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Post-glacial mass flow and associated deposits preserved in palaeovalleys: the Late Precambrian Morænesø Formation, North Greenland

John D. Collinson, Richard E. Bevins & Lars B. Clemmensen

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The Moræneso Formation is of Late Proterozoic age and is preserved as the fills of a series of palaeovalleys. The formation is made up of conglomerates and sandstones of fluvial and aeolian origin and of a series of breccias which resulted almost entirely from gravitational mass movement down the sides of the palaeovalleys. At the most extensive exposure, examples of local rock-fall, rock-slide and matrix-poor breccia flows are observed close to the valley side. Their movement was probably favoured by freeze-thaw mechanisms. More widespread diamictites overlie valley-floor sands and were deposited under water-saturated conditions as a series of mass flows apparently from the sides of the palaeovalleys. The diamictites contain far-travelled clasts, some of which show striated surfaces suggesting a phase of glacial transport prior to final emplacement. Only at one locality does diamictite directly overlie the basal unconformity and suggest possible *in situ* till. The diamictite sheets are overlain by a widespread but thin dolomite unit which shows spectacular stromatolitic domes. At other localities in the area, valley fills show evidence of floating lake ice with dropstone pebbles occurring in thin bedded sandstones and mudstones.

The palaeovalleys are thought to have been eroded by valley glaciers which, on retreat, left substantial volumes of till on the valley sides and possibly in tributary valleys. Any moraine deposited on the valley floor was eroded by fluvial activity prior to a phase of alluvial and aeolian aggradation which coincided with local mass movement in cold conditions. Catastrophic rainfall, probably related to a generally wetter palaeoclimate, remobilised lateral moraines and other deposits and emplaced them on the valley floor. Deep weathering of dolerites at the unconformity suggests an ameliorated climate and a substantial time gap prior to these mass flows. A body of shallow water, established on the valley floor soon after these events, led to deposition of stromatolitic dolomite.

The Moræneso Formation represents remarkable preservation of a complex series of local glacial and post-glacial deposits in an upland setting compared with the more widespread lowland or marine tillites of Late Proterozoic age in other areas.

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Matrix-supported conglomerates and breccias (diamictites) in certain continental and shallow water settings often present problems of interpretation, particularly in assessing the relative importance of direct glacial emplacement versus processes of mass flow, or the extent to which both types of processes may have occurred in close association. Recent work has greatly increased knowledge of both types of processes and of resulting facies and facies relationships. As a result, the interpretations of certain ancient "tillite" sequences are undergoing varying degrees of reassessment (e.g. Eyles & Eyles 1983) and more sophisticated reconstructions are being achieved.

The Late Proterozoic Moræneso Formation of eastern North Greenland was first described by Troelsen (1956) who interpreted it as a tillite on the basis of its diamictites and the presence of facetted and striated clasts. Jepsen (1971) established some of the broader field relationships and named the formation. Here we describe some of the remarkably preserved and complex sedimentological features of the formation and discuss the processes of emplacement of both the diamictites and the associated deposits. From this we attempt to assess the morphological setting and the changing palaeoclimate.

Certain aspects of the sedimentology were briefly

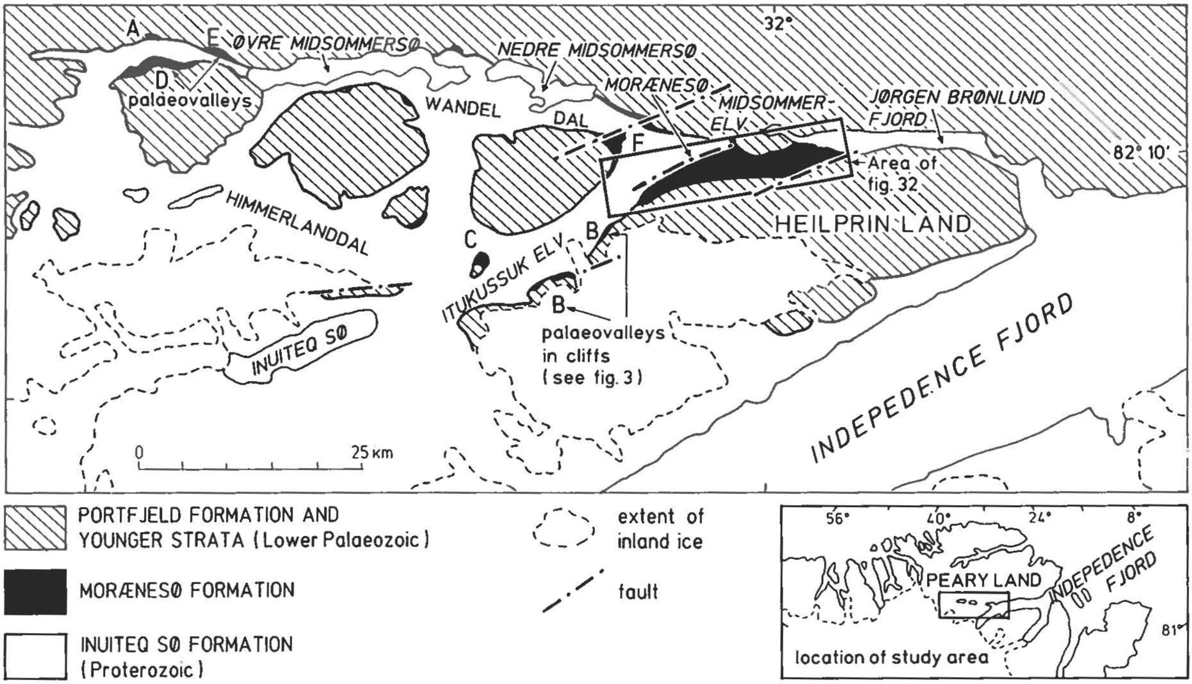

Fig. 1: Outline geological map showing the distribution of outcrops of the Moræneso Formation. Localities mentioned in the paper are labelled. Inset shows geographical setting of the area.

summarised by Clemmensen (1981) and those observations are extended and developed here. The field work was carried out in two short periods in 1978 and 1979. Clemmensen, in 1978, visited most of the outcrops of the formation whilst Bevins and Collinson, in 1979, concentrated particularly on mapping the type locality with shorter visits to some other localities. Time and logistical constraints did not allow the collection of as full a data set as the outcrops deserve but the problems of access make a further visit unlikely in the near future.

Regional setting and stratigraphy

The Morænesø Formation occurs in scattered outcrops in an area west and north of Independence Fjord in eastern north Greenland (Fig. 1). Rocks in the area are virtually undeformed with tectonic dips normally below 5°. The formation is bounded, above and below, by unconformities, the lower one having considerable relief (ca. 60 m), the upper one being extremely flat (Fig. 2).

The rocks below the Morænesø Formation are a flat-lying sequence of quartzitic sandstones with thin siltstone intervals, comprising the Inuiteq Sø Formation (Jepsen 1971, Collinson 1980), and which are intruded by sheets of dolerite and granophyre. These intrusions have yielded a well-defined whole-rock Rb-Sr isochron age of ca. 1230 Ma (Jepsen & Kalsbeek 1979, Kalsbeek

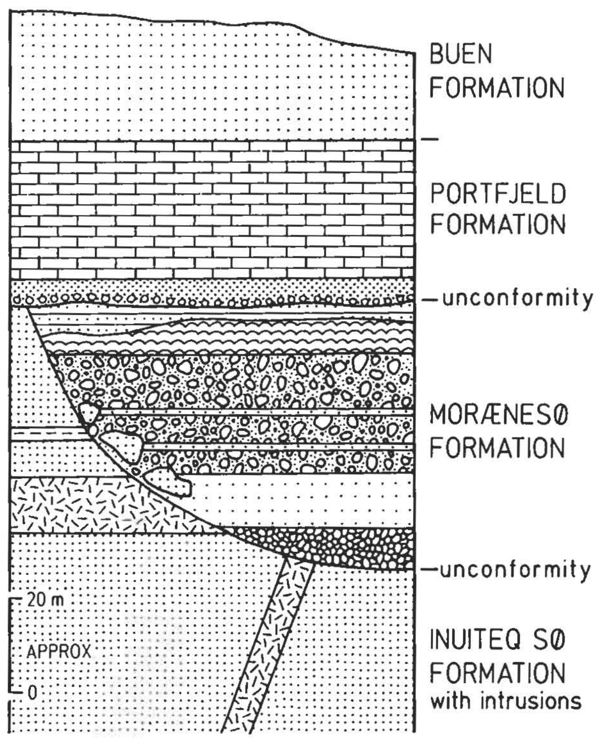

Fig. 2: Schematic stratigraphical column of the Morænesø Formation and adjacent formations, based on the relationships seen at the type locality. At other localities the sandstone unit directly above the stromatolitic dolomite may overlie topographically lower "hills" on the sub-Morænesø unconformity.

& Jepsen 1983) whilst radiometric ages from clays in the sediment sequence suggest an age of ca. 1380 Ma (Larsen & Graff-Petersen 1980). Close to intrusives, siltstones are dark in colour and more brittle. Above the Moræneso Formation, and separated from it by a remarkably flat unconformity, are 1–2 m of glauconitic sandstone which pass conformably up into the thick dolomite and cherts of the Portfjeld Formation (Jepsen 1971), which have yielded microfossils of early Cambrian age (Peel 1980). The age of the Morænesø Formation is therefore bracketed between 1230 Ma and the base of the Cambrian at ca. 570 Ma. The flat unconformity between the Morænesø and Portfjeld Formations truncates the pre-Morænesø palaeotopography. The tops of palaeohighs in the pre- and syn-Morænesø landscape were clearly eroded to develop this unconformity and unknown volumes of the Morænesø Formation itself have been removed. The time needed for this significant erosion suggests that the Morænesø Formation may be considerably older than latest Precambrian, down-grading possible correlation with the Varangian tillites of North Norway and elsewhere. On the other hand, the lower of the Varangian tillites in Finnmark, the Smalfjord Tillite, occurs in a palaeovalley (Føyn & Siedlecki 1980). There the associated palaeolandscape was peneplained prior to deposition of the Late Precambrian-Early Cambrian Dividal Group and the resultant truncation could compare with the unconformity between the Morænesø and Portfjeld Formations. A hiatus also separates the tillite-bearing sequence of central East Greenland from the overlying Cambrian sandstones (Hambrey & Spencer 1987).

Regional palaeotopography

The palaeorelief preserved at the base of the Morænesø Formation is truncated by the base-Portfjeld unconformity, so that present outcrops of the Morænesø correspond to topographic low areas or valleys in the palaeolandscape. Throughout the complete area of outcrop (85 km E-W x 25 km N-S), preserved relief is up to 190 m (Locality D, Fig. 1), though most examples show only a few tens of metres. Preserved apparent widths of palaeovalleys are commonly measured in hundreds of metres though examples in Wandel Dal and at the type locality are wider. Where complete cross-sections are seen, in steep walls of present-day valleys, the palaeovalleys show rather gently concave upward profiles (Fig. 3).

It is clearly impossible to accurately determine the total relief which prevailed in the area immediately prior to deposition of the Morænesø Formation. How-

Fig. 3: Palaeovalley exposed in the cliffs on the south side of Itukussuk Elv, west of Morænesø (western locality B, Fig. 1). The dark sediments of the Morænesø Formation thin away to either side and are overlain by the horizontally bedded Portfjeld Formation. The pale sandstones of the underlying Inuiteq Sø Formation are exposed just below the channel base. Dark material in the lower part of the hillside is dolerite intruded into the Inuiteq Sø Formation.

ever, it seems quite reasonable, given the shapes of the preserved palaeovalleys and the wide distance between some of them, that a total relief of several hundreds of metres could have been present.

The orientation of the palaeovalleys in a regional sense is similarly difficult to determine. At Moræneso in the east, a palaeovalley appears to trend to the east-northeast, whilst the large palaeovalley on the south side of Wandel Dal, west of Øvre Midsommersø, has palaeocurrents to just west of north. A regional dispersion/drainage from southwest to northeast may have prevailed, but data are too sparse to allow confidence.

The Morænesø locality

The most extensive and accessible outcrop of the formation occurs at the type locality around Morænesø (framed area, Fig. 1). However, the more scattered outcrops to the west show features which help to fill out the picture. The main account deals first with the type locality and then, in rather less detail, with these other localities.

The extensive and complex area of outcrop at Morænesø (Fig. 32; see inside back cover) extends some 10 km along the southern side of Wandel Dal from near its junction with Itukussuk Elv in the west. The complexity of the outcrop pattern results primarily from the intersection of present-day topography and the palaeotopography at the base of the Morænesø Formation (Fig. 4). In south of the mapped area, the present-day valley side rises steeply above 250 m and only Portfjeld Formation and younger units occur there. Below approximately 250 m, the slope is more gentle and coincides, more or less, with the sub-Morænesø unconformity which, in descending to the north, appears to form the southern side of a palaeovalley. At the western end of the outcrop a fault, trending SW-NE, truncates the Morænesø outcrop. To the northwest of the fault, no Morænesø Formation is preserved. The fault trends roughly parallel with palaeocurrents in the Morænesø Formation (flow to NE) and may coincide with the axis of the palaeovalley. Morænesø outcrops are therefore confined to sediments on the southern side of the palaeovalley. The widening of the outcrop eastwards seems to coincide with a flattening out of the unconformity, suggesting that the palaeovalley expanded downstream to the east to a width in excess of 3 km (Fig. 32).

The sub-Morænesø surface

The irregular outcrop of the sub-Morænesø unconformity (Fig. 32) reflects in part the medium-scale relief of this surface and the fact that its general dip corresponds closely with that of present topography. Inliers of Inuiteq Sø Formation or of dolerite commonly coincide with highs or "hills" on the unconformity. Some "hills" have rather rounded forms whereas others have stepped profiles which reflect bedding and jointing in the Inuiteq Sø Formation. There is no detectable preferred direction of facing of the steeper sides of these hills.

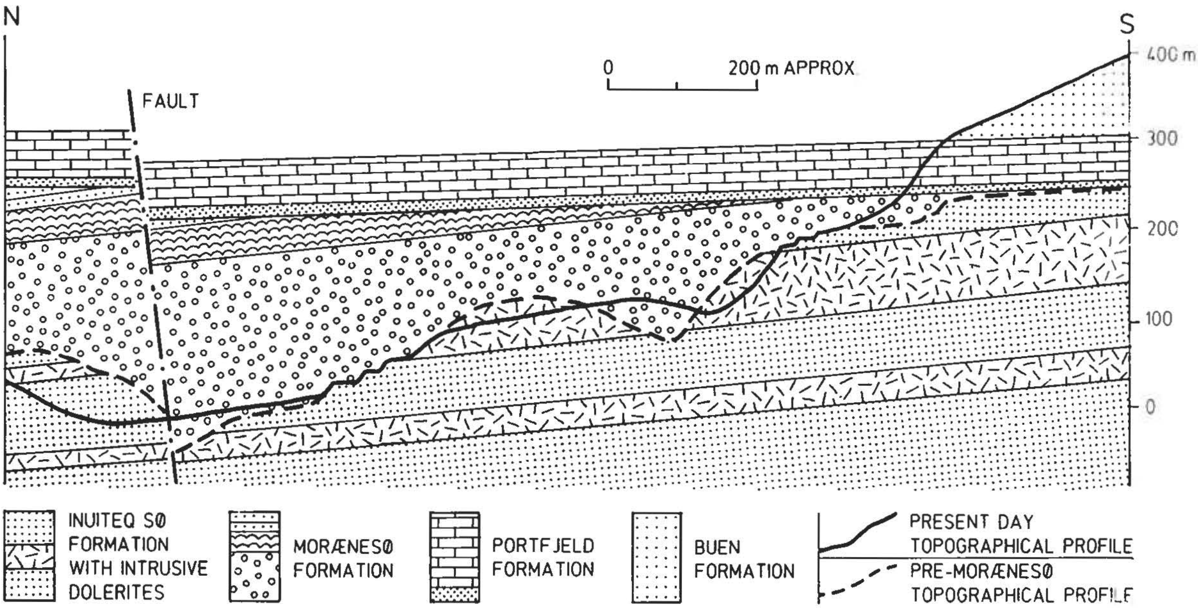

Fig. 4: Schematic north-south section across western part of the type locality, to illustrate the complex interference between the present-day topography and the palaeotopography of the sub-Morænesø unconformity. The lower clastic unit of the Morænesø is shown undifferentiated. Fig. 28 shows some of the facies relationships within this unit.

The surface of the unconformity varies from sharp to brecciated with a gradual transition from jointed, *in situ* Inuiteq Sø sandstone through a fragmented zone into conglomerates and breccias of the Moræneso Formation. Sand and gravel of the Morænesø Formation fill open joints which penetrate several metres into the Inuiteq Sø Formation.

In spite of their generally greater resistance to erosion in forming inlier "hills", some dolerites close to the unconformity show deep spheroidal weathering (Fig. 5), a feature which is absent in dolerites in the same area which have undergone glacial erosion and subsequent weathering in the Quaternary.

Nowhere on the exposed surface of the unconformity are there striations which cannot be accounted for by Quaternary glaciation.

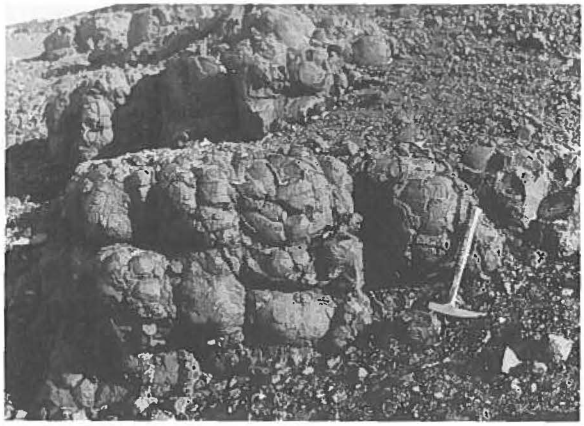

Fig. 5: Deep spheroidal weathering in intrusive dolerite within the Inuiteq Sø Formation, just below the sub-Morænesø unconformity at locality C (Fig. 32), just south of Morænesø. Such weathering is a feature of dolerites close to the unconformity and is absent in other dolerite in the area.

Facies associations and their distribution

The sediments of the Morænesø Formation at the type locality are dominated by sandstones, diamictites, conglomerates and breccias with a minor, though important, interval of dolomite. The clastic sediments show a wide range of grain sizes, textures and sedimentary structures which could be accommodated in a complex scheme of facies. However, when the sediments are considered in terms of both their internal characteristics and their field relationships, they fall into four associations. These associations are each related to suites of processes and they have specific stratigraphic and spatial distributions which suggest a very particular history of sedimentation within the palaeovalley.

A brief outline of the gross relationships of the associations and our view of their significance is presented at the outset, in order that the relevance of subsequent, detailed descriptions can be appreciated more readily.

Association 1 (valley floor sandstones and conglomerates) occurs principally in the deeper, more axial parts of the palaeovalley. These sediments directly overlie the unconformity in this area and comprise conglomerates and sandstones of mainly fluvial origin, with some aeolian components. They record valley floor deposition prior to deposition of the diamictites.

Association 2 (locally derived breccias) is a suite of breccias whose clasts are derived from the Inuiteq Sø Formation and its intrusives. They are locally distributed and occur closely above the unconformity, especially where that surface slopes steeply. These sediments are the products of a suite of gravity-driven mass movement processes which derived their material from the valley side. Some of the inferred processes occur most readily in cold climates where freezing and thawing of interstitial ice is important.

Association 3 (diamictites and related sediments) occur as a series of widespread beds directly overlying Associations 1 and 2. In addition to local clasts, they contain exotic clasts, some of which show flat-iron shapes and are striated. Parts of these units show evidence of movement toward the valley axis. They are interpreted as mass flow deposits which were emplaced suddenly on the valley floor following flow down the valley side. Their textures and clasts suggest an earlier phase of glacial transport, in which case they are most likely derived from earlier moraines deposited higher on the valley side or in tributary valleys at a time when a glacier occupied the valley.

Association 4 (dolomites and overlying sandstones) sharply overlies the highest diamictite sheet and is a unit of dolomite, a few metres thick, showing spectacular domal stromatolites, particularly well developed at the wider, eastern part of the palaeovalley. The unit represents the establishment of a body of shallow water on the valley floor, recording a rise of local base level and starvation of clastic sediment. A thin unit of sandstone infills and drapes the domes and reflects the re-establishment of clastic supply with wave action as the dominant energy source.

Facies Association 1: valley floor conglomerates and sandstones

This association is volumetrically the most important in the formation at the type locality. It consists of dark red conglomerates and sandstones along with units of better sorted, pale-coloured sandstone.

The conglomerates are thickest in the west of the outcrop, immediately south of the boundary fault, where some 25 m of conglomerate directly overlie the

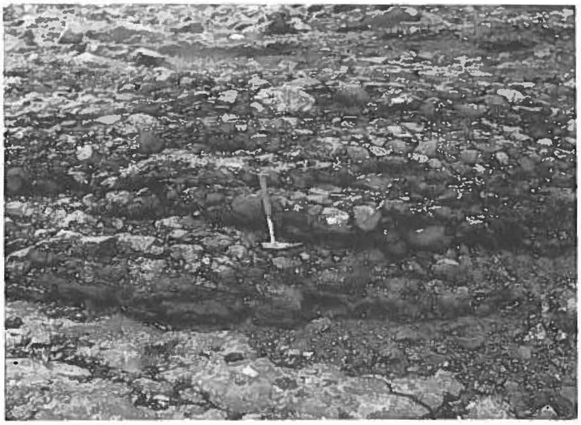

Fig. 6: Pebble-supported framework conflomerate with clast imbrication. These fluvial conglomerates occupy a relatively axial position in the deeper part of the fill of the palaeovalley at the western end of the type locality. 200m NW of locality B, Fig. 32.

unconformity with the Inuiteq Sø Formation (Loc. B, Fig. 32). The conglomerate contains clasts up to 1 m in diameter but most are in the cobble range. They consist mainly of quartzite but clasts of dolerite, various metamorphic rocks and dolomite are also present. Most of the conglomerate has a clast-supported framework (Fig. 6). In places there is a clear contact imbrication of flatter clasts and, on near horizontal surfaces, a preferred long axis orientation is apparent. In some beds a more abundant sandy matrix gives rise to a matrix-supported texture where weakly developed normal grading is occasionally present.

One exposure in the conglomerates near the western end of the outcrop (Loc. A, Fig. 32) is unusual in showing cross-bedding (Fig. 7). A single set, some 9 m thick, extends for at least 40 m in the direction of foreset dip. Foresets are inclined uniformally at 28° and the set is overlain by horizontally bedded conglomerate (Fig. 7).

The conglomerates are considered to be of fluvial origin, in a system where coarse sediment was confined to more central parts of the valley, and were a particular feature of the earliest stages of valley aggradation. Present levels of erosion make it impossible to say whether conglomerate deposition persisted in the axial parts of the valley up to the time of diamictite deposition. Clearly the currents needed to transport the conglomeratic clasts must have been powerful and were probably only active during floods. The presence of clast imbrication suggests fully turbulent flows with vigorous grain interaction close to the bed, whilst beds with more dispersed textures and grading may indicate conditions approaching those of a debris flow. The large-scale set of cross-bedding, occurring as it does close to the side of the palaeovalley (i.e. to the unconformity) may be a flood stage bedform similar to the "eddy" or "pendant" bars which formed on the sides of valleys in the channelled scablands of northwestern USA during major catastrophic flooding, caused by the bursting of ice dammed lakes (Baker 1973).

The conglomerates are interbedded at a spacing of around 1 m with sandstone units which range in thickness from a few centimetres to around a metre. These sandstones are mostly poorly sorted with scattered pebbles and commonly show a rather poorly defined parallel bedding or lamination. Some surfaces show primary current lineation. Thicker units of sandstone have silty

Fig. 7: Large scale cross-bedding in conglomerates. Cross-bedding dips to east. Hammer (arrowed) for scale. Locality A, Fig. 32, western end of type locality.

or muddy partings, some of which carry polygonal patterns of desiccation cracks. Other thicker sandstone units have cross-bedding in medium-scale trough sets.

In the western part of the outcrop, the conglomerates show a complex interfingering with sandstones, especially close to the northward sloping surface of the underlying unconformity (see Fig. 28 for a schematic illustration). There is an overall fining and thinning of conglomerate and a replacement by sandstone southwards from the area of its thickest and coarsest development close to the fault. The sandstones into which the conglomerate wedges out are mainly poorly sorted and pebbly and are mostly cross-bedded in broad trough sets, 20–30 cm thick. Pebbles are dispersed and also occur concentrated in lenses. Some troughs have thin muddy drapes. Thin units of sandstone interbedded with conglomerate show parallel lamination and primary current lineation, cross-lamination and ripple form sets. Scattered pebbles on some bedding surfaces have well developed scour crescents.

At one locality toward the eastern end of the outcrop (Loc. D, Fig. 32), medium-coarse sandstone lacking pebbles shows the development of unusual undulatory bedding in a series of domes, 70–80 cm in diameter and around 10 cm in relief (Fig. 8). Bedding, around 1 cm thick, parallels the undulations and the domes persist through about 1 m of sediment. Upper bedding surfaces carry primary current lineation. The forms are thought to represent deposition on standing waves developed in the upper flow regime. Whilst otherwise comparing well with other ancient supposed standing wave deposits (e.g. Hand et al. 1969, Walker 1967) these are unusual in persisting over a large vertical thickness.

Imbrication and cross-bedding in the conglomerates, their interbedded sandstones and the thicker sandstones

Fig. 8: Undulatory laminated sandstone, interpreted as standing wave deposits, in fluvial sandstones beneath the diamictite beds. Bedding surfaces show primary current lineation. Locality D. Fig. 32.

all show palaeocurrents toward the east and northeast. Structures within restricted areas show small vector dispersion. The general direction parallels the strike of the northward inclined unconformity suggesting that the surface represents the southern side of a palaeovalley along which currents flowed to the east.

All the sandstones described above are clearly waterlain and record currents of varied strength and depth. Dune bedforms dominated to give the trough cross-beds, but upper flow regime conditions were at times developed to give upper stage plane bed and, exceptionally, standing wave deposits. Mud drapes and desiccation cracks suggest a somewhat flashy discharge pattern leading at times to subaerial emergence. The general context and the unidirectional palaeocurrents suggest an alluvial valley floor. The lack of erosional channel forms and extensive lag conglomerates suggests that during high stage, the whole valley floor may have been the site of active transport and deposition.

At several places along the outcrop, close to the basal unconformity, pale coloured, yellow to orange, fine to medium grained sandstone occurs. These sandstones are either just above or laterally equivalent to the fluvial deposits described above. The geometry of the outcrop makes it impossible to judge. These sandstones are well sorted and pebble free and are cross-bedded in broad, trough and tabular sets up to 3 m thick. Several sets contain sand-flow stratification of typical aeolian appearance (cf. Hunter 1977). Sets are separated by thin, single pebble layers of small pebbles. Interbedded are layers of rather featureless but broadly parallel bedded sandstone, which show no signs of current lineation or other types of bedform. Locally these beds contain mm-thick lamination very similar to the climbing translatent strata of Hunter (1977). These units occur in close association with units of slightly pebbly sandstone showing trough cross-bedding.

The well sorted, cross-bedded sandstones seem to represent small aeolian dunes at the edge of the valley floor. The rather featureless, parallel-bedded sandstones probably represent aeolian sand sheet environments in which dune formation was inhibited by periodic flooding (cf. Kocurek & Nielson 1986). Thin pebble layers may be the result of wind deflation processes. The evidence of subaerial emergence in the alluvial sandstones and the lack of vegetation in the Proterozoic means that wind reworking of valley floor sediments is very likely.

Facies Association 2: locally derived breccias

Immediately adjacent to certain parts of the unconformity, particularly where steeply inclined, is a suite of breccias of differing aspect. All comprise clasts derived from the Inuiteq Sø Formation or the intrusive dolerites. Some breccias are of very restricted extent, often

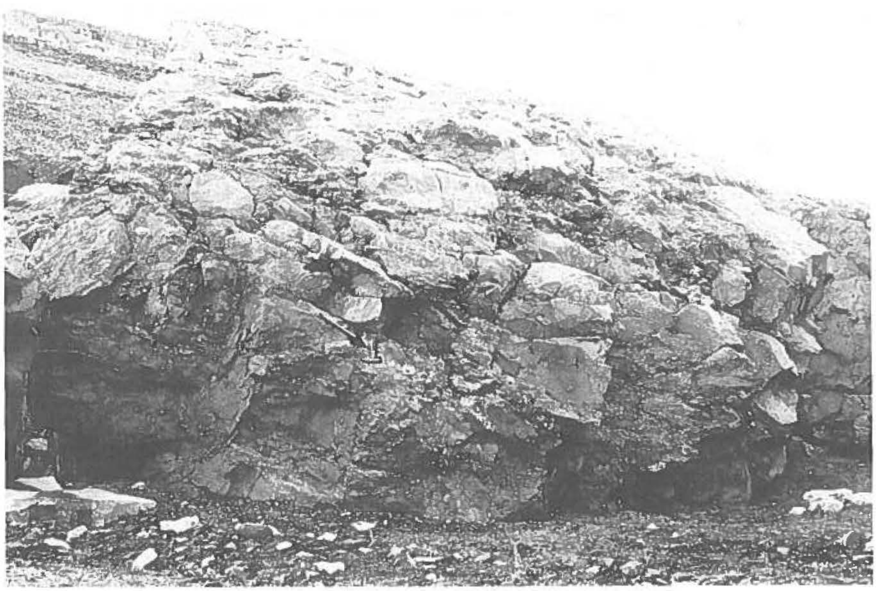

Fig. 9: Local coarse breccia of large angular boulders in close packed framework. The deposit occurs close to a steep step in the sub-Moræneso unconformity and is interpreted as a local scree deposit. Hammer (arrowed) for scale. Locality E, Fig. 32.

associated with very steep sectors of the unconformity, especially where there is a slight embayment in it. The coarsest breccias have angular blocks up to 2 m in length and form wedges up to 5 m thick against a steep unconformity step (Fig. 9). Breccia units with 20–30 cm clasts are commonly 1–2 m thick. These breccias seldom extend laterally away out from the unconformity for more than a few metres and rapidly pass into finer grained sediments of Association 1. The shape of sandstone blocks is controlled by earlier jointing and bedding. Dolerite clasts are more rounded, probably relating to the spheroidal weathering seen in *in situ* outcrops below the unconformity.

At one locality a larger, isolated block of Inuiteq Sø quartzite with exposed dimensions of 4 m x 5 m occurs embedded in cross-bedded sandstones of Facies Association 1, some 10 m horizontally from the foot of a very steep step on the unconformity which itself is covered by similar blocks up to 1 m in size. Bedding in the large block is vertical.

These breccias and blocks appear to have been emplaced by rock fall to accumulate mainly as small talus wedges. The large isolated block appears to have fallen down the hillside onto the valley floor to be eventually buried by alluvial sands. The shape of blocks suggests physical opening of joints and bedding planes, perhaps by freeze-thaw mechanisms.

Other local breccia units show signs of mass flowage

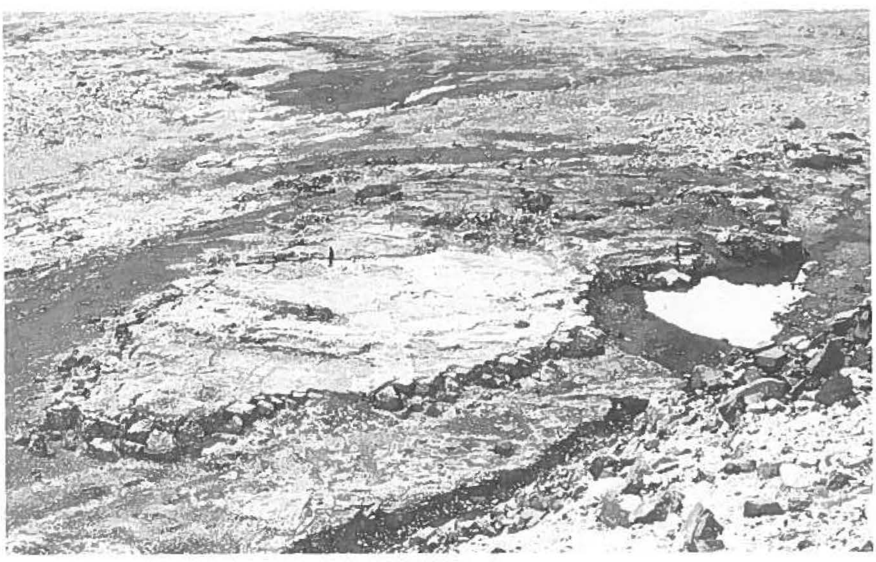

Fig. 10: Large slab of thinly bedded Inuiteq Sø sandstone resting on a nearly horizontal step on the unconformity. The internal structure of the slab is illustrated in Fig. 11. The fragmentation around the edges of the slab may be, in part, a modern effect and in part a palaeofragmentation. Figure for scale. Locality G, west end Fig. 32.

Fig. 11: Internal structure of the large slab illustrated in Fig. 10. The basal surface of the slab is just beneath the foot of the outcrop face. Note the downwards increase in the intensity of brecciation from intact sandstone beds at the top to disoriented breccia at the base. The brecciation is thought to result from the sliding of the slab on the basal surface.

Fig. 12: Siltstones of the Inuiteq Sø Formation baked by igneous intrusion and occurring at the unconformity with the Moræneso Formation. Note the upwards increase in brecciation of the siltstone towards the top surface, which is illustrated in Fig. 13. The structure is thought to result from brecciation and downslope flowage of the rock, possibly as a result of freeze-thaw action. Locality H, Fig. 32.

rather than rock fall. Three examples are described below:

a) At locality G (Fig. 32), the top of a thick sill forms a near-horizontal step, at least 50 m wide, on the unconformity. Directly above the step lies a slab of thinly-bedded quartzite, measuring 75 m x 35 m horizontally and 3 m thick (Fig. 10). The long dimension lies E-W along the step. The lithology matches that of the Inuiteq Sø Formation. In the upper half of the slab, the thin bedding (2–5 cm) is undisturbed and intact, but it becomes inceasingly brecciated and disrupted downward (Fig. 11). There is a downward increase in the relative displacements of small equidimensional angular blocks and spaces between the more widely separated blocks are filled with a red sandy matrix.

This pattern of brecciation suggests that the slab was moved by sliding on a basal shear plane probably through slow creep. Downward-increasing brecciation is common in slabs of thinly bedded material in present-day landslides. The displacement distance cannot be reconstructed, but seems unlikely to have been more than a few tens of metres. The surface on which movement took place was inclined at a low angle (probably less than 10°) and this implies some form of lubrication on the sole of the slab. Freeze-thaw of porewater or a high porewater pressure are possible mechanisms.

b) 100 m along slope to the northeast of the slab described above (Loc. H, Fig. 32), 2 m of dark, interbedded siltstone and thin sandstones of the Inuiteq Sø Formation, baked by a nearby dolerite intrusion, are exposed at the unconformity. The lowest 50 cm are undisturbed and *in situ* but upwards they pass gradationally into a breccia of very angular fragments, closely packed and lacking significant matrix (Fig. 12). On the upper surface of the breccia layer, the relative displacement of these blocks shows folds with lobate forms convex downslope to the north. These folds are 1–2 m wide and extend downslope for several metres (Fig. 13).

The downslope orientation of the folds and the upward increase in brecciation suggest that the surface layer was subjected to downslope flow or creep on a small scale. Horizontal displacement was probably only of the order of 10 m. The lack of significant sediment matrix and the close packing of angular clasts present a problem of lubrication. The lobate style of internal deformation invites comparison with some gelifluction

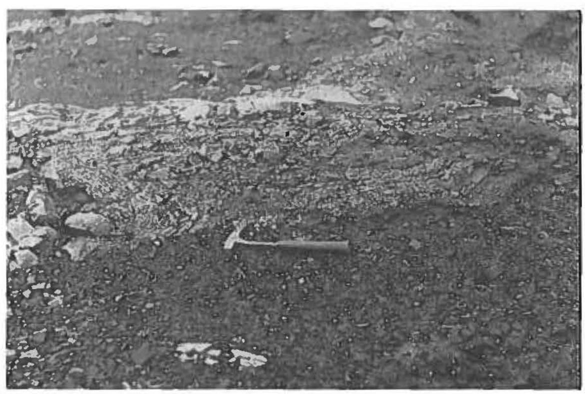

Fig. 13: Upper bedding surface of the unit illustrated in Fig. 12. The breccia of small blocks of sandstone and indurated siltstones are deformed into a series of folds suggesting flow lobes which moved to the north down the side of the palaeovalley.

Fig. 14: Downslope view of the large, breccia-filled gulley at locality J (Fig. 32). The darker rocks on either side are dolerites which form near-vertical walls to the gulley, which is about 16m wide and extends down slope for ca. 300m. The breccia in the centre has no obvious fabric but a vertical foliation is developed towards the margins.

features of seasonally cold environments (Benedict 1976) and suggests that freeze-thaw may have been important.

c) One of the most spectacular features of the Moræneso Formation is a large breccia- and sandstone-filled "gully" cut into underlying dolerite at locality J (Fig. 32). It is at least 2 m deep with near vertical walls. The base is not seen. It is broadly parallel sided, about 16 m wide and trends in a straight line directly down the slope of the palaeovalley side for some 300 m (Fig. 14). Protrusions and embayments in the steep walls have a rugosity of around 2 m. The fill of the gully is either medium sandstone or rather closely packed breccia, the latter being made up entirely of Inuiteq Sø quartzites. Close to both margins the fill shows a zone of pronounced vertical "foliation", parallel to the walls. In sandstone this foliation is a series of parting planes, whilst in the breccia it is a preferred orientation of clasts. These marginal zones are commonly 3–4 m wide, but in some areas a foliation occupies almost the full gully width. The foliation bends around irregularities on the gully walls so that it always parallels the margin. Between the foliated marginal zones is an axial zone of either structureless sand or breccia with no obviously preferred fabric. Contacts between these zones are gradational with foliation increasing toward the walls.

The orientation of this feature and the nature of its fill suggest mass movement along the gully. Foliation and clast orientation suggest shearing parallel with the gully walls whilst the structureless axial zone apparently behaved as a rigid plug. Judging from present-day topography, the downslope movement took place on a slope of around 5°. It is possible that the sandy parts of the fill could have moved as high viscosity debris flow, but the scarcity of matrix in the breccia raises questions about this interpretation. The deposit has some similarities with the "block streams" of periglacial settings (e.g. White 1976) or with rock glaciers (e.g. Serrat 1979), though on a small scale. Whilst it is possible that some matrix may have been removed by later flushing, this cannot be demonstrated. The possibility must therefore exist for freeze-thaw of interstitial ice or elevated pore water pressure to have played a role in promoting movement.

Facies Association 3:. diamictites and related sediments

This suite of sediments comprises diamictites and other breccias, thin sandstone interbeds and sandstone dykes. In addition, features seen at the contacts between the breccias and the underlying sediments of Association 1 are important in its interpretation.

The coarser sediments (i.e. breccias and diamictites) have a variable proportion of sandy matrix which ranges from around 30% when the texture is clast-supported (Fig. 15) (i.e. breccias) to more than 75% (in the extreme case 95%) when the texture is clearly matrix-supported (Fig. 16) (i.e. diamictite). The sandy matrix shows rather variable sorting. Some examples examined in thin section have quite well sorted medium sand, but most are less well sorted with angular grains and an abundant matrix of hematite-stained clay which gives the rock a dispersed (i.e. wacke) texture. This means that, for the diamictites, a dispersed texture exists at all scales of observation.

There is a continuous gradation in textures between clast-supported breccias and diamictites. At one locality it is possible to trace a lateral passage from one type to the other over a distance of around 100 m.

Fig. 15: Typical texture of a matrix-poor breccia, showing the relatively close packing of the larger clasts. Such breccias are commonly of restricted areal distribution and have push ridges at their sharp downslope margins. They may pass laterally into more dispersed diamictites. Locality L, Fig. 32.

Fig. 16: Typical texture of diamictite. Note the subhorizontal partings and the well dispersed fabric. Scale is 5 cm wide. Locality M, Fig. 32.

The breccia clasts are dominantly derived from the Inuiteq Sø Formation and from the intrusive dolerites, but in addition, there is a component of around 5% of exotic clasts, mainly of metamorphic rocks. The large clasts commonly range up to 30 cm in maximum length, but some as large as 80 cm are present. Most are angular or sub-angular, the exceptions being rounded dolerite clasts. Some have a flat-iron shape and a proportion, around 5%, carry striations on flatter surfaces (Figs 17 and 18). These are aligned parallel with the long axes of elongate clasts (Fig. 18). On some larger clasts, several sets of subparallel or cross-cutting striations are seen (Fig. 17).

There are conspicuous differences between breccias of contrasting texture in terms of their lateral extent and their relationships with other sediments.

Matrix-poor breccias are restricted in their lateral extent. It is never possible to trace them for more than 200 m either downslope or parallel to the palaeocontours. Such breccias occur as rather parallel-sided units up to about 3 m thick. In plan view units may show a lobate

Fig. 17: Striated clast from diamictites, with striations in several directions. Area east of Locality J, Fig. 32.

Fig. 18: Striations dominantly parallel to elongation of a clast from diamictite. Area east of Locality J, Fig. 32.

shape. Units which directly overlie the basal unconformity tend to occupy topographic lows on that surface. Breccia units which partially overlie earlier sediments of Association 1 have sharp lateral margins with those deposits. At the downslope ends of breccia units, deformational features occur. Contacts between breccia and sandstone are steep, in some cases approaching vertical. Bedding in the sandstone dips steeply parallel with the contact (Fig. 19). Sandstones downslope of the contact are folded in a zone up to 10 m wide across which deformation diminishes downslope (Fig. 20). Fold axes are parallel to the contact. The upper surface of the deformed sandstone has rounded hollows which preserve patches of breccia.

It is evident that the breccias were emplaced by downslope mass movement which ended when the flow encountered sands at the foot of the slope. The internal deformation suggests that the sands were soft and water-saturated, whilst the preservation of breccia patches in hollows on top of the sand suggests that part of the mass flow, perhaps an upper more mobile layer, overrode the valley floor sands.

The diamictites, in contrast, show a much wider spread, distributed as sheets, commonly around 5 m and up to 8 m thick. Their lateral margins are only seen where they are traced laterally, usually along slope, into the breccias showing the relationships described above. Diamictite sheets tend to maintain thickness laterally with broadly horizontal upper and lower surfaces. Exceptions are where such sheets drape topographic highs on the unconformity and in places wedge out against them. In such cases, relief on the base accommodates most of the thickness changes. Diamictite sheets build up composite units up to 50 m thick which cover several km^2. The individual sheets are separated by thin sandstones, described in more detail below. Internally the diamictite beds show no segregation of grains either as grading or as bedding. Only a pattern of sub-horizontal joints or partings weathers out to suggest that a very subtle fabric may be present (Fig. 16).

Measurement of elongate clasts, which are scarce in

Fig. 19: Sharp contact between matrix-poor breccia on the left and fluvial, valley-fill sandstones on the right. The breccias have pushed into sands by movement down slope from the left (south). The push-generated dips in the sandstones die out to the right over a distance of around 5 m. Small pockets of breccia on top of the sand rest in hollows and suggest that some of the breccias flowed over the sand and loaded slightly into it. 100 m NE of locality G, Fig. 32.

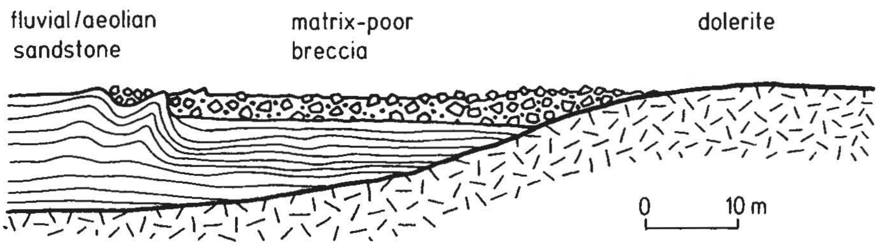

Fig. 20: Schematic cross-section through the down slope margin of a push ridge developed in front of a flow of matrix-poor breccia.

the diamictites, shows a NW-SE alignment with the majority of the clasts dipping towards the SE.

Sandstone dykes and sheets cut through the diamictite beds and are commonly associated with sandstone beds which lie between successive diamictites. In addition, sandstone beds of Association 1 which are directly overlain by diamictite are locally intensely internally deformed. The dykes, sheets and deformation are thought to be genetically related and are therefore described together.

The dykes range in width from a few centimetres up to about 60 cm and are seen to penetrate vertically over 3 m. They are mainly parallel-sided both in plan view and when seen in vertical section (Fig. 21). Some, however, wedge out upwards and others wedge out downwards. Those which wedge out downwards do not penetrate more than 0.5 m from the top of the diamictite bed concerned (Fig. 22). Some bedding plane exposures show dykes to be linked at triple junctions suggesting a polygonal pattern at the scale of 5 to 20 m.

The dykes consist of medium to coarse sandstone, commonly well sorted and with well rounded grains, a few of which are of granule size. Some examples also include scattered clasts up to pebble size as well as small deformed intraclasts of finer grained sandstone. The dykes are essentially homogeneous across their width and none show signs of multiple fill. The sandstone is commonly rather structureless, but some examples show a lamination or foliation parallel with the walls of the dyke.

Traced downwards, some dykes connect with deformed sandstone underlying the intruded diamictite unit. More commonly, dykes occur in diamictites which overlie deformed sandstone but no direct connection is seen. The deformation of lamination in underlying sandstones takes the form of intense folding, some near isoclinal with fold amplitudes of a few tens of centimetres and with apparently random orientation (Fig. 23B). The deformation is also related to irregular relief at the interface between the sandstone and the overlying diamictite. Exhumed surfaces show rather sharp peaks and more gently concave-up hollows with a relief of around 1 m (Fig. 23A). Patches of diamictite are preserved in some of the hollows. These features of the contact suggest loading of diamictite into the sandstone. The sandstone peaks are therefore essentially large flame structures.

Sandstone dykes also connect upwards with sandstone sheets which directly overlie the intruded diamictite unit. In one example, the transition from sand dyke to sand sheet is through a series of intense folds (Fig. 24). The sandstone sheets are commonly several

Fig. 21: Parallel-sided sandstone within softer weathering diamictite. Though not clear on the photograph, the sandstone has a weakly developed foliation parallel to the side of the dyke. Hammer (arrowed) for scale. Locality N, Fig. 32.

Fig. 22: Thin diamictite bed with small, downwards-tapering and slightly folded sandstone dykes which appears to link to thin sandstone bed above. West of locality L, Fig. 32.

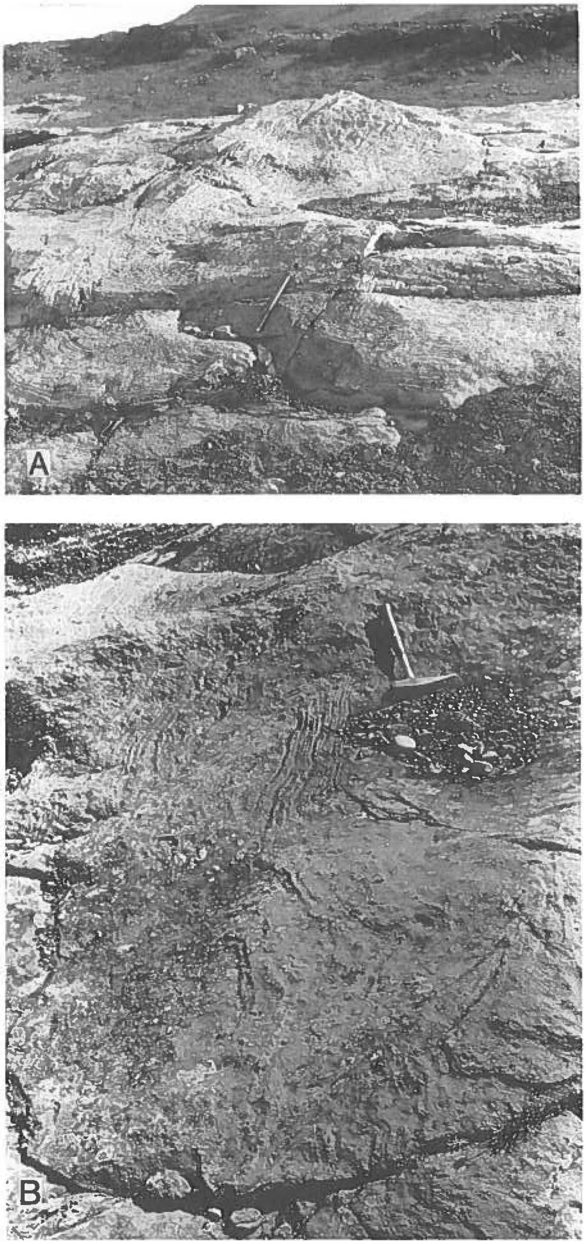

Fig. 24: Folding of a sandstone dyke intruded into a diamictite bed. The dyke (bottom right) becomes vertical when traced laterally outside the field of view. It passes through the folds illustrated and at the left hand side of the photograph it has become an extruded sand sheet on top of the diamictite bed. Hammer (arrowed) for scale. Locality P, Fig. 32.

Fig. 23: Deformation in valley floor sands beneath a diamictite sheet. A) The relief of the sandstone surface is close to that of the original interface between the sandstone and the diamictite. The diamictite, which forms the low cliff in the background, has been mainly eroded off, but pockets are preserved in hollows in the surface of the sandstone. The original lamination of the sandstone has been deformed into intense folds, which are shown in more detail in B. The deformation is thought to result from liquefaction and loading due to the rapid emplacement of the diamictite debris flow onto waterlogged sand. Locality L, Fig. 32.

tens of centimetres thick and are laterally extensive. Most are flat lying though some follow broad undulations on the tops of underlying diamictite. Internally the sandstone sheets show a weakly defined foliation or lamination which is commonly rather deformed suggesting flowage of a high viscosity sediment-water mixture or slurry (Fig. 25). Other sandstone beds show poorly defined grading, small-scale cross-bedding and rather poorly developed wave ripples.

Whilst some of the sandstone sheets were deposited, or at least reworked by flowing water, the origin of those displaying deformation and disturbed internal foliation seems to be closely linked with that of the sandstone dykes. The downward connection of dykes to underlying deformed sandstone and the upwards connection to sandstone sheets suggests upward movement of sediment-water mixtures. Foliation developed parallel to dyke walls probably results from shearing during this movement. Where the upward moving sand broke the upper surface of the diamictite, it flowed as a "fissure eruption" until water loss eventually resulted in loss of mobility (cf. Hutchinson & Bhandari 1971). Such dewatering may have contributed to a surface run-off capable of reworking the sand surface into small bedforms. Such transposition structures are well known in the ancient record (e.g. Hesse & Reading 1978) and modern examples of fissure eruptions and sand dykes are documented from earthquake zones (e.g. Swanson 1964, Reimnitz & Marshall 1965) and from the surfaces of mass flows (e.g. Johnson 1978, Kojan & Hutchinson 1978).

The polygonal pattern suggested by triple junctions the downward wedging of some dykes earlier led to the suggestion that these may be passive infills of pre-existing fissures such as periglacial sand wedges (Clemmen-

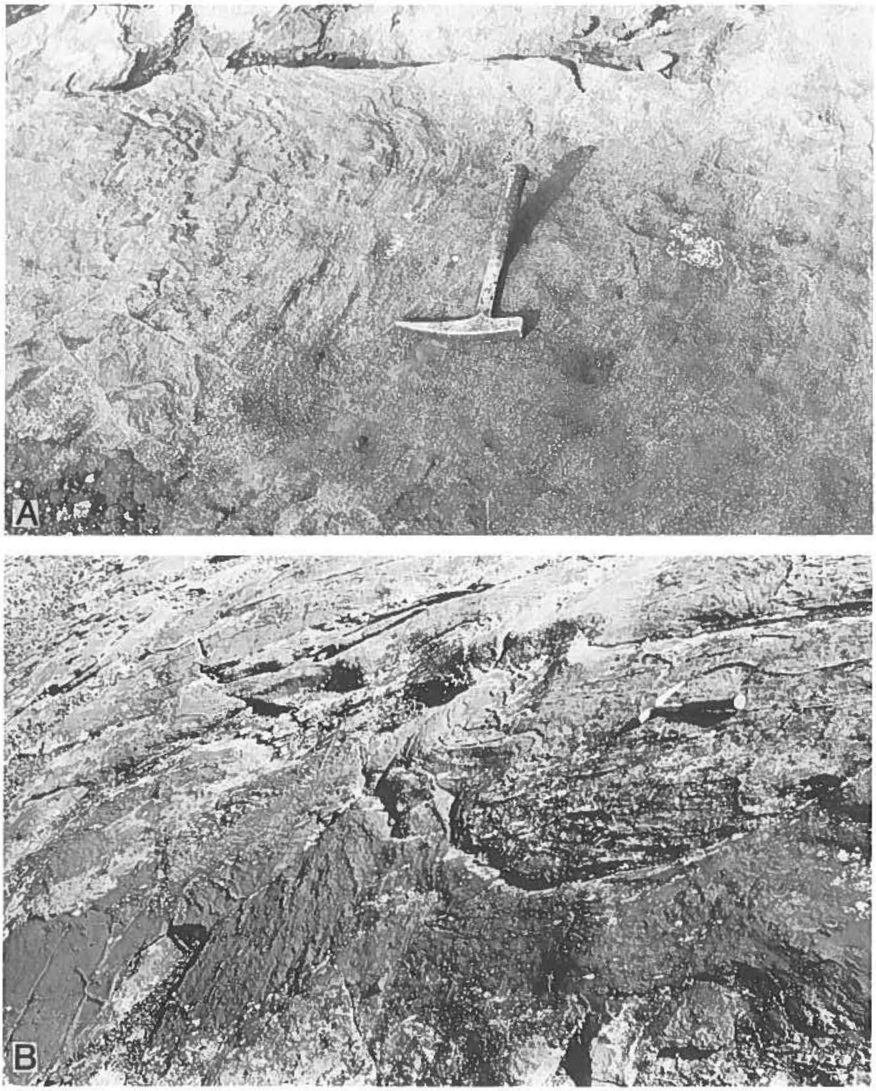

Fig. 25: Folded weak foliation in sand sheets resting on top of diamictite beds. These sheets can commonly be seen to connect up with sandstone dykes cutting the underlying diamictite and are thought to be the result of extrusion of liquefied sand from the dykes. The folded foliation results from the flowage of the liquefied sand prior to its dewatering. A. Locality Q. B. Locality R, Fig. 32.

sen 1981). However, polygonal patterns simply reflect isotropic horizontal tension and have been demonstrated to result from gravitational instability and dyke intrusion (e.g. Eyles & Clark 1985). It is possible that some of the downward wedging dykes represent a second phase of gravitational instability whereby sand initially extruded as a sheet on to the top of a diamict then undergoes vertical foundering back into the diamict through loading (cf. Eyles & Clark 1985). The undulation of sand sheets on top of diamictite units would support such a hypothesis. Other features also argue against a periglacial origin. Most Quaternary examples of both ice and sand wedges show a pronounced upwards flaring with down- and upturning of laminae and microfaulting in the host beds. Examples in the Morænesø either taper gently or are parallel sided and there is no deformation in adjacent diamictite. Ice wedges, in addition, commonly have heterogeneous fills with well differentiated layering sub-parallel to wedge walls in material mainly derived from the host sediment (e.g. Pewe 1959, Dylik 1966, Black 1976, Romanovskii 1973). The fills of Morænesø dykes are homogenous and clasts from the diamictite are virtually absent. Their foliated structure and, more particularly, their connection to overlying sand sheets makes such an interpretation unlikely. In addition, the dykes are exclusively features of the diamictites. If periglacial they might reasonably be expected in associated sediments as well.

The whole assemblage of features in Assemblage 3 is best explained in terms of the diamictite beds being emplaced by large and catastrophic debris flows which moved rapidly down the side of the valley and out over the valley floor at a time when the valley floor sediments were water-saturated. The widespread extent of the individual diamictite sheets, their rather flat upper surfaces and the fact that they thin or are absent over "hills" on the unconformity suggests considerable mobility, or low viscosity. The lateral passage of diamictites into breccias with lower matrix content which show clear evidence of having moved down the valley sides suggests that diamictites also moved in this direction, though in a more mobile state. Marginal zones of debris flows are commonly less mobile than the more central or upper parts and the matrix poor breccias may reflect this sorting process (cf. Curry 1966). The fact that movement was apparently down the side of the palaeovalley implies that large volumes of suitable material must have been stored on the valley side. The exotic nature of clasts, the clast shapes and the striated surfaces (cf. Dowdeswell, Hambrey & Wu 1985) all suggest that the material had undergone a phase of glacial transport before its final translation as debris flows to the valley floor. Such material could be envisaged as lateral dump moraines (cf. Boulton & Eyles 1979) left on the valley side following the retreat of a valley glacier though such deposits may have had rather limited volumes. The remobilisation of tills initially deposited in hanging tributary valleys, for which no direct evidence now remains because of post-Morænesø, pre-Portfjeld erosion, offers one solution to this volume problem.

The deformation at the interface between diamictites and the valley floor sandstones of Association 1 suggest a vertical loading between two water-saturated, low strength sediment units. The sudden emplacement of the diamictites as mobile debris flows would raise pore water pressure in the underlying sands to promote such instability. Elevated pore water pressure, if maintained, would also help to promote debris flow mobility by creating conditions of undrained loading (cf. Hutchinson & Bhandari 1971). Escape of at least some of the porewater was through intrusion and extrusion of liquefied sand as dykes and sheets.

Facies Association 4: dolomites and overlying sandstones

This association constitutes a relatively thin but widespread unit which mostly overlies the diamictite. Close to the side of the palaeovalley it oversteps on to breccias. The diamictite and the dolomite are commonly separated by a layer of sandstone commonly a few centimetres thick and showing evidence of limited reworking in the form of wave ripples. Locally this layer is up to 1 m thick. The sandstone is extensive and flat-lying. The dolomites lie directly on this sandstone and become more extensive to the east where the relief on the basal unconfomity appears to become more gentle. In this area the dolomite occurs in two distinct facies within a laterally continuous sheet up to 6 m thick. The first facies, domal stromatolites, is the more widespread and gives spectacular bedding surface exposures extending for several square kilometres (Fig. 26). Here, laterally linked stromatolite domes are exposed in full three-dimensional relief. The domes are up to 2 m high and 8 m in diameter though most are around 1 m high and 5 m diameter. Most are circular in plan and the few oval forms show no preferred orientation. Dips on the flanks are up to 45°. The dolomite is pale brown/cream in colour and lamination/thin bedding is on the scale of centimetres (Fig. 27). The second, less common facies is horizontally bedded red dolomites which pass laterally into the domal type. There is a clear relationship between red colouration and lack of domal development.

The domal stromatolites are overlain quite sharply by a thin unit of grey siltstone and sandstone which effectively infills the domal relief. It occurs as a coarsening upwards unit up to 6 m thick. Its lower part shows strong deformation with load balls up to 1 m diameter and intense convolute lamination. The deformation dies out upwards and the top 1 m shows thin sandstones with silty partings. Above is medium-coarse sandstone, 4–6 m thick and containing large-scale trough cross-bedding, horizontal lamination and wave ripples. This is capped by a pebble-rich horizon, which marks the unconformity between the Morænesø Formation and the glauconitic sandstones at the base of the Portfjeld Formation.

The dolomites clearly reflect the development of shallow water conditions in the area following diamictite deposition. The nature of the contact supports the suggestion that the top surface of the diamictites was generally flat across the valley floor. From the mapped extent of the dolomites, it seems that the water body opened out to the east from the more confined valley inferred for the western end of the outcrop. However, it is not clear from the stromatolites whether the water was a marine bay or part of a lake.

The overlying sandstones, which are clearly waterlain, reflect the re-establishment of clastic supply to a wave-aggitated setting, possibly a beach or shoreface. The intense deformation near the base of the sandstone unit reflects elevated pore water pressures, development of which may have been helped by the dolomite layer acting as a barrier to water movement. The instability may have been triggered by wave loading or by seismic activity.

Synthesis of the type locality

The type locality shows a succession of deposits which together form part of the infill of a palaeovalley which trends in an ENE-WSW direction and apparently opens out into an area of lower relief to the east. The valley side shows a stepped morphology with the steps related to bedding and jointing in the underlying rocks. The process of erosion of the valley is not evident from its morphology. Whilst there is no evidence in the form of striated surfaces to support a glacial origin, such a mechanism cannot be eliminated.

Fig. 26: Extensive bedding surface of stromatolite domes in dolomites overlying diamictite. View to east. Towards eastern end of type locality.

The earliest stages of infill (Fig. 28), which are apparently confined to the deeper, more axial part of the valley as seen at the western end of the outcrop, result from powerful fluvial currents which flowed eastwards and transported clasts derived from both distant and local source areas. Whilst facies relationships seen at outcrop do not allow a complete synthesis, the fluvial conglomerates appear to pass upwards and laterally, towards the valley side, into sandstones also of fluvial origin. Other sandstones, close to the side of the palaeovalley, are of apparent aeolian dune and sand sheet origin. This suggests that the fluvial system was ephemeral, allowing areas of alluvium to be reworked by the wind. Coincidentally with this fluvial and aeolian activity on the valley floor, the steeper rocky side of the palaeovalley was the site of local gravity flows and falls which involved clasts derived from the local bedrock. These accumulated as screes against steeper steps on the valley sides and as flow lobes, block slides and gulley fills on less steep sectors. The paucity of sedimentary matrix in the breccia flows suggests the operation of some other clast-support and lubrication mechanism. Freeze-thaw of pore waters seems most likely.

Fig. 27: Vertical section through stromatolitic dolomites, showing the laterally linked arrangement of the domes. Locality S, Fig. 32.

On to this valley floor setting were then deposited a series of diamictite beds whose relationships both with one another and with earlier valley floor sediments suggest that they were transported and deposited by mass flows which moved essentially down the valley side. The loading of diamictites into valley floor sands, the sandstone dykes and the extrusive sandstone sheets suggest that, at the time of deposition, the debris flows were highly water-saturated. The generally flat tops to the diamictite beds suggest that the flows were highly mobile, again suggesting high water content.

The diamictites include far-travelled clasts, many of which are angular and some of which show striations of

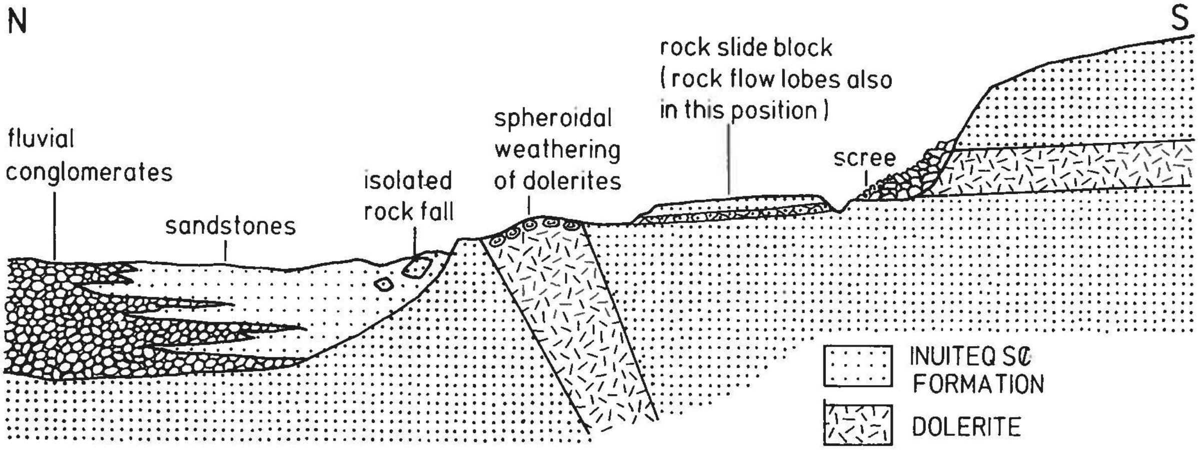

Fig. 28: Schematic north-south cross-section to show the distribution, within the palaeovalley of the type locality, of the facies which underlie the diamictite units.

likely glacial origin. These and the whole poorly sorted assemblage suggest a till which has undergone a phase of remobilisation. The fact that several diamictite beds occur in any one section suggests a series of flows though these need not have been very widely spaced in time and may even have been part of a series of retrogressive failures. The movement directions deduced for emplacement of the diamictites suggest that the earlier deposits from which they were derived were initially located higher on the valley side, possibly as lateral moraines or as the fills of now eroded hanging valleys.

A high level of water saturation must have existed to allow both mobilisation of the diamictites and the deformation of valley fill sands. Mobilisation of earlier glacial deposits was probably the result of a period of heavy and sustained precipitation, possibly building up levels of saturation over a period of time (cf. Eisbacher & Clague 1984). Alternatively, or in association with heavy precipitation, the bursting of a moraine-dammed lake may have played a role (cf. Eyles, Eyles & McCabe 1988). These possibilities suggest that any permafrost was deeply buried or non-existent at the time of mass flow. This would imply a period of climatic amelioration between initial deposition of the diamictites in their temporary storage site, probably as tills, and their eventual emplacement as mass flows. This inference is supported by the occurrence of deep spheroidal weathering in dolerites at the basal unconformity. Such weathered material is unlikely to have survived a phase of glacial erosion and the weathering is more likely to have taken place after the initial erosion of the valley. The apparent absence of *in situ* tills on the valley floor beneath the fluvial sediments also suggests a long interval of time between initial emplacement of diamictite on the valley side and in tributary valleys (presumably coinciding with the existence of a glacier in the valley) and final deposition of the diamictites on the valley floor.

The establishment of a body of shallow water over the surface of the diamictite sheets seems to have occurred with minimal reworking of the diamictites, suggesting low energy setting and a short time interval. Whether this water body was associated in some way with the emplacement of the diamictites, for example through damming of the valley by other mass flows further downstream, can only be a matter of speculation. The carbonate productivity might well have been favoured by the existence of a temperate climate. Stromatolitic dolomites which succeed the upper tillite-bearing Storeelv Formation in central East Greenland have associated halite pseudomorphs, arguing more strongly for a warmer climate (Hambrey & Spencer 1987).

The Morænesø Formation outside the type locality

Whilst the facies relationships important in establishing the depositional conditions of the diamictites are best seen at the type locality, features seen at other localities in the area help to fill out the broader picture of the palaeogeography.

Northeastern side of Rundfjell. – Approximately 10 km to the northwest of the type locality (Loc F, Fig. 1), a small outcrop of the Morænesø Formation occurs, composed of diamictite of which only the lowest 10 m is exposed. The locality is interesting because the diamictite here rests directly on heavily disintegrated sandstones of the Inuiteq Sø Formation, in contrast to other localities where diamictites are always separated from the unconformity by waterlain sediments. This diamictite, which contains striated clasts of glacial origin, may represent the only preserved, *in situ* till in the whole area.

Itukussuk Elv. – Traced southwest from the type locality, the unconformity between the Inuiteq Sø and Portfjeld Formations gradually rises, due to regional tectonic dip, up the steep cliffs on the south side of Itukussuk Elv (Loc. B, Fig. 1). Here three major palaeovalleys occur, each with concave upwards bases and filled with Moræneso Formation (Fig. 3). Two are inaccessible whilst the base of one can just be reached. All three are around 100 m deep and are several hundreds of metres in apparent width. True widths are unknown as it is impossible to determine the orientation of the valleys in relation to the cliff. All three contain bedded red sandstones with some conglomerates in their lower parts. Bedding varies from thin and horizontal beds with thin silty partings and desiccation cracks to thicker beds with broad gentle scours.In all the valleys, a unit of diamictite some 10–15 m thick occupies the upper part of the preserved fill and appears to rest on the underlying sediments with no obvious erosion or disturbance.

In these examples it seems that a major phase of valley filling by probable sheet flood and stream deposits preceded the emplacement of the diamictites. The inaccessibility of the outcrops prevents any detailed comments on the mode of emplacement other than that deposition was accomplished without significant erosion of the underlying sediments.

Northwest of Inuiteq Sø. – 14 km northwest of Inuiteq Sø (Loc. C, Fig. 1) a sequence of some 125 m of Morænesø sediments is preserved to the south of a large rounded dolerite intrusion into the Inuiteq Sø Formation. At the base, breccias, pebbly sandstones and well sorted sandstones have been faulted and partly folded to a degree not noticed elsewhere in the Morænesø or overlying formations. The greater part of the section is made up of well stratified fluvial conglomerates and pebbly sandstones, coarse crudely bedded breccias and units of aeolian sandstone.

South side of Wandel Dal. – Mapping in the area west of Øvre Midsummersø (Loc. D, Fig. 1) suggests that about 190 m of relief is preserved at the base of the Morænesø Formation. Exposures are rather patchy but up to 65 m of bedded coarse conglomerate occur in the lower part. These sediments compare with those in the lower axial part of the palaeovalley at the type locality and appear to be waterlain. Trough cross-stratification in sandier units indicates flow to the north.

Some 80 m above the base is a unit of cream-coloured dolomite in a unit which is up to 4 m thick but which wedges out to the west. The bedding within the dolomite shows a series of quite sharp anticlinal cuspate folds with an amplitude of around 30 cm, a pattern which is commonly associated with large-scale polygonal patterns in plan view. The dolomite occurs as pisolites up to 6 cm in diameter between which is a matrix of micritic and sparry dolomite. It is not clear from petrographic examination whether the pisolites are of algal origin (i.e. oncolites) or result from processes in the vadose zone. The occurrence of algal stromatolites elsewhere in the sequence suggests that algal activity is perhaps more likely. The dolomite is overlain by new conglomerates and the sequence ends in a further dolomite horizon with stromatolitic lamination.

This locality apparently lacks diamictites and the sequence seems to result from fluvial aggradation on a valley floor. This aggradation was punctuated by and ends with phases of clastic sediment starvation and the establishment of shallow water wherein carbonate deposition was active.

North side of Wandel Dal. – Two palaeovalleys occur on the north side of Wandel Dal just to the west of Øvre Midsummersø. The westernmost one lies almost directly across the valley from the example described above and may be a continuation of it. Here some 105 m of sediments are exposed. In the lowest 15 m, fluvial sandstones and conglomerates dominate; above these is a thin unit of sandstones and siltstones interbedded at the centimetre scale in couplets and containing outsize pebbles (Fig. 29). The unit, in turn, is overlain by 5 m of diamictite. The upper 50 m of the fill includes two diamictite units, one 29 m and the other around 5 m thick. These are interbedded with units of thin, sometimes graded beds of pebbly sandstone and thin mudstone. Several units contain outsize pebbles both isolated and in clusters and between 2 and 10 cm in diameter which clearly penetrate the layering. These sediments contain several cm- to dm-thick, matrix-rich diamictites.

The units of pebbly sandstone and mudstone are interpreted as lacustrine deposits, the coarser layers reflecting floods or reworked dump material. The outsize clasts appear very similar to Pleistocene dropstones (e.g. Thomas & Connell 1985) which, in the context of a Proterozoic sequence, are most likely to have been delivered by floating ice. The emplacement of m-thick diamictite beds may have been by mass flow but not as a series of closely related events as suggested for the diamictites of the type locality. The sequence ends with a unit of stromatolitic dolomite and an overlying clastic unit of siltstone and pebbly, cross-bedded sandstone.

The second palaeovalley lies some 5 km to the east and has a depth of at least 65 m. The base is not seen and the lowest part of the exposed fill consists of horizontally bedded conglomerates and breccias in beds 0.5-1 m thick with sandy interbeds up to 15 cm thick. Fabrics of the coarser beds vary from clast-supported to matrix-supported. Some of the finer conglomerates and sandstones are cross-bedded and some sandy units show soft-sediment deformation and water escape structures. The sequence becomes sandier upwards. Conglomeratic lenses are more common in the more axial parts of the valley fill away from the valley side and are associated with cross-bedding and scoured surfaces. In this sandy upper part, discrete conglomerate beds up to 2 m thick

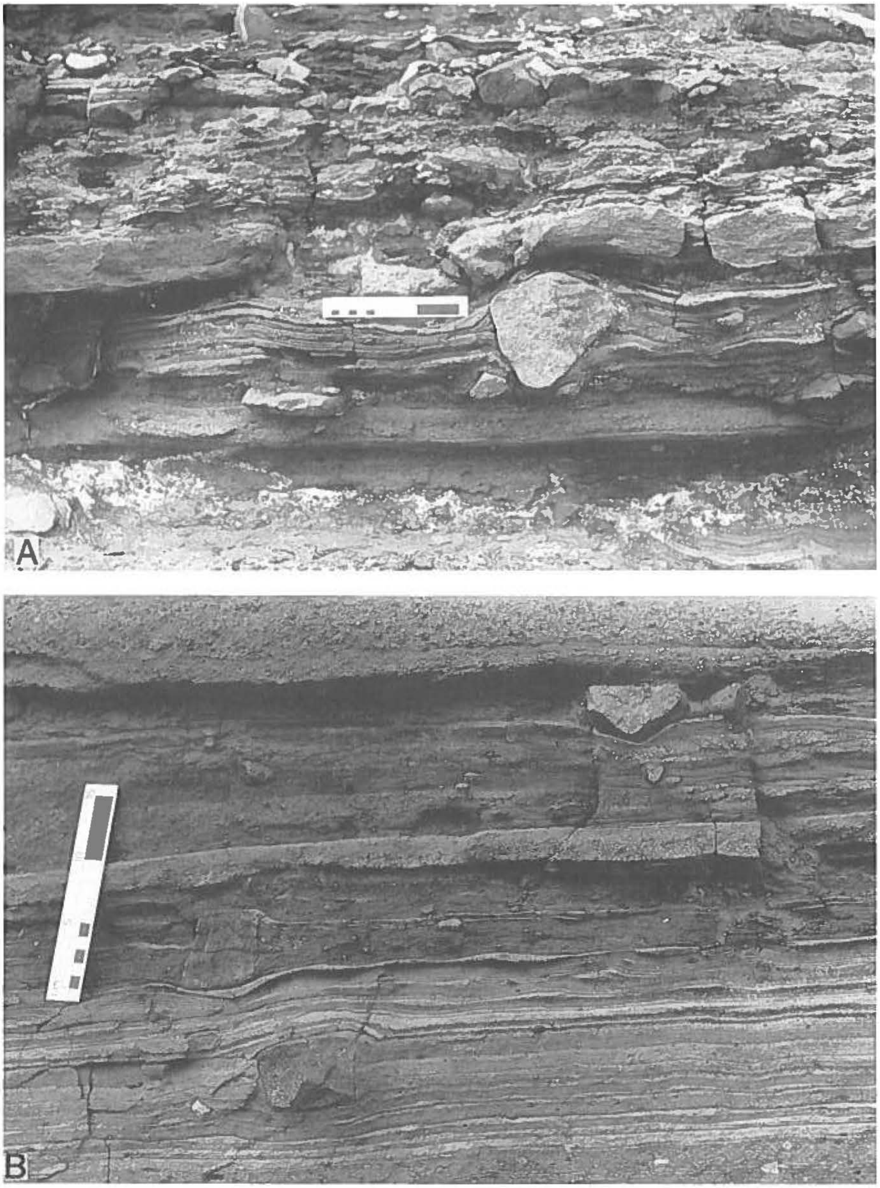

Fig. 29: Two examples of laminated siltstone and sandstone with oversize "dropstone" clasts, interpreted as the result of floating ice, probably developed on a small local lake. Locality A, Fig. 1.

occur. Pebbles protruding from their upper surfaces are draped by overlying sands. Upwards the sequence passes gradually into thinly, horizontally bedded dolomites with an increasingly clear stromatolitic lamination which is mainly horizontal but with some sharp anticlinal folds. On bedding surfaces these are related to polygonal patterns of ridges. The dolomites are some 30 m below the tops of the exposed valley sides but the upper part of the fill is unexposed. On the crest of the palaeohigh immediately east of this valley, blocks of almost in-place Inuiteq Sø sandstone are slightly shifted and rotated at the locally flat-lying unconformity (Fig. 30).

This valley fill seems to reflect mainly fluvial deposition interupted by small-scale mass flow events some of which could have come from the steep valley sides. The activity diminishes upwards and a phase of relative sediment starvation leads to carbonate precipitation and the growth of algal mats in bodies of shallow water. The *in situ* brecciation and local movement of blocks at the unconformity may have resulted from freeze-thaw processes.

Summary of other localites. – The sequences displayed by all localities outside the type area have three main features in common. First the lower part of the valley fills are dominated by fluvial deposition which seems to have been the result of powerful though flashy currents.

Fig. 30: Rotated blocks of Inuiteq Sø Sandstone on top of a "hill" in the palaeotopography at Locality E, Fig. 1, near the western end of Øvre Midsommersø. The blocks are overlain by a thin unit of breccia.

Second, diamictites, when present, were emplaced after an episode of fluvial activity and only in one case rest directly on the unconformity in the deeper parts of the palaeovalleys. Third, there is at least one phase of quiescence of clastic supply during the later stages of the preserved fills during which stromatolitic carbonate deposition was important.

Whilst considerable local variation occurs, the general character of these sequences is in broad accord with the type locality. If valley erosion was glacial, any valley floor tills were removed at most localities presumably by fluvial activity, prior to a phase of fluvial and, locally, lacustrine aggradation. The only direct evidence for cold conditions during aggradaton comes from the dropstones in the lacustrine intevals, but some of the breccias which lack significant matrix are most likely to have moved through the freezing and thawing of interstitial water. Climatic amelioration, suggested by deep weathering of dolerites at the type locality, preceded emplacement of diamictites. This appears to have resulted from remobilisation of diamictite initially deposited by glaciers in topographically higher parts of the palaeolandscape. The mobilisation seems most likely to have been the result of an increasingly wet climate which eventually led to water saturation of these earlier deposits. Evidence from Wandel Dal suggests that several events, separated in time, gave rise to the diamictites there. The absence of any evidence of ice in association with the stromatolites and indeed the level of carbonate productivity, support the idea of climatic amelioration.

Synthesis and conclusions

The Moræneso Formation constitues the infill of a series of palaeovalleys eroded into the older sediments of the Inuiteq Sø Formation and its associated intrusive dolerites. Only at one locality is direct evidence of the erosive processes preserved, but the broadly concave upwards, rounded forms of those valleys preserved in cross-section could be taken as an argument for glacial erosion. The infilling sediments themselves show a wide range of facies and facies relationships, none of which provide clear evidence of direct glacial deposition.

If glaciers were involved in the erosion of the palaeolandscape (Fig. 31, Stage 1), then nearly all the deposits on the valley floor must have been eroded and reworked by later fluvial activity (Fig. 31, Stages 2–3). The situation contrasts strongly with the sequence observed in the fills of other glacially eroded valleys where the basal erosion surface of the valley floor is directly overlain by diamictites interpreted as lodgement tills (e.g. Visser 1982, Visser & Kingsley 1982). The fluvial activity seems to have been quite powerful with large clasts being transported and large gravel bedforms being formed. It also seems to have been somewhat flashy in nature allowing sands to be reworked into aeolian dunes which are preserved close to the valley side. Evidence that the climate was at least seasonally cold during this phase, is provided by dropstones in lake beds and by the presence of local breccias whose development as screes, local flow lobes and gulley flows would be greatly aided by freeze-thaw processes.

Into these settings diamictites were emplaced catastrophically as mobile debris flows (Fig. 31, Stage 4), possible as a series of closely spaced events raising the possibility of retrogressive flow slides (Andresen & Bjerrum 1967, Koppejan, Van Wamelen & Weinberg 1948). The detailed facies relationships of the diamictites suggest that the debris flows moved out over the valley floor after moving down the side of the palaeovalley. Movement coincided with a time of intense water saturation of the valley floor sediments so that mobility of the flows may have been aided by excess pore water pressures and the operation of the processes of "undrained loading" (cf. Hutchinson & Bhandari, 1971). The mass flows are most likely to have resulted from a climatic change involving intense rainfall which, in addition to mobilising the diamictites, also flooded the valley floor. The onset of this wetter climate may have post-dated the glacial episode by a considerable period of time, allowing for the deep weathering of dolerites.

The nature of the source area and the source material for the diamictite can only be inferred. The clast content of the diamictites, in terms of lithology, clast shape and striations suggests a glacial origin and indeed these are the features which were used in earlier interpretations of the diamictites as tillites. The evidence that mass movement was down the side of the palaeovalley suggests that the source was a poorly sorted, glacially transported debris which had been deposited higher on the sides of the palaeovalleys, either as lateral moraines or as the tills within hanging valleys. It must then have been remobilised, under a more humid climate, some time, perhaps thousands of years, after deglaciation.

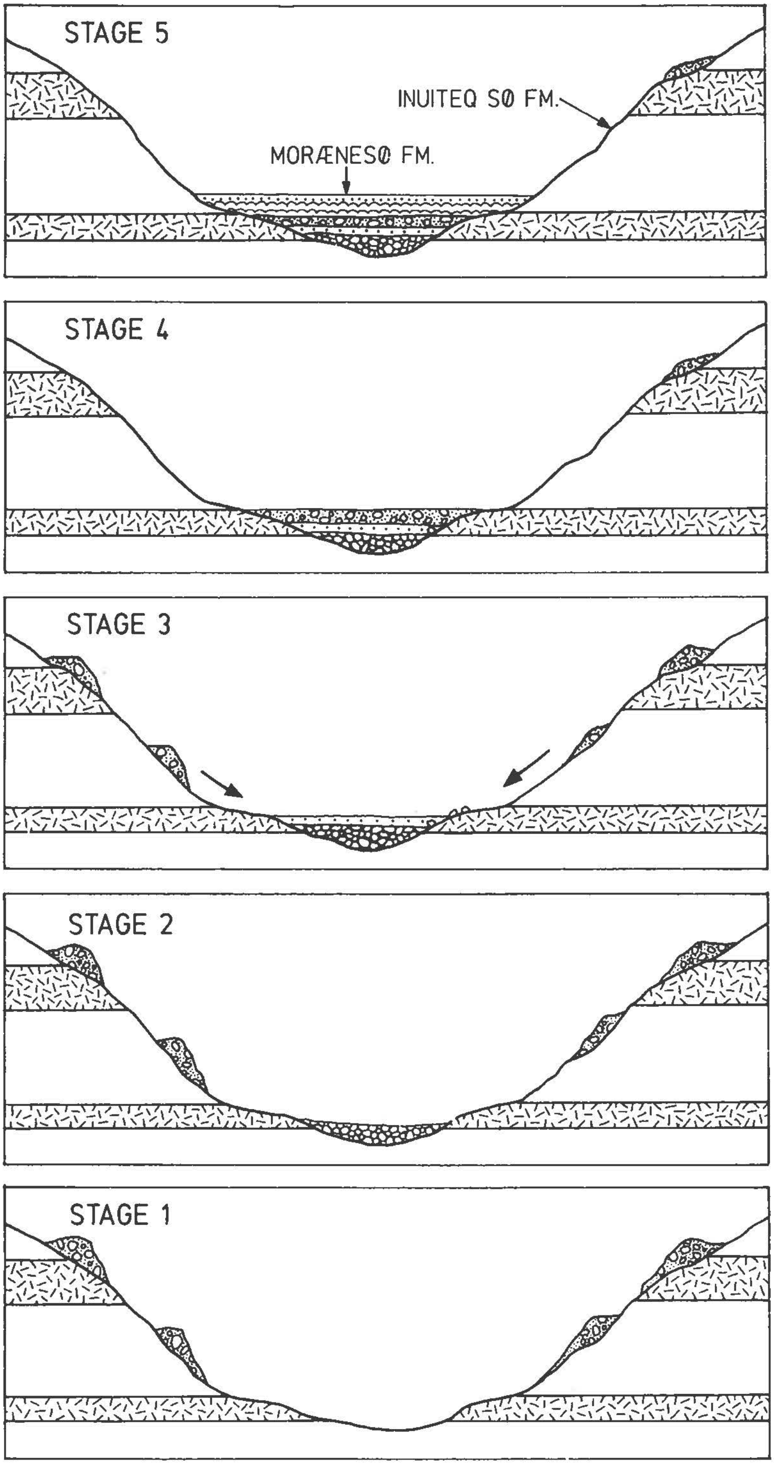

Fig. 31: Model for the sequential development of the features observed in the Morænesø Formation. The earlier deposits which are the source of the later mass flows, may have been most abundantly developed in tributary valleys rather than perched on hillsides as lateral moraines.

The later widespread development of shallow water in which algal stromatolites flourished may be related to intervals when lakes formed on the valley floors perhaps as a result of damming by the mass flows (Fig. 31, Stage 5). Alternatively it might record the incursion into the valley systems of marine water as the result of changing tectonic behaviour or an independent or post-glacial marine transgression. The development of such stromatolites may have been favoured by a warmer climate and evidence at a possibly similar stratigraphic level from central East Greenland provides further evidence for such an amelioration (Hambrey & Spencer 1987).

It seems that the Moræneső Formation only rarely records the direct results of glacial deposition but rather the result of catastrophic resedimentation of glacial tills some time after glacial retreat. By that time the climate was temperate and movement was triggered by heavy water saturation in a more humid climate. The vegetation which would be associated with such a climatic change in much of the Phanerozoic would be absent in the Proterozoic, allowing mobile conditions to be more readily achieved.

The Morænesø Formation therefore preserves, in superb exposures, the evidence of a complex suite of processes related to the deglaciation of the area with different stages developing in reponse to the changing palaeoclimate. In the context of the larger-scale palaeogeography, it would seem that, if the Morænesø Formation correlates with the Vendian tillites of Scandinavia, Britain, East Greenland etc. (see e.g. Hambrey & Harland 1981, Nystuen 1985, Hambrey & Spencer 1987), then it represents the reponse of a more upland setting. In these other areas the tillites are developed as more widespread though internally variable sheets suggesting more extensive lowland or marine glaciation.

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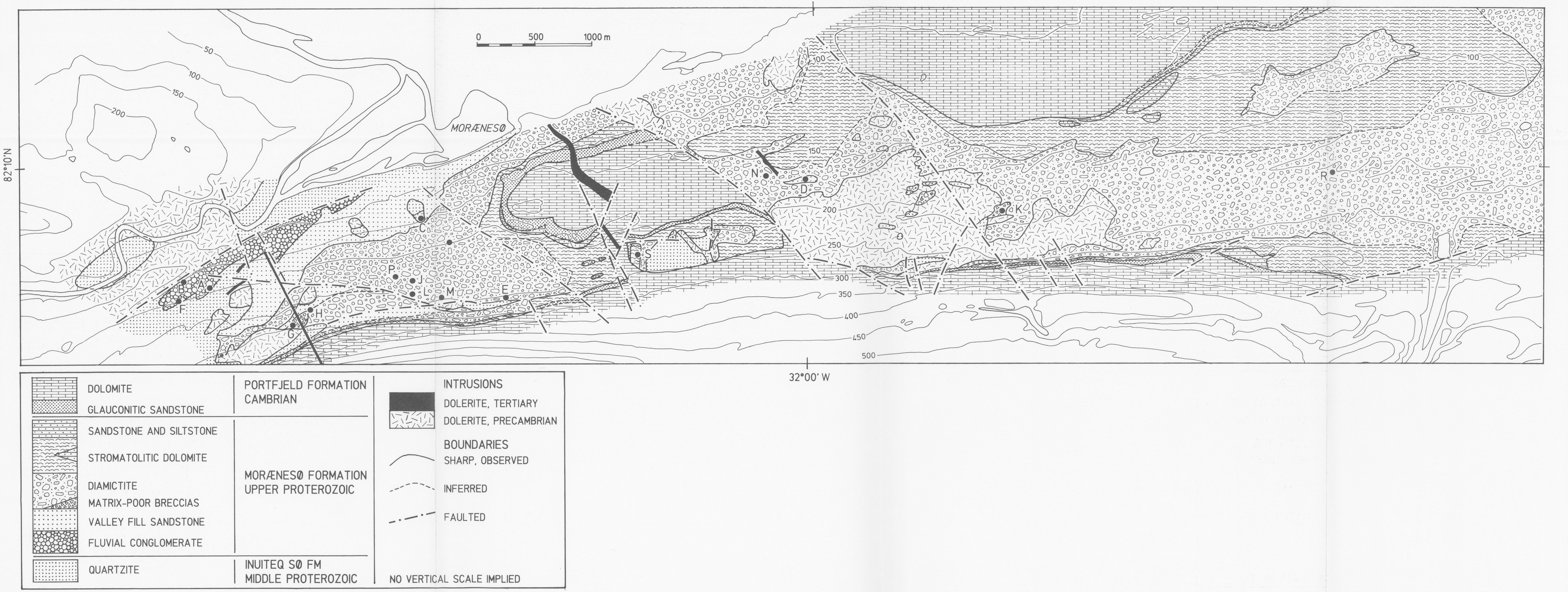
Fig. 32 (in back pocket): Detailed geological map of the type locality at Moræneso. For regional setting see Fig. 1. Individual localities mentioned in the text or in the captions of the figures are lettered on the map.



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PORTFJELD FORMATION
CAMBRIAN
SANDSTONE AND SILTSTONE
STROMATOLITIC DOLOMITE
DIAMICTITE
MATRIX-POOR BRECCIAS
VALLEY FILL SANDSTONE
FLUVIAL CONGLOMERATE
MORÆNESØ FORMATION
UPPER PROTEROZOIC
QUARTZITE
INUITEQ SØ FM
MIDDLE PROTEROZOIC
INTRUSIONS
DOLERITE, TERTIARY
DOLERITE, PRECAMBRIAN
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