creates the fining upward cyclothem of Allen (1964, 1970), Figure 10. Visher's (1965) model is almost certainly too generalized although it does provide a rough yardstick for comparison with presumed fluviatile sediments.

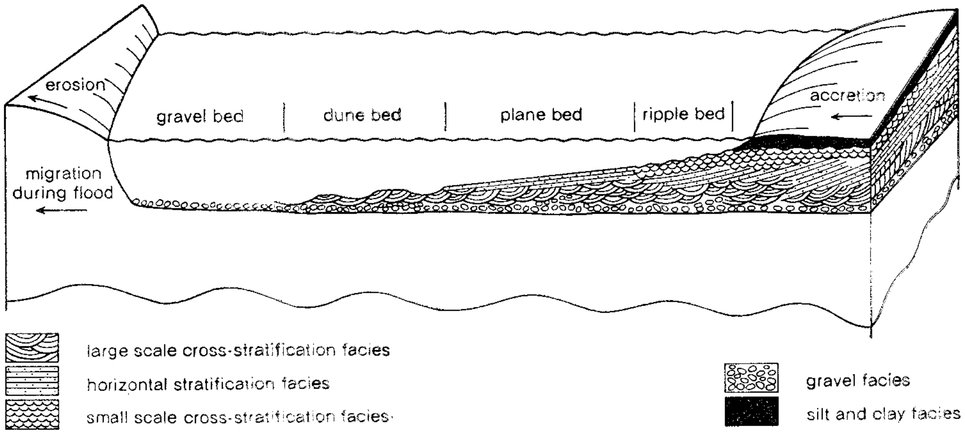


FIG. 10.

Bedform and facies superimposition associated with a meandering stream.

Generally the sedimentary sequences described in this section do not show an upward fining trend. However, they do exhibit an approximate lateral distribution of the facies in Visher's model. If vertical sedimentation occurs without appreciable lateral migration we would expected to find the sediment facies preserved in a consistent spatial position and not in the consistent vertical sequence of the migrating stream model. This appears to have been the case at the sites described. A central coarse gravel zone gives way laterally to finer zones deposited under increasingly variable conditions. In order that such "multi-storied" sediments accumulate it is necessary to invoke some constraint on lateral migration of the depositing streams. The widespread faulting, particularly in lateral positions, and the ridge topography offer evidence that the steams were bounded by ice walls. The final collapse of these walls having caused faulting (Plate V) as lateral support was removed.

A further test of the validity of the model of vertical accumulation in ice-walled channels is presented by evidence from palaeocurrent estimates. Palaeocurrent estimates from the sites are given in Figure 11. A very striking unimodal flow direction is seen at each site. Such a distribution of flow is exactly that to be expected in a relatively straight ice bounded chennel.

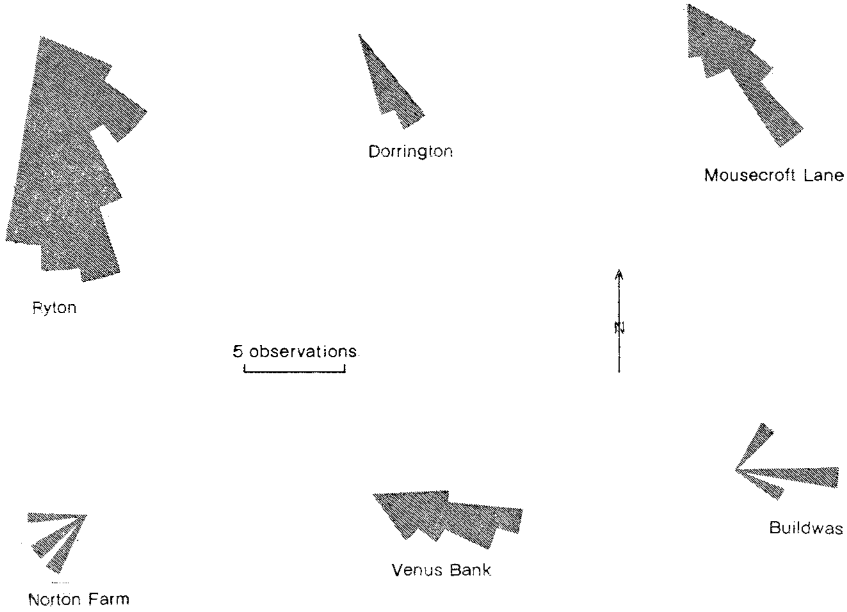


FIG. 11.
Palaeocurrent estimates based on cross-strata and imbrication measurements within the sands and gravels.

A more exhaustive discussion of the conditions during deposition is presented elsewhere (Shaw, in press). However, it may be generally concluded that the sediments described were deposited in low sinuosity streams bounded by ice walls. The unimodal current direction and widespread occurrence of high flow regime plane bedding support the suggestion of low sinuosity.

Deltaic Deposits

At Norton Farm and Venus Bank the lowermost deposits exposed are comprised of gravel beds dipping consistently at around 30°. These are undoubtedly delta foreset beds. The steep dip and coarse texture of these beds are a result of sedimentation from a relatively high energy stream flowing into a standing water body. A third site at

Eyton-on-Severn (570067) also exhibits deltaic sediments. Again gravel foreset beds occur but in this case the base of the foreset is revealed and they are seen to overlie bottomset beds of fine sand, silt and clay.

The nature of the water bodies into which the deltas were building is of particular interest to this work. As already stated, the sedimentation was from high energy streams. The height of the top of the foreset beds at each site gives an approximate estimate of the height of the water body surface. These heights for the three sites are Norton Farm 81·4 m (267 ft.) O.D.; Venus Bank 45·7 m (150 ft.) O.D.; Eyton-on-Severn 67·05 m (220 ft.) O.D.

From the wide range of heights the deltaic sedimentation was unlikely to have been into the same body of water. The Venus Bank topset level lies close to the present day level of the floor of the Ironbridge gorge, 44 m (145 ft.) O.D. The palaeocurrent directions at Venus Bank and Buildwas indicate flows directly toward the gorge; it may be assumed that through drainage occurred above a level of about 45·7 m (150 ft.) O.D. during the period under discussion. It is, of course, possible that drainage through the gorge occurred below this level and that the Venus Bank deltaic sediments represent local ponding by ice. However, the deltaic sediments at Eyton lie above the 45 m level and also have a source in what is now the Severn Valley. There can be little doubt that these represent deposition into a body of water supported between ice occupying the Severn Valley, and the higher land of Charlton Hill. The Norton Farm deposits lie in the Cound Brook drainage system which has a lowest outlet at approximately 61 m (200 ft.). It is probable that the Norton Farm deltaic beds were deposited in standing water with a surface at 81·4 m (267 ft.) O.D. which eventually drained through the Cound brook gorge into the Severn drainage system (Fig. 2).

The important conclusions to be made from the deltaic sediments are, first, there is not evidence for a widespread lake in the study area, and second, the Ironbridge gorge was open at least to a depth of 45·7 m (150 ft.) O.D. at the time of deposition of the sands and gravels under discussion. It should also be pointed out that the three deltaic units were deposited in ice-contact situations.

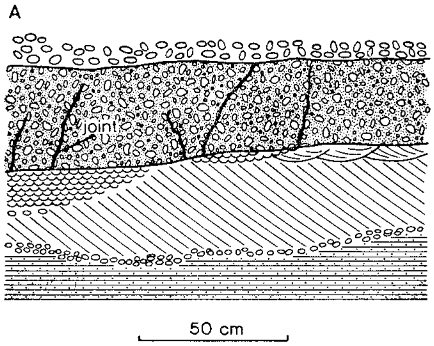
Till Stratified Drift Association

At several sites tills have been noted lying above the sands and gravels. Generally these tills are thin and are intimately associated with the water lain deposits. Basically the tills are differentiated from the lower till on the basis of stratigraphic position and may be referred to as upper tills. Differences in the properties of the lower and upper tills will now be established. The differences can then be used to illustrate the nature of transport and deposition of moraine in the Irish Sea ice sheet.

The main observations in this section were made at Mousecroft Lane (475109), where the upper till occurs overlying fluvial sediments of Irish Sea provenance, and at Wood Lane (423328) (Plate VI) where at least two Irish Sea till sheets are intimately associated with fluvial sediments of similar provenance.

Where extensive sections of the upper till are observed the tills invariably show sheet or lens form. In most cases the sheets are discontinuous. However, the external geometry appears to be as much a function of subsequent erosion as of deposition. Thickness of the till units range from 6 cm at a minimum to a maximum of 2·5 m. Erosional upper surfaces are general and the above measurements can only be taken as minimum estimates of original till thicknesses. However, there can be little doubt that we are dealing with tills which are appreciably thinner than the lower tills discussed earlier in this work.

The relationship between the till sheets and associated stratified sediments provides valuable information on the mode of till deposition. Contacts at the base of the tills may be abrupt with a simple planar form (Fig. 12a) or may be gradational with intercalated beds of till and stratified materials (Fig. 12b).



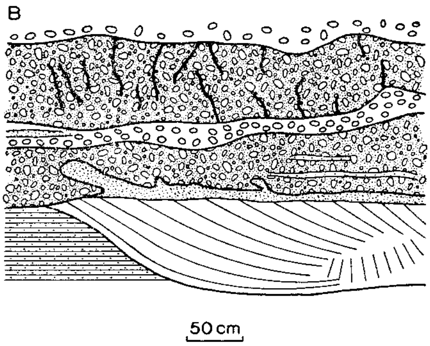


FIG. 12a.
Abrupt planar contact between upper till and associated stratified deposits.

FIG. 12b.
Gradational intercalatory contact between upper till and associated stratified deposits. (see Fig. 9 for key.)

Absence of lateral transposition structures (Elliot, 1965) in the sediments underlying till sheets is a common factor. As a general rule where the till is thick and continuous the underlying sediments show undisturbed preservation of even the most delicate primary sedimentary structures. The rule does not hold at the edge of till sheets or where the till is thin. Typical disturbances in these positions are illustrated (Fig. 13). The nature of these disturbances reveal both the condition of the sediments during displacement, and also the nature of the formation processes. As movement evidently occurred without destruction of lamination, hydroplastic sediment behaviour is inferred. The structures exhibit a high order of symmetry and involve

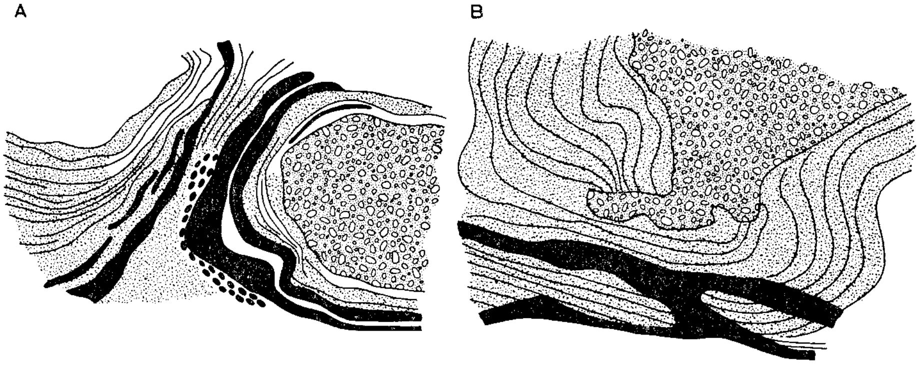


FIG. 13.
Load structures at the margins of upper till lenses. (see Fig. 9 for key.)

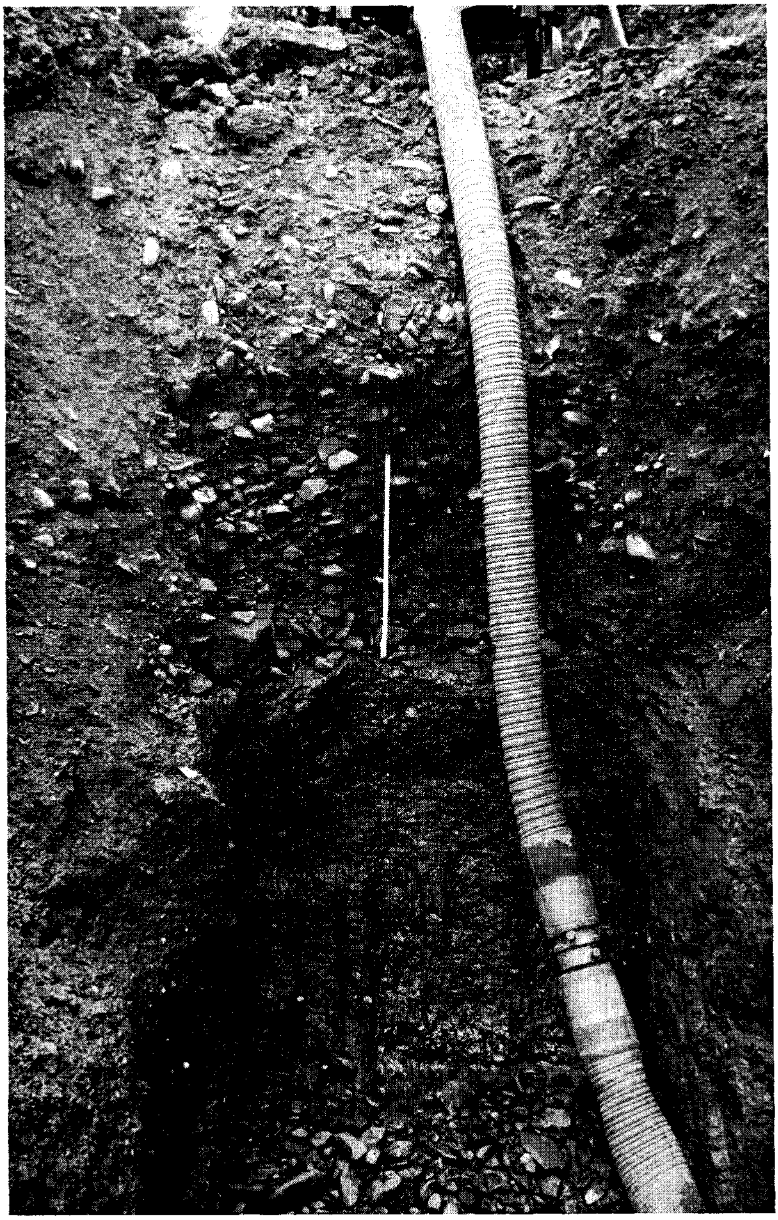


PLATE I.

Lower till at Ditherington below imbricated river gravels. Shattered Keele sandstone occurs below the till. Photograph 1968. Scale 50 cm.

[*facing page 622*

Plate II.
Central gravel deposits, Ryton.

Plate III.
Sub-marginal sand deposits, Ryton. Note the appearance of the large-scale trough cross-stratification in transverse section (behind the figure) and in longitudinal section (to the left of the figure). Palaeocurrent direction from left to right. Horizontal stratification is to be seen interbedded with the large-scale trough cross-stratification. Photograph 1968.

PLATE IV.
Marginal sands and silts, Ryton. Note the rapid alternation of beds. Close inspection of this face reveals horizontal stratification in sands, parallel laminated silts and some ripple bedding. Photograph 1968.

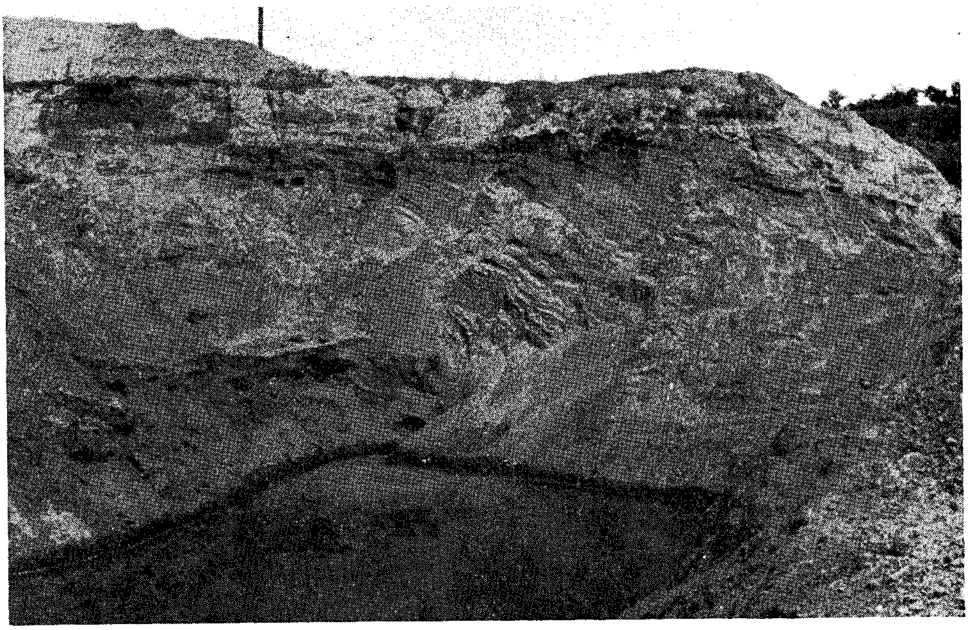


PLATE V.
Downfolded and faulted marginal sediments, Dorrington. (Scale in centre of photograph, 50 cm.). Photograph 1968.

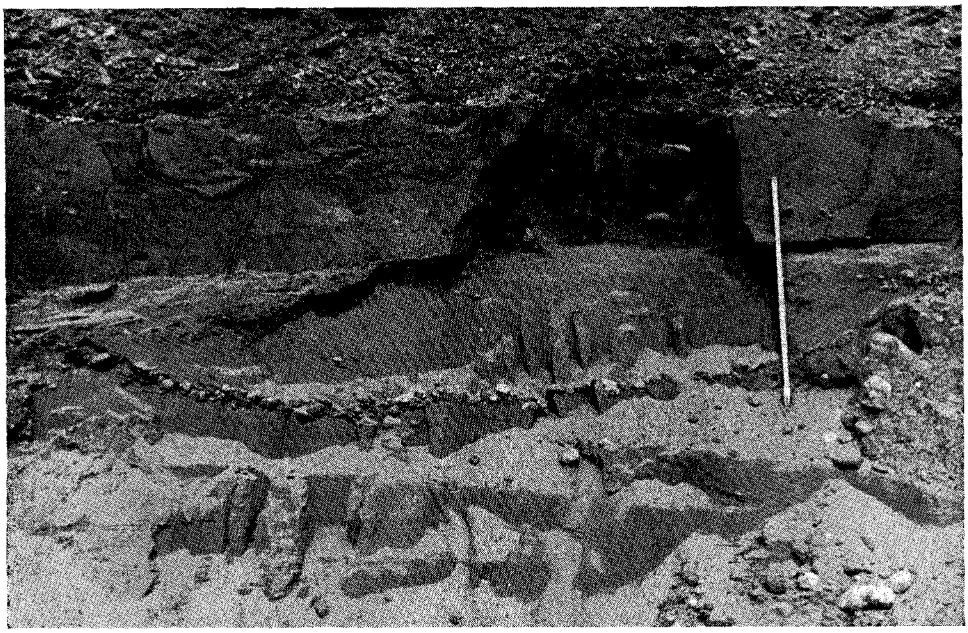


PLATE VI.

Upper till at Wood Lane showing planar contact with underlying fluvio-glacial sediments. Note the vertical joints which are characteristic of this till. Photograph 1968. Scale 50 cm.

vertical movements rather than lateral transposition. One of two possibilities exists to account for the absence of lateral transportation structures:

(a) lateral shear stress was not exerted on the sands underlying the till,

(b) lateral shear stress was exerted but the internal strength of the sands was sufficient to prevent displacement.

It is unlikely that unconsolidated sands could withstand the shear of an overriding glacier without distortion occurring. Alternatively the sands may have been frozen but the observations of MacKay and Stager (1966) suggest that even frozen sands would be disturbed by glacial overriding. Therefore, it appears that the sands were not exposed to lateral shearing but that the tills were let down vertically on to the sands, with the vertical transposition structures representing the sediment response to loading.

In discussing the lower till, foliation was concluded to be a function of compaction that was facilitated by high water content and a high proportion of fine-grained material. The upper tills are consistently finer than the lower group (Fig. 5) and consequently, for equivalence of water content and pressure, are more easily foliated. However, only one case of foliation was noted in the upper tills. Significantly this one case occurred in the finest till. Occasional sand stringers give some horizontal structure to the upper tills but generally irregular, near vertical joints form the dominant structure. Boulton (1968, p. 406) describes similar irregular joint patterns in tills of Vestspitzbergen glaciers.

One of the most striking contrasts between the lower and upper tills is in terms of particle orientation and dip distributions. Figure 4 illustrates the orientation patterns for basal till sites. It was noted that this pattern parallels the ice flow direction inferred from striae in the area. Orientation diagrams from Wood Lane and Mousecroft Lane are shown in Figure 14. The outstanding feature of the patterns of Figure 14 is that with few exceptions the preferred orientation is approximately northeast-southwest, that is at right angles or highly oblique to the direction of ice flow, and also the direction of fluvio-glacial drainage.

Interpretation

Shaw (1969) considers several hypotheses to account for the deposition of the upper tills. In this work only the most plausible of these will be presented. Briefly stated, it is believed that upper tills are deposited from debris layers carried in the upper parts of the ice. West and Donner (1957) note that long axis orientation transverse to presumed ice movement is liable to occur in narrow-band tills, which may be associated with thrust planes. Boulton (1968, Fig. 3) shows a very pronounced transverse orientation in a narrow-band debris layer lying above a thrust plane in a modern glacier. Therefore, the thickness of the upper tills and their highly developed long axis orientation are compatible with their origin as debris bands. Debris bands are carried to their final depositional site in a position well above the glacier bed. Consequently their textural and lithological characteristics are expected to be derived from country rock up-glacier from this site. The fine grained nature of the upper tills is, in fact, more closely related to bedrock outcrops to the north, the Keuper Marl, than the more sandy deposits in the study area. Further research on the petrological relationships would be valuable in establishing the provenance of the upper tills.

The development of sub-glacial drainage, shown in the previous section, implies

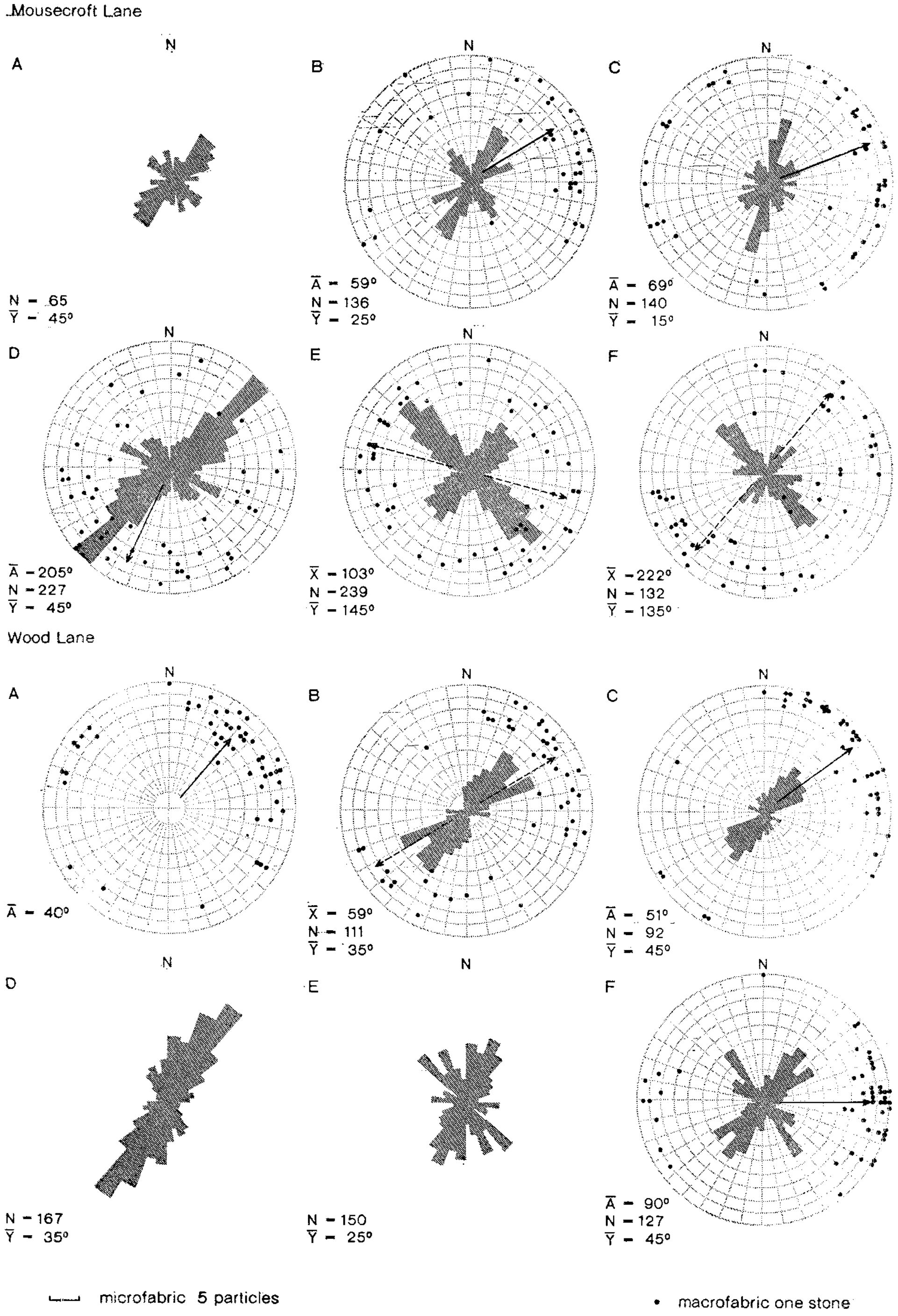


Fig. 14.

Till particle long axis orientation from macro and micro analysis of the upper tills.
$\bar{A}$ = Vector mean direction for the macro-fabric three-dimensional 360° distribution.
$\bar{X}$ = Vector mean direction for the macro-fabric two-dimensional 180° distribution.
N = Number of micro-fabric particles.
$\bar{Y}$ = Mid-point of the 30° micro-fabric mode.

a high degree of undermelt. Under these conditions a gradual lowering of till on to sub-glacially deposited, saturated underlying sediments is to be expected. Vertical loading by the weight of till on the underlying sediment will result from this process, and the release of this loading is most likely to occur in vertical transposition structures. Such structures are expected to occur where the till sheet is thin or absent in which case there is minimum resistance to vertical movement. The paucity of lateral transposition structures and the undisturbed preservation of delicate primary structures, however, may support the above hypothesis. Boulton (1968) has indicated that lateral deformation need not necessarily accompany glacial overriding. The absence of foliation in the upper tills is thought to result from there being insufficient ice pressure at the time of deposition.

Deposition of the upper till by flowage rather than directly from ice is a possibility that must be considered. Okko (1955), Hartshorn (1958), MacKay (1960), Clayton (1967), and Boulton (1967, 1968) have produced evidence for till deposition by flowage into crevasses or into pro-glacial environments. Flowage is generally invoked to explain complex interdigitations of till and water sorted sediments.

In this work the upper tills are thought to have been transported as debris bands but melt-out and flowage are considered as two alternative modes of deposition. The absence of lateral transposition structures does not invalidate flowage. Boulton (1968, p. 410) discussing flow tills states ". . . complex till/stratified-sediment interbedding structures may occur, or the till may be massive and structureless, with a sharp planar base and no disturbance of the underlying sediments." Linday (1966) studying Carboniferous sub-aqueous mud flows in New South Wales has shown that they are closely associated with sandstone dikes and load casts, vertical transposition structures. Lindsay also reports the settling of large pebbles toward the base of the flow units. Large pebbles are frequently observed at the base on upper till units.

The observations of stratigraphic position, basal contacts and interdigitations of tills and fluvio-glacial deposits are quite compatible with a flow till origin for the upper tills. Furthermore, under this hypothesis the tills are not subject to compression by an overlying glacier, but flow freely. The almost total absence of foliation and the evidence of desiccation jointing are therefore to be expected. However, the relatively consistent transverse preferred orientation pattern for the upper tills militates against the flow till hypothesis. This is especially the case at Wood Lane where the preferred orientation of till particles is at right angles to the palaeoslope indicated by flow direction estimates from fluvial sediments.

It is concluded that the upper tills originated from debris bands in the ice and that deposition was most likely by direct melt-out from ice although the possibility of emplacement from flowage should not be discounted. A summary of the properties of the lower tills, thought to have been deposited basally, and the upper tills, of narrow-band origin, are given in Table 1.

Discussion

Irish Sea Ice Sheet Characteristics

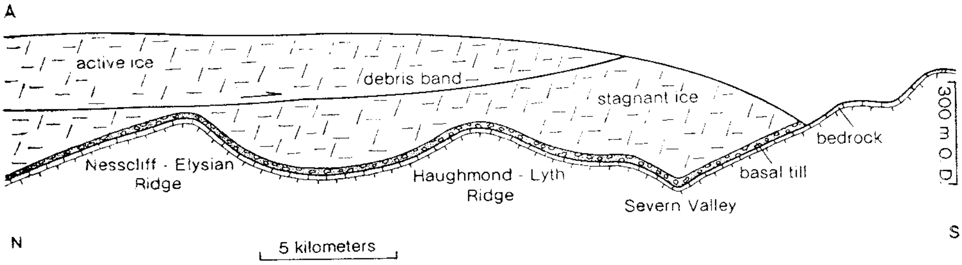
The conclusions set out for the environmental conditions of deposition of the three major lithologic units related to Irish Sea ice may now be synthesized into a discussion of the general conditions of ice movement and decay. Evidently Irish Sea ice moved into the area from the north or north-west and accomplished considerable erosion. Detritus consequently became concentrated in the basal parts of the ice.

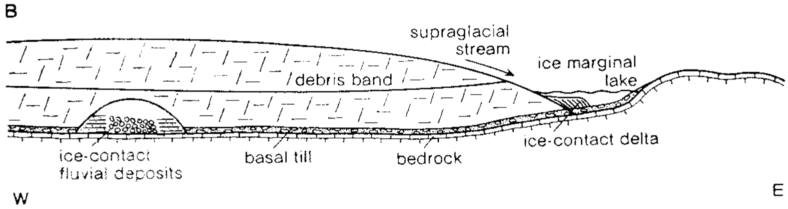
Table I.

	Basal tills	Tills in Fluvial Complexes
Stratigraphic position	Toward the base of a depositional suite	Interbedded with and commonly above associated fluviatile/lacustrine deposits.
External geometry	Extensive, sheet or tabular Thickness 3–20 m.	Discontinuous sheet, or lens Thickness 0·06–3 m.
Nature of contacts and sediment response	Erosional. Lateral transposition structures	Planar, simple transition, complex interdigitation. Vertical transposition structures common. Lateral transposition structures rare
Internal Structure		
(a) Foliation	Extremely common	Rare
(b) Incorporated deposits	Common	Common
(c) Particle long axis orientation	Parallel	Transverse, parallel, irregular
(d) Texture	Related to bedrock in the vicinity of the site of deposition	Related to bedrock up-glacier from the site of deposition

Till stones in this detritus became orientated parallel to the direction of ice flow and in areas of compressive flow took on an up-glacier dip. Final deposition of this till is believed to have occurred by sub-glacial melt-out from the basal parts of the ice. Consequently the orientation of till stones represents the ice flow direction. Other properties, foliation, external geometry, incorporated water lain deposits, coarse texture and locally derived clasts confirm the basal origin for the lower till. The overlying sands and gravels and the upper till complex illustrate the manner of ice wasting. The presence of a north-east to south-west physiographic grain to the local topography has already been illustrated. This relief trend is at right angles or at least highly oblique to the direction of ice movement and would, therefore, provide resistance to ice flow. Consequently ice stagnation is to be expected at a relatively early stage in the decay of the Irish Sea ice sheet. The sands and gravels arranged in topographic highs and showing widespread faulting were evidently laid down in crevasses or tunnels in a stagnating ice sheet. However, most of the sands were deposited from running water. The palaeocurrent directions (Fig. 11) indicate a well integrated drainage system within the wasting ice. Deltaic structures which do occur are either closely related to present drainage levels or alternatively are found in what were ice marginal positions. Ice marginal bodies of water, into which the deltas were deposited, were undoubtedly held between higher land and the stagnating ice.

The occurrence of ice stagnation in the study area provides explanation for the properties of the upper till. With stagnation in the area of physiographic obstacles, active ice to the north would have overriden the stagnant ice. Basal till of northern provenance would, therefore, be carried high into the glacier along the shear plane or planes between the active and stagnant ice. The similarities of the observed properties of the upper till and the expected properties of deposited debris bands has already been shown. Figure 15a is a much idealized illustration of the relationship between the basal and debris band tills. Figure 15b illustrates the general situation at some point in the downwasting of the Irish Sea sheet. The proposed relative positions of the various deposits already discussed are illustrated. It is not difficult to imagine the disposition of sediment and landforms with the final wasting of the glacier (Fig. 15c). Figure 15c illustrates the essential relationships of the major





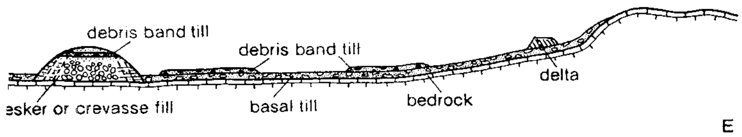


Fig. 15a.

Idealized longitudinal cross-section of the Irish Sea ice-sheet after the stagnation of the lower part.

Fig. 15b.

A stage in the deposition from the Irish Sea ice-sheet.

Fig. 15c.

Resultant field relationships of the lithostratigraphic units.

(Note. The scale only applies to Fig. 15a. The depositional landforms of Fig. 15b, c are drawn schematically.)

lithological groups considered in this paper. It is important to remember that the final conclusion of deposition from a single ice sheet is based on a consideration of the properties of the preserved sediments. The properties discussed in the previous section are in every way consistent with the conclusions on their mode of deposition.

The Status of Lake Lapworth

Glacial geomorphologists have expressed a great deal of interest in the problem of ice-dammed lakes. The area under discussion has been suggested to be the site of one of the classic pro-glacial lakes in Britain, Lake Lapworth. Although the presence of the lake had been suggested by others Wills (1924) crystallized the idea. The evidence for the lake is based largely on geomorphic setting, on marginal drainage channels and postulated wave-cut shorelines.

Wills (1924) proposed the existence of an unbreached Wenlock-Pennine watershed at the time of the Irish Sea advance discussed above. Although Poole and Whiteman (1961, p. 121) appear to consider Lake Lapworth to be associated with an ice advance subsequent to the above Irish Sea advance, they do, however, postulate a "300 ft. Middle Sands Lake" associated with the Irish Sea advance. According to Wills the level of Lake Lapworth is believed to have been controlled by several overflow channels but with the eventual ascendency of the overflow channel at Ironbridge (Fig. 2). A major stage of the lake is supposed to have occurred with a water surface at 91 m (300 ft.) O.D. It is claimed that wave-cut shorelines at the above height verify the existence of the lake (Dixon, 1921). Pocock *et al.* (1938) also accept that the Ironbridge gorge was unbreached during the retreat of the Irish Sea ice sheet although (p. 198) they conclude that the Buildwas stretch of the valley was excavated to its present depth at the time of retreat. If Lake Lapworth is to be accepted it is evidently crucial that the Ironbridge gorge was unbreached at the time of Irish Sea ice retreat. However, at Buildwas and at Venus Bank ice-contact, fluvial sediments are noted close to the present level of the Ironbridge gorge. The palaeocurrent directions at both sites trend directly toward the gorge which appears to have functioned as an outlet for an integrated ice drainage system. Therefore, we see that the gorge was open during the wasting of the Irish Sea ice and a 300 ft. lake is clearly impossible at this time.

The extremely high sediment load furnished to the meltwater evidently caused aggradation. This aggradation is manifest in the preserved fluviatile sediments described above. It is quite likely that the Ironbridge gorge became filled with sediment to approximately 300 ft., the height of the surface of the Buildwas sands (Wills, 1924, p. 307). One can envisage that at a later stage as ice decay advanced large areas would have been below the level of the ice-supported stream beds. These areas would be inundated and no doubt formed widespread interconnected water bodies into which suspension sediments were deposited. Indeed, at both Mousecroft Lane and Venus Bank borehole records indicate large thicknesses of clay and silt marginal to the ice-contact sands and gravels. However, the final downcutting through unconsolidated sands would have been extremely rapid.

Many of the supposed lake shoreline features could conceivably have been formed in small ice-marginal water bodies similar to the one into which the Eyton delta was deposited.

It is, therefore, suggested that there is no evidence for a widespread lake of the Lake Lapworth type during the retreat of the Irish Sea ice. The Ironbridge gorge existed before this retreat, although no explanation is given here for the circumstance which led to the formation of the gorge at some earlier time.

Chronology

Establishing a chronology for the ice advance under discussion requires reference to areas outside the study area and also involves the introduction of observations not previously mentioned in this work. The accepted glacial history in recent years correlated the retreat of the Irish Sea ice sheet with the development of the Main Severn terrace (Wills, 1924, p. 307). Coope *et al.* (1961) established that a correlative of the Main terrace at Upton Warren was under formation 41,500 ± 1,200 radiocarbon years B.P. By comparison with the European Continental succession the Upton Warren deposits and the Main Terrace are correlated with the Gottweig Interstadial, the Irish Sea advance maxima falling in the Older Würm (Weichselian) maximum. To the north of the study area a very pronounced bi-lobate moraine, the Woore-Bar Hill moraine, was interpreted by Boulton and Worsley (1965) as being a re-advance moraine of Late Wurm (Weichselian) age. However, more recent work by Shotton (1967) has shown that glacial till to the south of the Woore-Bar Hill moraine is also of Late Weichselian age (post 30,655±765 radiocarbon years B.P.). It is probable that the deposits discussed in this paper are correlatives of the till described by Shotton (1967). Therefore, it would appear that the deposits discussed are probably Late Würm (Weichselian) in age corresponding to a glacial maximum post 25,000 years B.P. The Bar Hill-Woore moraine must then be considered a recessional or minor re-advance stage during the general retreat of the Late Würm advance. The above conclusions question the correlation of the Irish Sea ice sediments and the Main Severn terrace. Detailed surveying of the terrace sequence above and below the Ironbridge gorge could provide valuable information on the glacial history of the area.

Two glacial advances of Welsh provenance are noted in the study area. One is represented by an extremely compact, fissile till which was noted below the lower Irish Sea till at Ditherington. This till gives evidence of Welsh ice in the study area before the incursion of Irish Sea ice sheet. The time interval between the two ice sheets cannot be established. The second suite of Welsh glacial deposits occurs above the Irish Sea sediments. The relationship is best exposed at Mousecroft Lane. Pro-glacial outwash gravels of Welsh origin underlie till of similar provenance. Evidently after the dissipation of the Irish Sea ice sheet a re-advance of Welsh ice occurred. This readvance has been referred to as the Little Welsh Re-advance (Wills, 1950). It is important to note that buried blocks of Irish Sea ice survived the intervening period between the two advances (Shaw, 1969). Structural evidence from the deposits of the Welsh glacier indicate that this was of the Polar type (i.e. a cold ice-sheet which behaved differently from the Irish Sea ice) and, therefore, we may conclude was associated with a marked cold period (Shaw, 1971). It appears likely that the Little Welsh Advance was also late Würm and that it marks a cold period subsequent to the climatic amelioration which caused the dissipation of the Irish Sea ice sheet. The Severn terraces upstream from Ironbridge are believed to be associated with denudation following a general period of pro-glacial aggradation associated with the Little Welsh Advance. However, this is a speculative statement and work is still needed on the details of the terrace succession.

ACKNOWLEDGEMENTS

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