Discussion of Session 1a

Dr. A.B. Hawkins, Bristol University, Chairman, Session IA.

In this discussion session we shall begin with contributions dealing with temporary and sustained loading. Then I wish us to discuss tills, followed by glacio-fluvial deposits and, finally, glacio-marine deposits. After that we will deal with whatever topics we have time for, seeing how the discussion has progressed. So we begin by asking Charles Harris to show us some slides dealing with glacially disturbed bedrock.

Dr. C. Harris, University of Wales, Cardiff.

What I propose to do is to show some slides which perhaps provide a site specific example which could be interpreted along the lines which Geoffrey Boulton was suggesting this morning for tills, except that I want to talk about bedrock. The site is at Wylfa on the north coast of Anglesey, there's the little location map at the top, and Geoffrey Boulton in his map of these ice streams, if you remember, had an ice stream coming down the Irish Sea basin. So if we start with that premise, we have an ice stream coming down the Irish Sea basin, a low profile glacier moving over a soft deformable bed and it suddenly hits the north coast of Anglesey. What seems to have happened is that the bedrock continued to behave in a similar fashion to the soft deformable sediments. The bedrock in this case is a Cambrian meta-sediment of relatively incompetent phyllites, and these have been sheared off or deformed. If you look in the inspection trenches you can find compression folding. The scale there is 50 cm. This kind of compression occurred as the glacier actually hit the north coast and was overriding a reverse slope. Elsewhere on the site a stepped bedrock is produced. The bedrock dip is northwards so that it's dipping up glacier, and the glacier overrode that dip slope, and the bedrock was apparently deforming downstream as the glacier overrode it. That's the cleaned up rock head and near the top there where it comes close to the surface it's striated, so there was obviously a decollement, a shearing across that bedrock surface, between the mobile crushed bedrock and the intact bedrock.

That's looking the other way, it's a roches moutonnees type of profile, apparently some sort of glacial plucking was taking place on this downstream side. As we walk down that dip slope joints begin to open and till is packed into those joints, presumably under quite high pressure, suggesting shearing of the bedrock. As we look back from this site of rapid bedrock erosion we see on the horizon a drumlinised topography. Therefore within the site there is an area in the immediate coastal zone with relatively thin drift and glacio-tectonically deformed bedrock and immediately adjacent to its drift up to 25 metres thick which is drumlinised. What I'm suggesting is that high basal water pressures facilitated this deformation of the bedrock. But where you have sub-glacial drainage, possibly through joints or faults in the bedrock, the lower water pressures and higher effective stress encourage the lodgement of till. Therefore within this site, which is only a few kilometres across, there is a zone of considerable lodgement of sub-glacial material into drumlinised bodies, and immediately adjacent to is severely disrupted and eroded bedrock. It has been suggested by others that these coastal tills in the Irish Sea basin are actually glacial marine sediments and were not deposited by a grounded glacier. But here at Wylfa (which projects right out into the Irish Sea basin and is only 75 kilometres south of the Isle of Man) there is very good evidence that the glacier was certainly grounded and it was hitting the bedrock fairly hard.

Professor S. Thomson
University of Alberta

These few 35 mm slides illustrate ice-shoved bedrock in Alberta and Saskatchewan, Canada. Our recent research has indicated three...
settings where ice-shoved bedrock is likely to be found. The first slide illustrates the normal, flat lying bedrock, the marker bed is a thin coal seam. The next slide shows a series of hills in the order of 150 m high and extending over a distance of several kilometres. These are ice-shove features located in mid-eastern Alberta and referred to as the Neutral Hills. The gap to the right of the photo is a meltwater gap with a lacustrine basin in the foreground. The ridge in the next slide is in the road cut and the anticlinal nature and faulting of the bedrock is apparent. The anticlinal folding due to ice-shoving can range from open to closed and in some cases the fold may be overturned as illustrated in this next slide. In this case the upper part of the fold has been eroded and a till deposited.

The previous set of slides have shown an 'escarpment' setting. In this setting the ice approached an escarpment and between the ice front and the escarpment meltwater had been impounded. This lake caused a deterioration of the underlying permafrost which allowed distortion of the bedrock. The next slide illustrates another setting in which the ground, or prairie, is flat and there is no surface expression of the bedrock. The ice-shoved bedrock is clearly visible in the ditch at the side of the road. The ditch is less than 2 m deep.

Dr. A. B. Hawkins

Thank you very much Stan. And we have one last person who wishes to talk on this subject, Professor Peacock, before I ask for any comments from the floor on the disturbance of rock beneath the glacier.

Professor D. Peacock
Heriot-Watt University

Well, I've been told that I have volunteered to say a few words, so I shall say a few words. I have spent a good part of my career mapping hard rock, particularly in the Scottish Highlands and it has occurred to me that the incorporation of debris into the base of a glacier (quarrying and abrasion) could be assisted by stress relief as the ice wastes away. In the first slide, from the island of Rhum, off the Scottish west coast, we see classic roches moutonnees that have been moulded by ice moving from right to left across gabbro and ultra basic rock. Note the penetrative cracking of the bedrock surface, which is almost free of joints. My second slide, taken in the highly glaciated valley of Glen Cannich in the central part of the Highlands, shows a roche moutonnee that has been partly broken up and the fragments slightly displaced. Till has filled the cracks. My third example is from the area of metamorphic rocks around Sondre Stromfjord in west Greenland. Much of it is an intensely glaciated, ice-moulded plateau, not dissimilar to parts of the Scottish Highlands. At two localities the slides show fresh-looking fault-line scarps in which the low cliffs a few metres high face into the direction of former ice-movement. Whether or not the faults are the result of glacial unloading, there has been intense spalling of angular blocks from the free faces, far more than from other crags in the area.

All three examples suggest that the bedrock has been broken during or immediately following deglaciation and, in the latter case, the stress release has caused considerable spalling. We know that rapid removal of a thick ice-sheet or glacier can result theoretically in stresses that exceed the strength of a rock, even where unjointed. Could we not have here an additional mechanism for rock breakage, with the resulting debris being available for incorporation in any remaining ice and for subsequent deposition as till?

Dr. A. B. Hawkins

Right, I'm going to move straight on and turn to tills. In fact I'm going to pose one or two questions for Geoffrey Boulton. One of the things that concerns me is exactly how do we get these lodgement tills
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deposited, particularly if they slide over and shear the mature till underneath them? Are the shears described by Professor Boulton earlier today more numerous in the older tills than they are in the recent tills? What mechanisms actually cause the deposition of lodgement till?

Professor G. Boulton, Edinburgh University

Work in recent years has suggested that the traditional view of erosion and till deposition, based on observations from mountain areas, is inappropriate when applied to extensive sediment-covered lowlands. This traditional view states that glaciers erode debris from bedrock, carry this eroded debris as disseminated mineral and rock grains within the basal layers of the ice, and then deposit it sub-glacially by melting of the basal boundary. Studies of modern glaciers in rocky alpine regions, where it is possible to establish that such processes dominate, show that the quantity of debris contained in basal ice is very small and that the rate of till production is also very small. By contrast, it is possible to demonstrate that many tills in lowland areas far from any bedrock source, such as around the great lakes of North America, in northern Germany and Poland, or in northern East Anglia have accumulated in a very short period of time. The classical mechanism is simply not able to deliver sufficient debris at a high enough rate to generate these till masses.

Recent work has demonstrated that glaciers flowing over un lithified sediments can cause shear deformation of the sediment to a depth of several metres and indeed that over 90% of the forward movement of the glacier may be due to deformation within the sediment rather than slip at the ice/sediment interface or flow within the ice. In other words, the deforming sediment is a zone of easy shear deformation which largely determines the flow rate of the glacier. Glaciers in such areas can therefore, no longer be considered as owing their dynamic behaviour to the rheology of ice alone, flowing over a passive bed. Rather, their dynamics may be to a large degree controlled by the rheology of sub-glacial sediment. Theoretical work has now demonstrated that unless substantial sub-glacial aquifers exist, capable of draining water from immediately sub-glacial sediments, it is almost inevitable that this type of deformation will occur. In addition, the process of sub-glacial sediment deformation not only determines to a large degree the dynamics of the glacier but also produces a till which is a consequence of the deformation of mixing of a variety of sub-glacial lithologies.

If we consider this mode of erosion and deposition in the context of the large scale dynamics of glaciers, then it is possible to produce time-dependent theories accounting for the large scale patterns of erosion and deposition which glaciers will produce in sediment-covered lowlands. The forward velocity of ice in a large ice sheet increases away from the ice divide, where it is approximately zero, to a maximum beneath the area of the snow line. From here to the glacier terminus the velocity decreases. This distribution is a consequence of the ice flux which is necessary along the flow line to discharge the snow and ice which accumulates on the ice sheet surface. If forward movement of a glacier is largely determined by deformation of sediment on its bed then there must be longitudinal extension in the deforming mass in the area of increasing glacier velocity, and a longitudinal compression within the deforming mass in the zone of reducing velocity near to the terminus. In order to sustain the discharge of deforming sediment necessary to maintain the ice flux in the glacier, the base of the deforming layer must become progressively deeper in the up-glacier zone and therefore effectively erode underlying undeforming material, whilst in the down-glacier zone deforming material will accumulate as till.
Thus we expect a broad up-glacier zone of erosion and a broad down-glacier zone where thick till masses accumulate. Reconstructions of the distribution of till produced by the last mid-latitude ice sheets in North America and Europe suggest that this is precisely the pattern which is found.

There are some characteristics of these deforming sequences which can be easily illustrated from areas of modern glaciation, and which are commonly found in Britain. For instance, material in the deforming layer deforms at water contents very close to the liquid limit. At one site in Spitsbergen, a glacier flowed over an arm of the sea and sheared along beneath it marine muds containing mollusc shells. This deformation till was then sheared up on to an island some few kilometres from its source, where we find intact and hinged shells within the till, suggesting that effective pressures during deformation were negligible and that there was very little internal friction within the deforming mass. Under these conditions very high, surge velocities can be developed, with values of the order of 700 m per year. However during surging a glacier breaks up readily into a very highly crevassed state. When the surge ceases the highly crevassed glacier settles into the fluid till beneath which then consolidates. During the consolidation process till is squeezed up the crevasses, and when the ice eventually melts leaves reticulate patterns of ridges in an extremely hummocky topography.

Transport in this highly fluid state and then final consolidation beneath very thin ice may well explain the fact that very many tills are pre-consolidated to relatively low values of a few hundred kPa.

Mr. G. West, TRRL

All road engineers know about the phenomenon of frost heave, which happens when there is a very severe winter. Frost heave occurs when freezing goes down through the road structure and an ice lens forms at the position of the zero isotherm. The ice lens forms because of the high suction set up at this position which draws up water from the water table below. The ice lens can attain considerable thickness causing the road to heave, but during the subsequent thaw the ice melts, releasing an excess of water within the road structure which leads to loss of strength and disruption of the road. As well as happening in roads, this phenomenon must happen in nature whenever there is freezing ice in the ground combined with availability of water from the water table. This could account for the example that Professor Fookes showed this morning, and probably accounts for a lot of the disturbed features seen in tills.

Dr. M. de Freitas, Imperial College

When you look at text books they show permafrost coming down from the Polar Caps and yet you describe glaciers which apparently run over unfrozen ground. I wonder whether Professor Boulton could tell us when a glacier moves over ground that is frozen and when it moves over ground that is not frozen.

Professor G. Boulton

Thermal mechanical modelling of glaciers in middle latitudes has produced very robust results showing that whereas the inner part of an ice sheet may well have a basal temperature below freezing an extensive terminal zone will exist where the basal temperature is at the melting point. However, when these glaciers extend they do not extend over unfrozen ground but over permafrost. Modelling of this condition however, shows that after the glacier has moved over the surface of the permafrost, degradation of the permafrost will occur rather rapidly so that it soon melts after having been
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Mr. A. Howland,
A.F. Howland Associates.

Can I ask another question of
Geoffrey Boulton? I've always been
confused by what happens at the
bottom of ice and now I know I'm
never going to understand it. On
the north Norfolk coast there are
massive slabs of chalk with zones
of till at the bottom which have
always confused me. Can he explain
how the ice picks these up and
moves them along when he's just
described a lubricating surface at
the ice sediment interface? How do
you actually get the ice attaching
itself to the solid geology, and
then moving that along?

Professor G. Boulton

For a glacier such as I have
described earlier, advancing over
permafrost and with a zone of sub-
glacial freezing extending for some
distance from the glacier terminus,
I would suggest the following
mechanism. The interface between
ice and the rock surface at a
temperature of less than about -3°C
has a high shear strength. At
typical glacial shear stresses we
would expect adhesion between ice
and rock. However, the glacier is
still moving and therefore must
carry with it its frozen
substratum. Some depth beneath the
glacier/bed interface however we
would expect there to be a contact
between frozen and underlying
unfrozen material which would be a
natural plane of decollement,
permitting the overlying frozen
material to move along with the
glacier. Moreover if the terminal
zone of the glacier overlies a
frozen bed, sub-glacial meltwater
moving towards the glacier terminus
within the bed would tend to be
blocked in the frozen terminal zone
and drive up pore water pressures
so as to decrease effective
pressures. Under these
circumstances the contact between
sub-glacial frozen sediments and
the underlying unfrozen sediments
could well be one of low shear
strength. If the terminal zone of
the glacier is one of longitudinal
compressional strain as I have
suggested above, then we might
expect these frozen masses to

overridden by the glacier. Thus
during its advance, I would expect
a Pleistocene ice sheet in Britain
or Northern Europe to have a frozen
sub-stratum in a narrow outer zone,
for this to be succeeded by a broad
zone of melting and for there to be
an inner zone where the bed is
frozen. During retreat however we
would expect the entire outer part
of the glacier to overlie an
unfrozen bed and only the inner
part, near the ice divide, to be
underlain by frozen sediment.

One interesting feature of the
advance phase in which a glacier
overrides permafrost is that frozen
ground may melt at a time when it
is overlain by several hundreds of
metres of ice. If we assume the
water content immediately after
melting to be appropriate to an
unglaciated sediment overlain by
little if any overburden and yet
the actual overburden at the time
of melting to be large it is quite
clear that this is a potentially
extremely unstable state which
could lead to some instability in
the terminal zone of the glacier.

How deep does winter freezing go in
glaciers in relatively warmer
regions such as Iceland?
The winter cold wave penetrates at
most a few tens of metres. Once
you are more than about 30 or 40m
from the glacier terminus there are
no seasonal fluctuations of
temperature at the glacier bed.

Dr. N. Fannin, BGS, Edinburgh.

Just a further comment on Professor
Boulton's point about the frozen
dge of the ice sheet. One of the
hypotheses proposed for the
excavation of tunnel valley systems
under the Laurentian ice sheet is
that the frozen edge of the ice
mass allowed the development of a
very high hydrostatic head behind
it and this would have been one of
the contributing factors towards
the high breakout velocities that
created these tunnel valleys.

Dr. A. B. Hawkins

Thank you Nigel. More comments
from the floor?
accumulate one above the other as a series of stacked lenticles with intervening thrust plains.

Dr. A. B. Hawkins

Thank you, the last question.

Professor P. Fookes

My question is principally for Professor Boulton and results from his excellent lecture and also from descriptions and views given by subsequent authors.

Many of the simplified engineering models of glaciers, glacial action and glacial deposits which have helped develop a rationale about glacial sediments for engineers and engineering geologists have been based on valley glaciers, e.g. like those occurring in South Wales. Much of what has been said at this morning's session, however, has been based on continental and piedmont glaciers where the mechanisms and deposits are often significantly different. Could Professor Boulton elaborate for us on the significant differences both geologically and in terms of the engineering consequences.

Professor G. Boulton

I do think it is now appropriate for engineers at least to distinguish between the style of glaciation and the nature of glacial processes that occur in upland zones over predominantly bedrock surfaces and those which occur in lowland areas where glaciers over-ran predominantly soft, un lithified sediments.

Dr. A. B. Hawkins

We will now move on to the glacio-fluvial deposits; Mr. Stevens, your contribution, please.

Mr. P. Stevens,
Engineering Geology Ltd.

Just recently we completed a desk study for the Department of the Environment which was intended to produce a statement of sand and gravel resources for the entire County of Durham for planning purposes. We had to base this study purely on third party boreholes and, although we had 6000 boreholes in our database, we had no direct control over the spacing of the data or its quality. So we had to start to think about how we could correlate these data. Sand and gravel in County Durham is predominantly glacial outwash of Devensian age. This is a subdivision of the BGS mapping that we compiled as we went along; it splits the sand and gravel into channel deposits, outwash sheets, alluvial fans, eskers and cone terraces. So there is a great variety of sedimentary environments within the broad term of "outwash deposits", and to confidently predict where and how good the deposits were, we had to understand those environments. The distribution of the deposits was greatly influenced by the position of the ice fronts in the Devensian and the patterns of the recession of that ice, as well as the bedrock topography. We also recognised that the quality of the deposits, quality in an engineering sense, was also influenced by those factors. Therefore we have been looking at bedrock topography and other isopachyter maps as a parallel study.

With only third party data we decided that it would be rather naive to give a factual representation of which boreholes encountered sand and gravel. A more appropriate approach would be to develop a facies model of the sedimentary environment to allow interpolation and correlation between the boreholes.

This is a very simplified cross-section of the Devensian and later sediments through the County of Durham, running from the sea up the Pennines, the Magnesian Limestone escarpment, and then the broad central lowlands where the City of Durham is situated. We see the result of these very large buried channels that Professor Boulton talked about this morning, large bodies of clays and sands and gravels, with a lot of reworking and terracing on the edges. It's
rather simplified but there are many channels cutting through older deposits, moraine terminal deposits from the coastal ice stream that came to rest against the Magnesian Limestone escarpment, and a basal till.

During the study we started to think whereabouts these environments would be. It was fairly obvious there was a large alluvial fan here representing cross-drainage from the Weir catchment into the Tees. There's a fairly similar coarse-grained channel deposit down here representing flow from the Tees valley out into the lowlands. There are lake deposits around Durham, Bishop Auckland, and on the coast. So, this is where we postulate major subglacial drainage.

We had to keep the simplification to some degree, but recognise that we were looking at a very complex suite of sediments indeed.

We went further and this slide shows Darlington, Winston, Ferryhill and Durham. We were able to divide the deposits into suites, into units representing suites of deposits, from which we could start to make resource assessments. We have a delta here flowing through from another valley. We have a lake deposit and we have channels of coarser graded sediments within general spreads of outwash deposits probably representing distributary sands although they may represent eskers and other channel deposits.

Mr. D. Long, BGS, Edinburgh.

This is a boomer trace for a time scale of 25 milliseconds in these sort of sediments in the top 20 metres or so. This extremely well layered unit is very characteristic of the central North Sea and we can extrapolate them for perhaps 50 kilometres. It's a very diagnostic unit and these reflectors obviously stretch out. Here in the centre is very soft clay and yet going along this line as we rise up from about 140 metres depth to about 115, 110 metres, we still find some clay but here very silty, and as we get to the very edge of the basin it's still exactly the same seismic signature. We're actually into almost pure sands. So there we have a seismic signature which actually gives us no clue as to the lithological component we're looking at, so there we can't use it. And we can see the same sort of thing in reverse. If we go back to the first slide here we have this thin well layered unit. This is a sparker record. But take the boomer across the same site, it's slightly clearer, seeing these very fine lamination layers and an opaque unit here. But, by looking at the borehole at this site there is very little change in the lithology, with no change in the geotechnical properties across that division, between the very well layered acoustic unit and the opaque unit there is a change in the shear strength properties at depth, but that's actually into a different unit. The explanation for this I hope Mike Paul will now illustrate.

Dr. M. A. Paul, Heriot-Watt University

I would like to continue the theme which David Long has introduced by showing you an example in which the seismic stratigraphy is, to an engineer, possibly misleading. The example is taken from the Witch Ground, in the north-central North Sea, and is described in full in the preprint volume. The seismic data were made available by the British Geological Survey, to whom I extend my thanks.

The seismic stratigraphy shows a clear division into two distinct signatures: a lower one which is essentially disordered, and an upper one which is well laminated. This distinction is maintained over distances of several kilometres. However, a borehole which penetrated both signatures, and which I have studied in detail, has shown the material to be almost uniform with depth; certainly, there is no gross distinction between the upper and lower units, nor are there any minor features such as sand laminae to explain the laminations in the upper signature.
A study of the engineering properties has shown a more simple story. The sediment is a normally consolidated, silty clay. The seismic velocity is almost constant throughout the sediment. We have obtained a bulk density profile for the core using the scanning X-ray densitometer at Oxford University and thank Gilliane Sills for this facility. The consolidated trend can be seen from this bulk density profile, and superimposed on it are a large number of apparently insignificant density variations. Since the velocity is constant, these density variations lead to similar variations in the acoustic impedance, each of which generates a small seismic reflection. The cumulative effect of these is the complex layered signature that appears in the upper part of the profile, which has been reproduced synthetically by a numerical model. I would like to point out, incidentally, that the model showed the importance of peg-leg multiples in the production of the signature.

The distinction between the upper and lower signatures appears to be due to penecontemporaneous disturbance of the lower part of the sediment during deposition. The BGS group has proposed that this is due to the effect of grounded ice, and I see no reason to dispute this. When the water depth in the basin increased sufficiently, the ice ceased to ground, and the layered structure in the sediment was preserved. The moral for the engineer is that a complex seismic stratigraphy can result from physical factors that may be of limited importance in the engineering behaviour of the sediment.

Mr. G. Butenko, Norsk Hydro.

The seismic profiles that we have seen are on single channel seismic profiles which means their signal is sent and received in one channel. I want to stress the importance of using multi-channel seismic reflection for engineering purposes and I want to show an example on the Troll Field in the Norwegian part of the Continental Shelf. This is a multi-channel seismic reflection profile and here we have 13 reflectors in the Quaternary. They were correlated with a geotechnical boring that was located 9 kilometres away from this particular place. There were two problems that we noticed. Firstly there was a face reverse reflector here that could be associated with shallow gas and there was another reflector at this position that could also be associated with shallow gas. So we decided to reprocess these seismic sections. Here you can see more clearly the face reversed reflector, and also here the face change. Traditionally this would be interpreted as shallow gas that could create some problems for the foundations. So we obtained a much higher resolution seismic profile, and here you can see this face reversed reflector in fact is an acoustic interference of thin sound layers the same as here, so the conclusion we came to was that these particular reflectors were caused by sonic interference and not by shallow gas.

Finally I want to show you the result of the prediction as compared to the obtained stratigraphy. This is the predicted stratigraphy based on multi-channel high resolution seismic profiles in a geotechnical boring located 9 kilometres away, and this is the stratigraphy obtained at the site. Effectively, an accuracy of between 1 metre and 20cm was achieved in the upper 92m. This surface was explicable as a change of the undrained shear strength, from 300 kPa to 600 kPa.

Dr. A. B. Hawkins

Thank you very much. I'd like to end this Session by thanking all those people who have contributed.

Dr. J. A. Little, Heriot-Watt University: supplementary written contribution to discussion, Session 1A

Professor Boulton's comments regarding the fluid nature of till sheets during transportation are interesting. For some time the author has been unable to reconcile...
the visual evidence he has observed with the supposed method of formation of lodgement till. The classical model of formation for such tills invokes, inter alia, the processes of a) plucking of material at source, b) its encapsulation within the basal traction zone of a moving ice sheet, and c) its transportation over, on occasions, large distances. During these stages, the entrained clasts undergo abrasion, attrition and comminution, with the result that the end project, at least in terms of particle size, should reflect the considerable wearing down that has taken place.

Professor Boulton has described a contemporary till found on Cora Island, Spitsbergen which contains an intact delicate shelly fauna having survived transportation. It is not difficult to find other examples of intact, extremely well preserved fauna, from within older bodies of till, that have travelled much greater distances. West and Donner (1956), Gibbard (1977) and Cheesher (1986) have all inferred a northern provenance for the Anglian tills found in the Vale of St. Albans. Little (1984) demonstrated that these tills contain a fauna derived from the Jurassic and Cretaceous. He showed that within these tills were representatives of microfauna from the Lias to the Kimmeridge, including an abundant Middle Jurassic (Bathonian) ostracod fauna (e.g. Lophocythere sp., Bairdia sp.) and ostracods from the Lias (Hungarella sp.) and the Kimmeridge (Galliclacytheridea sp.). In addition, there was a conspicuous presence of well preserved, intact larger fauna, notably bivalves, presumably of similar age and provenance to the microfauna.

Reference to the Geological Survey 'Ten Mile' geological map, sheet 2, 1957, indicates that the Kimmeridge outcrop thins west of Newmarket in E. Anglia and is absent altogether over a distance of 50km (with the exception of a small outcrop around Ampthill) to the north of the Vale of St. Albans. It eventually reappears west of Leighton Buzzard.

A provenance for one of the tills from west of north west is therefore indicated. Furthermore, the presence of a Lias fauna in these tills extends the distances over which ice sheets carrying these materials must have travelled. The nearest outcrops of the Lower Jurassic are found at Bedford (50km NNW of the Vale) and Northampton (70km NW). No Lias is found in E. Anglia; a provenance from the east and east north east therefore seems unlikely. It is difficult to understand how these fauna could have survived, intact, transportation over such large distances.

One possibility is that ice moved large amounts of material en masse from source to lodgement, a process which would have minimised the attrition of clasts and fauna. (See for example, A. Howland, discussion Session IA.) However, there is no evidence to support this idea, at least so far as the Anglian tills in the Vale of St. Albans are concerned. On the contrary, there is evidence to refute it: (i) within the matrix there is much evidence of "faunal mixing", i.e. fauna from different stratigraphic horizons occur closely together in a random fashion, and (ii) intact shells are now completely infilled with (stiff) clay from the matrix of the till. Furthermore, scanning electron micrographs of chalk clasts within the till show evidence of their having been smoothed and rounded, but not necessarily striated. The very strongly developed clast fabric which characterises these tills could most easily have come about by a mechanism which permitted free rotation and alignment. It is difficult to imagine this happening within a body of stiff till. Finally, these tills also display a fabric of discontinuities which Little (1984) suggested was inherited from the jointing in the underlying Chalk on deglaciation. At this stage the till must have been stiffer than when infilling of the shelly fauna occurred.

In conclusion, there is other evidence, from older tills
elsewhere, to support Professor Boulton's contention that lodgement tills undergo part of the transportation process in a highly fluid, mobile state prior to their emplacement and before drainage, consolidation and overconsolidation of the sediment takes place.

References


