Some comments on the glacial geomorphology of the Viborg area of Jutland, Denmark

By C. A. M. King

C.A.M. King, 1975: Some comments on the glacial geomorphology of the Viborg area of Jutland, Denmark. Geografisk Tidsskrift, 74: 1–11. København, Juni 1., 1975.

Fabric analyses and the morphology suggest that ice could have shaped the deposits and eroded effectively into the Hald Sø valley. The tunnel valleys were probably cut subglacially by meltwater as the ice became stagnant.

C.A.M. King, Professor Sc.D. The Geography Department. The University, Nottingham NG7 2RD, UK.

Introduction and location

The area around Viborg in central Jutland from the geomorphological point of view is one of the most interesting in Denmark, because it lies near the right angle in the so-called Main Stationary Line (see inset in Figure 1.) This line marks a halt stage, during which conspicuous morainic features were built up near the limit of advance of the most recent ice mass to affect Denmark, the ice of Weichsel age. The ice margin lay close to the Main Stationary Line during the period from about 25,000 to about 15,000 years ago. This line forms a conspicuous morphological feature, and it is characterised by some of the higher ground in the country. Heights reach about 70 m in the Viborg area, compared with a maximum height of 173 m, reached in the highest hill of east Jutland. The undulating hills of the Main Stationary Line run southwards from the Viborg area towards southern Jutland, and westwards towards the North Sea coast of Jutland. Much of the meltwater draining from the ice sheet as it started to decay found its way towards the angle in the Main Stationary Line of ice front. These meltwaters have played an important part in creating the distinctive features of the landscapes in this area. These features include both erosional and depositional forms and they are the subject of these comments.

The landforms and the problems they raise

The area to be considered in most detail lies immediately to the east of Viborg and includes a number of distinctive landforms, each of which raises its own problems. These problems include the following: a) the part played by, and the evidence for, glacial erosion. b) the origin of the deposits that form the land surface. c) the origin of the most conspicuous element of the landscape, the well developed "tunnel" valleys. d) the morphology of the interfluve areas; these are characterised by very flat surfaces in places, but they are also dissected by small, steep valleys tributary to the main tunnel valleys. These topics will be considered in turn.

a) *Evidence for glacial erosion.* It might well be argued that glacial erosion would be minimal towards the limit of an ice sheet that had its source far to the north in the highlands of Norway and Sweden, and which had travelled a long way over fairly flat ground. That the ice sheet was at least a powerful transporting agent is amply shown by the number and size of Swedish and Norwegian erratics that are found in the drift deposits of Denmark. One point must, however, be considered, and this is the extremely localised nature of glacial erosion in many areas. It can frequently be shown that an actively eroding ice stream produces signs of glacial erosion alongside an area in which the ice was protective. This situation occurs, for example, in the Cairngorm Mountains of eastern Scotland. The situation around Viborg was such that ice was tending to concentrate from several directions towards the apex of the Main Stationary Line. Such a concentration could effectively increase the speed and thickness of the ice, even near its margin, to such an extent that it could locally prove an effective agent of erosion. Evidence must, therefore, be examined to locate such possible areas of glacial erosion and to assess the effect of the erosion on the landscape. This idea has already been expressed by K. Hansen (1971), whose views will be considered in the next section.

b) *The deposits.* There is no outcrop of solid rocks in the area to the east of Viborg, the whole landscape being built up of superficial deposits. The origin and age of these deposits raise important problems, and their relationship with the erosional features of the landscape needs to be established. One of the main problems is to establish whether the deposits were laid down more or less contemporaneously with the processes that caused erosion in the area, or whether they were merely dissected by the erosional processes, having been deposited by an earlier ice advance. There is also the possibility that some of the deposits are more recent than others. It is also necessary to establish whether the sediments were laid down directly by actively advancing ice, by slow-moving or static ice, or by glacial meltwaters. The first gives rise to true

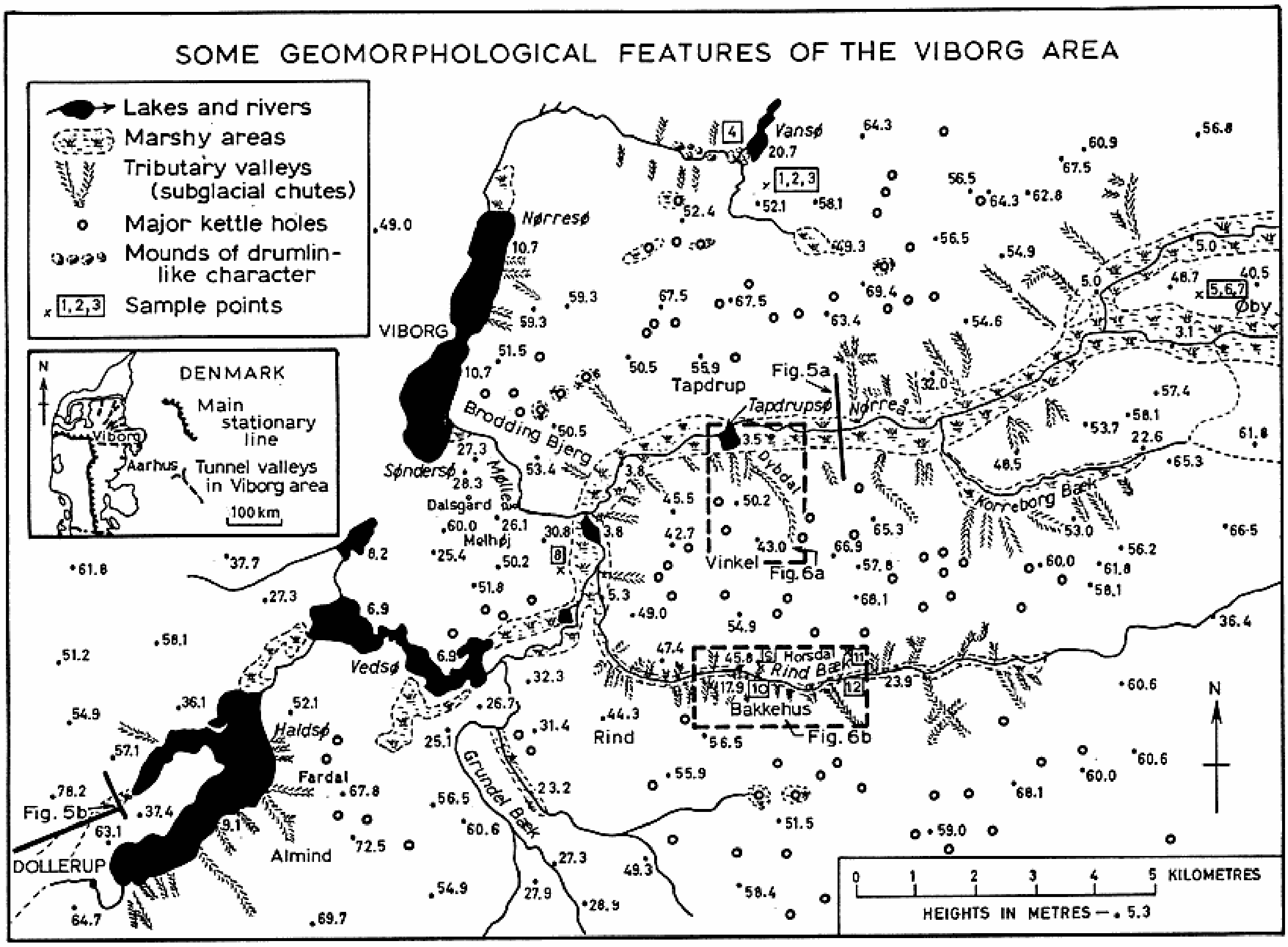


Fig. 1. Træk af geomorfologien og prøvelokaliteter.
Fig. 1. Location map, showing some features of the geomorphology and the sample sites.

moraine, the second to disintegration or stagnation deposits and the third to fluvioglacial deposits. An examination of the size distribution within the sediments, and especially of the structural and sedimentary characteristics of the deposits, provides clues that can be used to elucidate these problems. Fabric analyses can also provide useful evidence.

c) *The major valleys.* Perhaps the most conspicuous feature of the morphology of the area around Viborg is the large number of major valleys now occupied by misfit streams. These so-called "tunnel" valleys are generally thought to have been eroded by meltwaters flowing in tunnels under the ice sheet. They are broad and flat-floored, and in general have fairly steep, but not very deep sides. Not all, however, have flat floors; some contain deep lakes, of which Hald Sø is the best example, while another is characterised by round or oval mounds on its floor. The conditions under which they were formed require elucidation, and their pattern poses problems concerning the development of the drainage of the area. Their relationship to the deposits through which they are incised is also intriguing, and ties in with the problems of the origin and date of the deposits. Some of the tunnel valleys are major, long distance drainage lines that are now followed by the present rivers, while others are of more local origin, and are now frequently occupied only by small misfit streams. There has thus been considerable modification of the drainage system through time, an important aspect of which has been the creation of the tunnel valleys.

d) *The interfluve areas.* The interfluve areas between the major tunnel valleys give rise to other problems. One of these is to account for the very level nature of the surface morphology in some areas. This characteristic is well exemplified in part of the interfluve area between the valley of the Nørreå on the north and the Rind Bæk on the south, as area covering the parish of Vinkel. The flatness of this area is broken mainly by irregular kettle holes, which form marshy hollows in the generally level surface. Other significant features of the interfluve areas are the narrow, short and steep-sided gullies that lead down to the tunnel valleys. These small tributary valleys incise the margins of the flat interfluve areas. They are frequently complex, with bifurcations, and many have minor tributaries of their own. Their relationship to the main tunnel valleys requires elucidation. The processes that formed them must be established, a matter that is also connected with the time of their formation relative to that when the major valleys being eroded.

Areas of more hummocky relief are found particularly around the head of Hald Sø and in the Brodding Bjerg area east of Nørresø in the Viborg region (see fig. 1). These areas have rather different types of deposits, thus providing a relationship between the material and morphology, which can both be associated with the processes operating to form them. It is necessary to relate the material to the morphology, in order to suggest possible processes that created these special problematic features of the landscape. Before the evidence of material and morphology is considered a brief review of previous work will be given.

Previous work

One of the most conspicuous features of the geomorphology of Jutland, and one that has provoked the most discussion, are the so-called "tunnel" valleys, and their associated outwash spreads or "sandur" which is the Icelandic term for these broad sand and gravel fans. These features were originally described by N. V. Ussing (1903, 1904 and 1907), who recognised two types of valley, the proglacial meltwater valleys and the so-called "fjord" valleys, which Ussing considered to have been cut by subglacial meltwater. The fjord valleys, he suggested, led up to the apices of the outwash fans, citing the Viborg valleys and the Dollerup fan as an example. Ussing realised that the uphill profile of the valleys would require subglacial flow under hydrostatic pressure in a tunnel beneath the ice. V. Madsen (1921) changed the name "fjord" valley to "tunnel" valley, to stress their subglacial character.

This view of the formation of the tunnel valleys has been followed by most subsequent geomorphologists, including A. Schou, in the diagrams illustrating the geomorphological development of Denmark published in the Atlas of Denmark. V. Nordmann (1958) expressed some doubts concerning this hypothesis, suggesting that several anastomosing tunnels could have been responsible for the larger valleys. K. Milthers (1935), in his detailed discussion of the stages of deglaciation in central Jutland, indicates a series of subglacial tunnel valleys converging from the northeast at the apex of the outwash fan near Dollerup, when the ice front lay along the Main Stationary Line. As the ice slowly withdrew the higher outwash spreads were incised to form terraces, and new outlets were exposed for the meltwaters. He suggests a complex pattern of drainage changes during deglaciation. Towards the end of the deglaciation the sea invaded the lower tunnel valleys including that of the Nørreå. These incursions help to account for the flat, marshy floors of many of the valleys.

The genetic relationship between the outwash spreads and the tunnel valleys has been questioned by P. Jaspersen (1953) and E. M. Weiss (1958) on the basis that the two features are not necessarily found in association with each other. These authors also consider that the velocities necessary to carry the material that builds up the sandur could not have been achieved in the marginal zone of the ice sheet. This view cannot, however, be upheld; the material has been carried to the area in which it now lies and, therefore, velocities sufficient to transport it must have been reached. This argument would rather support the existence of rapidly flowing streams, at least locally, within the marginal zone of the ice sheet. Such streams must have been capable of carrying the coarse material found in the sandur and on the new moraine interfluve areas.

The tunnel valleys of Denmark have been contrasted with the buried tunnel valleys of East Anglia by A. W. Woodland (1970). He argues that the erosion of the tunnel valleys was achieved by the gravel load carried by the subglacial streams. Because of the erodible nature of their beds and banks, these streams were able to erode laterally, thus accounting for the great width and small depth of the Danish tunnel valleys in comparison to those of East Anglia, which are cut through chalk. He also points to the convergence of a series of four large tunnel valleys at the end of Hald Sø, near the site of Viborg. The valley in which Hald Sø lies ends very abruptly as shown in figure 5 b, and has been cut through at least 100 m of glacial outwash. Woodland suggests that the debris-laden meltwater debouched under pressure at the upper end of the slope, spreading out the gravel to form the fan the apex of which lies in the Dollerup hills at 80 m above sea level at Skelhøje.

K. Hansen (1971) points out that the local relief of the Hald Sø, Dollerup area implies an uphill flow of 113 m, because the surface of Hald Sø is 8.85 m and the lake is 34 m deep at its western end, which contains 8 to 10 m thickness of sediment. Hansen considers it unlikely that a stream near a receding, low gradient ice margin could carry sand and gravel up a steep gradient over a vertical distance of 113 m. He, therefore, argues that glacial erosion is a more plausible process to account for the form of the Hald Sø valley. The ice advanced over an undulating terrain, according to his view, and where valleys existed the ice became concentrated. More rapid flow in these zones would allow effective glacier erosion, which would intensify by positive feedback relationships; as the valley was deepened, so the ice flow would become further concentrated.

The arguments for glacial erosion playing a larger part

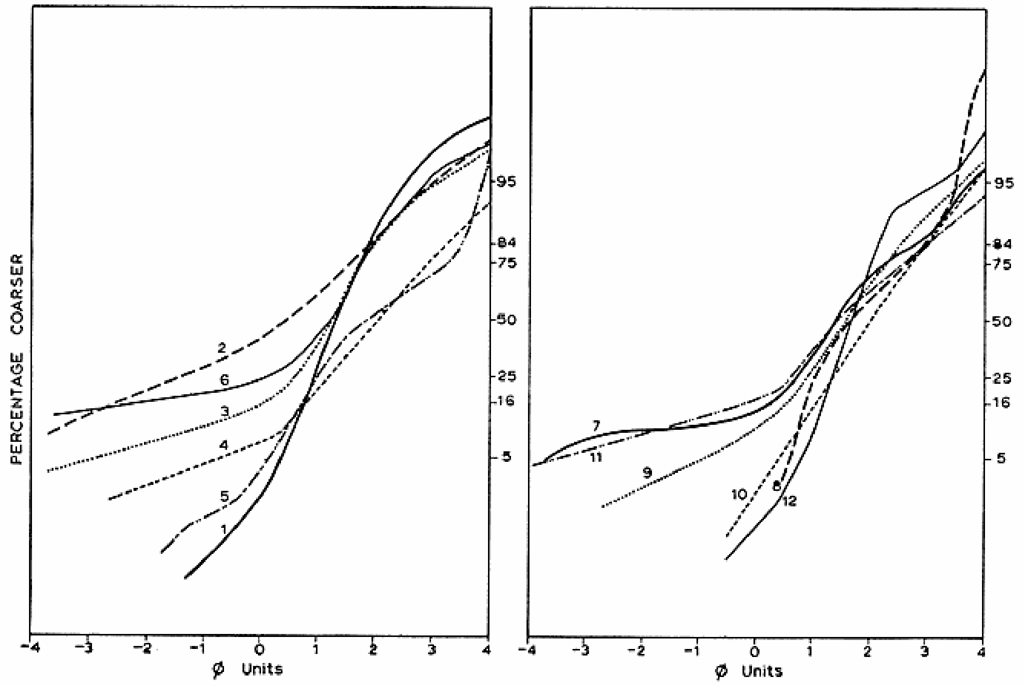


Fig. 2. Size distribution of the sediment samples.
Fig. 2. Sedimentprøvernes størrelsesfordeling.

in the development of tunnel valleys is worthy of further consideration. It must, however, be borne in mind that erosion is likely to have been very localised, and that the Hald Sø area is particularly favourable situated for erosion to have been effective, because of the convergence of several major valleys in this vicinity. However, it should also be remembered that the outwash spread, the apex of which is at Dollerup, has been built up by fluvioglacial processes, and is not a direct glacial deposit. It must, therefore, be assumed that meltwater flowed through the Hald Sø valley and up the steep slope at its southwestern end, even if the hollow had been eroded by ice previously. The alternative to this assumption is that all the meltwater must have been produced actually at the snout of the glacier at this point, which is not a likely occurrence. Ice sheets, especially during still-stands or periods of decay, normally have well-developed englacial and subglacial meltwater drainage systems, which produce large meltwater streams that issue at topographically favourable points.

The pattern of valleys in the Hald Sø area, according to H. Lykke Andersen (1972) may reflect the relief of the sub-drift surface. They tend to converge from various directions towards Hald Sø, including the north-northeast to south-southwest valley of Nørresø and Sønderso, the east to west valley of the Rind Bæk, and the southeast to northwest valley of the Grundel Bæk, south of Rind, as shown in figure 1. The Tertiary strata form a basin falling to the southwest, centred on Dollerup at the head of Hald Sø, along which streams could have drained from the north, northeast and east. Many of the valleys are aligned from east-northeast to west-southwest. This pattern could have influenced both the sedimentation and its subsequent dissection to form the tunnel valleys, if these early lines of drainage had been maintained throughout the deposition of the sediments and the development of the relief of the area. The form of the Hald Sø area supports this interpretation, which can be linked with the more active glacial erosion suggested for this area.

The suggestion of glacial erosion in localised channels in which the ice became concentrated as several streams converged on the Dollerup hills could find support in the landforms of the Vansø valley, which is one of the valleys contributing to the Hald Sø valley ice. This valley is the only one in the neighbourhood to show signs of active ice in the form of the glacial deposits. There are elongated hills on the valley floor that resemble drumlins, and if this is what they are, they would support the view that actively flowing ice was passing through some of the valleys after they had been eroded. The unique character of the Hald Sø valley and the relief of the vicinity suggest that if glacial erosion were effective it would have been very localised. There is very little, if any, evidence of glacial erosion elsewhere in the area, nor indeed is there much other evidence of actively flowing ice.

Evidence

MATERIAL

The materials around Viborg include a wide range of size and sedimentary structures. They are revealed in a number of sand pits and other exposures in the area. Four aspects will be mentioned: 1) the size of the material, 2)

Tabel 1. Details of sediment characteristics.

Sample	Mean	Median	Sorting	Skewness	Kurtosis
1	1.33	1.30	0.604 M	+ 0.122	1.170
2	0.02	0.55	2.293 VP	+ 0.068	1.082
3	1.13	1.30	1.425 P	÷ 0.313	2.062
4	2.05	2.07	1.408 P	÷ 0.056	1.125
5	2.10	2.07	1.260 P	+ 0.005	0.680
6*	0.30	1.26	2.350 VP	÷ 0.523	
7	1.52	1.40	1.866 P	÷ 0.117	1.925
8	1.66	1.65	0.972 M	+ 0.297	0.725
9	1.56	1.63	1.125 P	÷ 0.100	1.290
10	2.04	2.04	1.027 P	+ 0.022	0.987
11	1.43	1.43	2.040 VP	÷ 0.016	1.650
12	1.72	1.70	0.650 M	+ 0.137	1.350

* Inman measures used owing to very coarse nature of sample, all other values refer to Folk and Ward measures.

Sample	Location	Type of curve
1	Vansø stratified sand	Single
2	Vansø upper sand	Double, course and medium
3	Vansø unstratified	Double, course and medium
4	Vansø valley bottom mound	Triple, medium and fine
5*	Øby lowest fine sand	Four + clay
6	Øby middle pebbly sand	Double + course part
7	Øby upper orange sand	Double, course and medium
8*	Clay from brick pit	Single + clay
9	Visdal	Double, course and medium
10	Rindbæk tributary valley	Single, normal distribution
11	Horsdal tributary valley	Triple, course and medium
12	Horsdal	Double, medium and fine

* Refers to samples with a large clay content, sample 5 contained only 35 % sand and silt, fine material excluded from the analysis.

the fabric, 3) the sedimentary character, and 4) the distribution.

1. Size distribution. The glacially derived material includes a wide range of sizes, the largest being huge boulders carried from northern Scandinavia where hard rocks outcrop, providing large boulders. These boulders are an obstacle to cultivation and have, therefore, been collected from much of the surface area, in addition, they have traditionally been used for foundations in building construction. Hence it is not possible to assess their original distribution. Their large dimensions can, however, be appreciated. Their size shows that the ice was capable of carrying a heavy load. Most of the large boulders are of hard rocks, including much granite, but there are also numerous smaller flints and quartzites in the drift. The flints must have been derived from the Cretaceous outcrops on the east coast of Jutland, which was probably more widely exposed before glacial depositions took place.

The source of the material can be derived from petrological analysis, while evidence of the distance travelled by the stones in the drift can be obtained by studying their roundness. A number of records of stone roundness using Cailleux's index were made. This index is useful in that it provides a measure of the degree of wear the stone

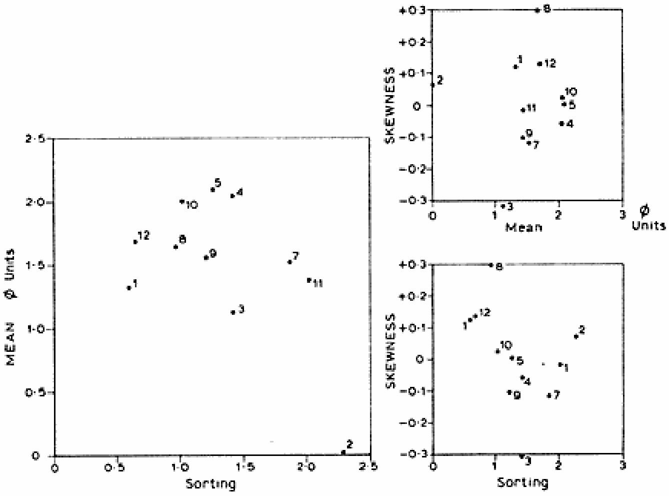


Fig. 3. Graphs illustating the relationship between sedimentary parameters.

Fig. 3. Kurver over relationerne mellem sedimentparametre.

has undergone during transport. A sample of granite pebbles with a long axis of between 20 and 40 mm, gave a roundness value of 341, while two samples, each of 50 stones, of quartzite pebbles gave results of 404 and 530. These all indicate a high degree of rounding, and hence long transport, as the rocks are hard and resistant to wear. A sample of flints, on the other hand, produced a roundness value of only 194, which indicates considerably angularity. This angularity is due in part to the shorter transport distance, but is also partly the result of later frost shattering, as flint is particularly liable to frost shattering, and many of the breaks in the pebbles appeared of recent origin.

The bulk of the sediment in the area is of sand size. Some samples of sand from several pits, the sites of which are shown on figure 1, have been analysed in order to examine the pattern of size distribution. The details of the analysis are given in table 1. Figure 2 shows the size distribution of the sand portion of the samples plotted on arithmetic probability paper, which allows the normality of the distribution to be readily seen.

The samples can be divided into those that show only one normal section and those that show two or more. Only one sample shows a single almost normal distribution, while another shows a rather more irregular single curve. Thus most samples are composite, indicating that conditions of deposition were changeable, and the transporting media had access to a wide range of particle size. These conditions are typical of the decay regions of ice sheets, which are characterised by conditions of variable discharge and load, in both space as well as time. The sediments show a wide range in skewness values, a point that again indicates their variability. The skewness values are equally divided between positive and negative signs;

the former imply a tail of fine deposits and usually a fairly quiet, low-energy sedimentary environment, while the negative skewness is associated with more vigorous conditions, with a tail of coarse deposits, using the Ø notation. There is a slight tendency for the positively skewed sediments to be better sorted, but this trend is not significant, nor is there any relationship between size and sorting, or skewness and size, as shown in figure 3.

Most of the samples show poor sorting, a few are very poorly sorted, and only two are moderately sorted. This characteristic again points to the variability in sedimentation and the wide range of sediments available, although nearly all the mean values fall within the range 1 to 2 Ø, a result that depends in part on the exclusion of the finer and coarser elements from two of the samples (5 and 8), both of which contained much fine material.

Samples 1 to 4 were obtained from a sand pit near Vansø at Neder Kokholm and a mound in the valley floor near Vansø. Sample 1 comes from a stratified layer and is one of the best sorted of the samples analysed, showing fairly constant conditions of water sedimentation, with the typical positive skewness. Samples 2 and 3 come from the upper part of the Neder Kokholm sand pit, where stratification was either disturbed or absent. These samples are much less well sorted and contain some pebbles. They show two main elements in the size distribution curve, a coarse, poorly-sorted element and a finer, better-sorted element. This pattern suggests a combination of water-laid material and coarser load carried directly by the ice, an interpretation that agrees with the lack of stratification. Sample 4, from a valley-floor mound, shows similar characteristics. Its two elements contain a medium and finer element, the material as a whole being finer that the first three samples. The skewness value is low. It seems likely that the material is water-laid. The mound could well be the result of erosion of former deposits by moving ice, rather than a purely depositional feature.

Samples 5 to 7 come from a large sand pit on the Øby "island" in the Nørreå valley. These samples come from three different sedimentary units exposed in the sand face, sample 5 being the lowest and sample 7 the uppermost. They include the finest mean size and one of the coarsest samples. This great variabilily within a few metres vertically and horizontally illustrates the changeable nature of the sedimentation, which is also evident in the multiple nature of the components that make up the samples. Sample 5 is exceptionally fine and sample 6 is exceptionally coarse, while sample 7 is more typical water-deposited sand, although the sorting is still poor.

Sample 8, from the brick pit near Bruunshåb, consists of fine sediment. The finer samples indicate that in places sedimentation took place nnder quiet conditions, probably in temporary lakes. Samples 9 to 12 come from the small tributary valleys to Rind Bæk on the south side of Vinkel parish. Samples 9 and 10 come from Visdal, 9 from the side of the valley and 10 from the floor of the tributary valley. Sample 9 has a dual curve, while sample 10 is the only one to consist of a single, normal curve. This suggests that the sand on the floor of the small tributary valleys may have been deposited under conditions of uniform stream flow, by which the sand-sized material available was sorted out and deposited. Samples 11 and 12 come from Horsdal, a little further east. Sample 11, from the upper part of the tributary valley, is less well sorted and consists of three elements, again suggesting more variable sedimentation near the upper part of the interfluve areas, while the lower sample 12 is a much better sorted sediment, laid down under water flow that gave the usual positive skewness value.

The sediment analysis on the whole indicates that sedimentation was very variable. Conditions were probably more uniform when the lower deposits were being laid down, with variability increasing upwards. The conclusion may be suggested that the ice may have been nearer and had a stronger direct effect on the deposition of the upper sediments than on the lower, which may have been deposited further away from an advancing ice front. The fabrics and structures tend to support these conclusions.

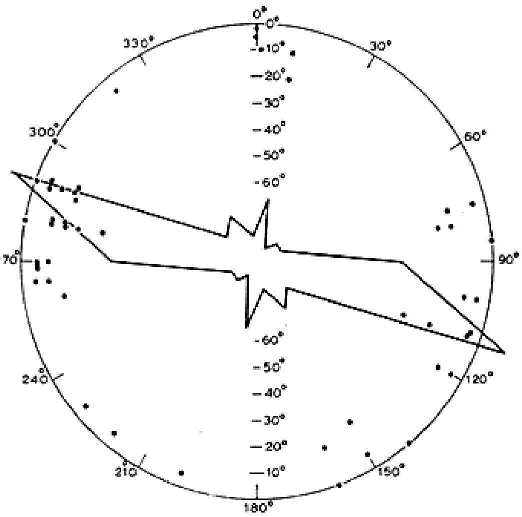


Fig. 4. Fabric analysis of the preferred orientation of elongated stones in an unstratified layer of material from the Neder Kokholm sand pit near Vansø.

Fig. 4. Teksturanalyse af aflange stens hyppigste orientering i ikke-lagdelt materiale i Neder Kokholm sandgrav ved Vansø.

2. Fabric analysis. A fabric recorded in the upper unstratified material in the Neder Kokholm sand pit near Vansø showed a very strong preferred orientation, with a chi square value of 55.6 for a 180 degree distribution. The preferred orientation of the fabric, which is shown in figure 4, was between 100 and 110 degrees, with a minor peak normal to this at about 10 degrees. The main direction is parallel to the valley that leads from Vansø westwards towards Nørresø and Søndersø into Hald Sø. This fabric supports the view that ice may have been moving actively in the valleys that fed into the Hald Sø valley at a late stage in the glaciation. The orientation is also parallel to the elongation of the mounds in the valley to the west of Vansø, from one of which sample 4 was taken.

This strong fabric contrasts with a non-significant fabric (chi square 10.0) recorded in a thin layer of unstratified stony drift on the flat plateau surface near Dalsgård. This material is probably ablation moraine melted out from the superficial debris on stagnant ice. A strong fabric would not be expected in these circumstances. The fabrics, therefore, confirm the suggestion of variations in ice activity within short distances, according to the local relief and the ice concentration depending on it.

3. Sedimentary structures. One of the most striking features of the sedimentary structures exposed in the various sand pits is the very widespread occurrence of stratified deposits. The unstratified material is mainly found in the upper part of the sections forming a capping of coarser, mixed sediment. This upper, unstratified material is almost certainly ablation moraine. The small thickness of this ablation moraine suggests that the ice sheets must have carried little supraglacial load, a point mentioned by Woodland (1970). Beneath the thin capping of ablation till lie complex sequences of stratified material. The material is largely sandy, as indicated by the sediment analyses, but it also contains pebbly deposits as well as some finer sediments. The stratification varies from horizontally-bedded sands to steeply dipping beds of material, including gravel lenses. This type of sequence was observed in the Neder Kokholm sand pit near Vansø.

Rather different features were exposed in a sand pit on the south side of the Nørreå valley opposite the "island" of Øby. The stratified sand and gravel deposits exposed in this pit were contorted in places. Some unstratified material was included in the contorted material. The upper part of the exposure, on the other hand, was very evenly bedded sand and gravel. The total exposure approached 30 m in height. Some minor faulting, causing dislocation of the structures, was also seen. The contortions occurred in the lower part of the exposure, and they suggest that dead ice was present as the sediments accumulated. The coarse, unstratified lenses were probably the result of melting out of incorporated masses of very dirty ice. The minor faulting suggests frozen conditions at times. Lenses of stratified gravels are interbedded with sands, and dips are generally high, suggesting a type of deltaic sedimentation by vigorous streams in a proglacial or subglacial water body. Variability of sedimentation is shown by the presence of cross stratification, typical of dune formation under lower flow regime, and planar bedding, typical of antidune formation under upper flow regime. The rapid changes from sand to gravel also shows varied water and sediment availability. The lack of fine sediment indicates a vigorous environment of sedimentation. The very even bedding of the upper part of the section suggests a more stable sedimentary situation, probably characterised by upper flow regime, although horizontal bedding can also be created a lower flow regime before the velocity is rapid enough to initiate ripping or dune formation, with its typical cross bedding. The dead ice in the lower part of the section must have melted by the time the upper part accumulated, as there are no signs of disturbance in the upper sediments. Another possible explanation is that the lower part of the section was deposited subglacially, while the upper part was a supraglacial or proglacial deposit. These sediments must predate the formation of the Nørreå valley, which is steeply incised into them.

Not all the exposures show more even sedimentation in the upper layers, so that there must have been a considerable variety in the environments of sedimentation. The general conclusions to be drawn from the structural evidence are that most of the deposits were laid down by meltwater. There is also evidence of the presence of static and stagnating ice in many areas, although in a few places the ice may have been more active. There is some indication that at times the deposits may have been in a frozen conditions, typical of cold-based ice sheets. The variability of the sedimentary structures indicates rapidly changing conditions of sedimentation, most of which suggest rapid flow of heavily laden meltwater streams.

4. Distribution. In all the exposures available the same type of mixed deposits and structures were found. It seems, therefore, that this type of mainly stratified, largely sandy sediment is widespread in the area. This extensive distribution would be consistent with an extensive, slowly stagnating ice sheet, fed by ice streams carrying mainly sandy material, but with coarse debris, including large boulders as well as some finer material. The bulk of the sediment has been redistributed by meltwater from the decaying ice, and only locally was material directly deposited by the ice to form the undulating morainic hills, such as those around the southern end of Hald Sø. Some of the material brought by the ice has been deposited proglacially to form the very large outwash spreads that occur most extensively beyond the Newer Moraine landscape in the Older Moraine landscape, although there are also deposits of proglacial material within the Newer Moraine area. The material forming the major outwash spreads could have been at least partially derived from the tunnel valleys as they were being cut through the previously deposited outwash sediments.

MORPHOLOGY

Three aspects of the morphology will be examined briefly. Firstly, the alignment and form of the tunnel valleys, which form the most striking relief features of the area will be commented upon. Secondly, the flat, plateau-like

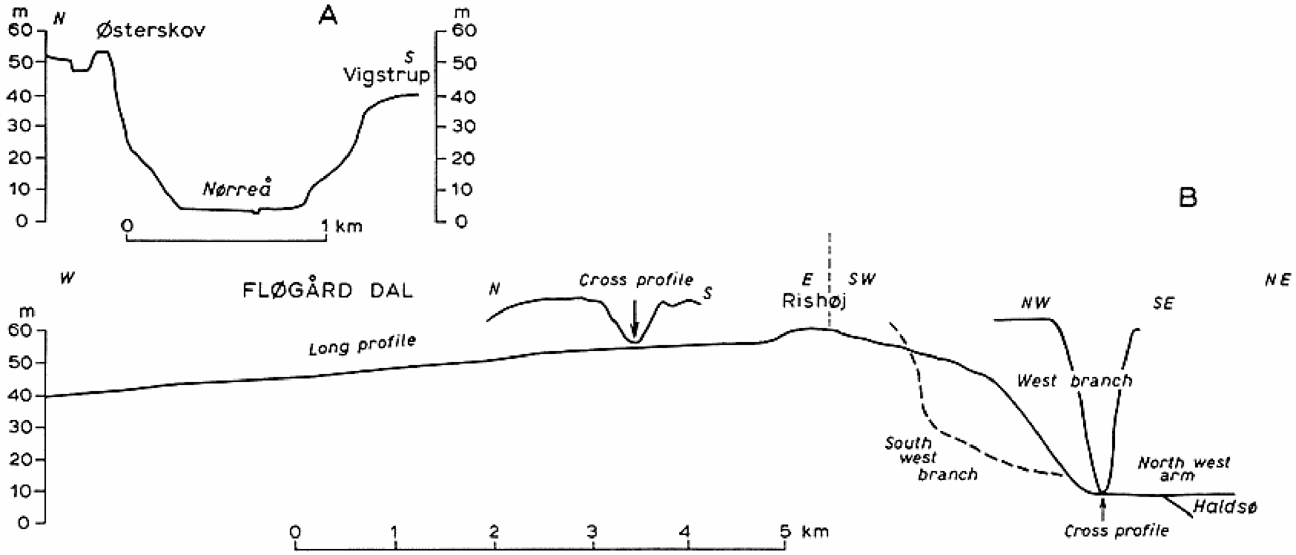


Fig. 5a. Cross profile of the major tunnel valley of the Nørreå. For location see figure 1.
Fig. 5b. Longitudinal and cross profiles of the outlet of the Hald Sø valley, showing the upper part of the major outwash spread centred on the Dollerup hills.
Fig. 5a. Tværsnit af Nørreådalen. Lokalitet: se fig. 1.
Fig. 5b. Længde- og tværprofiler af Hald Sø-dalens udløb, der viser den øvre del af den store udvaskningsaflejring med centrum ved Dollerup banker.

interfluve areas, with their kettle holes, are worthy of consideration, and thirdly, the relation of the minor valleys to the tunnel valleys into which they drain will be considered. These small valleys dissect the margins of the level plateaux.

1. Tunnel valleys. Some of the tunnel valleys are major drainage lines that must have carried large volumes of meltwater from distant parts of the decaying ice sheet, while others are smaller, gathering drainage more locally. The Nørreå valley is an example of the former and that of the Rind Bæk of the latter. A profile across the Nørreå valley is shown in figure 5 a. Both valleys are wider than they are deep, a characteristic that Woodland (1970) reasonably refers to the fact that they are incised through superficial deposits that are readily eroded. This quality produces the characteristic braided pattern of stream channels that develop under such conditions, especially when the discharge is subject to considerable variations with the alternating seasons. It thus seems likely that the whole valley was rarely completely covered by flowing water at any time, and that the bifurcation and rejoining typical of braided streams occurred frequently. Such a flow pattern could account for the occasional islands that occur within the tunnel valleys, of which the "island" of Øby in the Nørreå valley is a very good example.

One of the most characteristic features of the tunnel valleys is their irregular longitudinal profiles. This feature is consonent with the view that they were cut by meltwaters flowing under hydrostatic pressure beneath the ice. The deepest hollow within the tunnel valleys of the Viborg area is that which holds Hald Sø, and the arguments that this hollow may be partially due to glacial, rather than fluvioglacial, erosion have already been discussed. The extent of the reversed slope is shown in figure 5 b. There are also several other lakes situated in tunnel valleys, including Vansø, Vedsø, Søndersø and Nørresø, as well as several smaller lakes. These lakes could well owe their beds to erosion by glacial meltwaters flowing under hydrostatic pressure. However, some of the lakes, such as Vansø, may have been caused by the deposition of material in their valleys. A low hill at the northeastern end of this lake forms a barrier across which it now drains northeastwards. This valley is, however, the only one in the immediate neighbourhood to show this feature. It is also unique in having mounds on the valley floor.

2. Interfluve plateaux. The interfluve area between the Nørreå and the Rind Bæk has a very level surface at between 60 and 70 m, most of the area lying between 65 and 68 m above sea level. The main interruptions of the flatness of the surface are the kettle holes and the valleys that incise its margins. The presence of the kettle holes demonstrates the existence of masses of dead ice during the accumulation of the deposits that build up the interfluve areas. The level surface is consistent with the creation of these surfaces by depositions of fluvioglacial material by meltwater, but is not explained if they were morainic material directly deposited from ice. There are, as already mentioned, a few areas of more hummocky ground that are probably true morainic deposits.

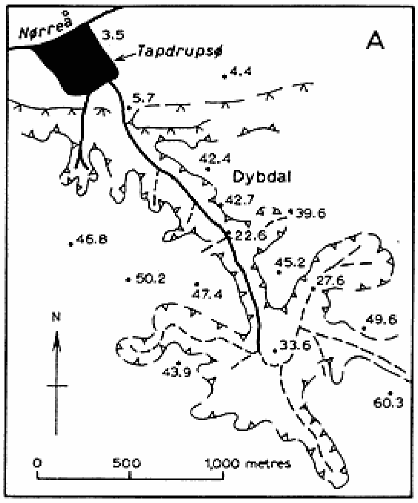
The area between Søndersø to the north, Vedsø to the south and the Nørreå to the east provides evidence for the stages of development of the plateau areas. The drainage of this area has taken place at different levels at different times. The highest point of the area is Melhøj, which is 60.0 m high; it is probably a morainic hummock. To the northeast of this high point there is a well-developed outwash spread grading down from 30.8 m at the southeast end to about 28 m at the northwest end, where the meltwater forming it must have merged into the southern end of the Sønderso drainage. Mølleå represents a later stage of down-cutting, and, on the evidence of terraces sloping in a northwesterly direction at the eastern end of the valley near its link with Nørreå, was probably initiated by a stream draining northwestwards. A still later phase was the reversal of the drainage to link the Søndersø with the Nørreå, the present drainage direction, when the Nørreå could eventually drain eastwards as the ice finally disappeared. The concave outward bluff on the southwest side of Melhøj, at a height of about 25 m at its base, has been planed to a very level surface by meltwater flowing across the ground at the foot of the bluff. These levels are all considerably below those on the Vinkel parish plateau and, therefore, probably represent later stages in the deglaciation process.

One of the problems is to ascertain the association between these very level surfaces and the sediments of which they are built up. The lower levels are likely to be erosional, while the higher surfaces, including the Vinkel plateau, could be depositional in character. The occurrence of ablation moraine at the surface in many exposures supports this view.

3. Minor tributary valleys. Many short steep valleys incise the edges of the plateaux, only a few of the larger ones exceeding 1 km in length, while many are only half this length. Dybdal, shown in figure 6 a, is an example of a long valley of this type. Some of the smaller valleys are simple features, but many of them are complex with several tributaries uniting. An example of the complex type is that on the south side of Rind Bæk at Bakkehus, which is shown in figure 6 b. It consists of three tributaries which join before they meet the main valley. The outer two grade to a common level, which is below the level of the central one. This central valley, which hangs slightly above the outer ones, has a gently rounded head, while the outer two have narrower, steeper heads. From their junction the joint valley grades down evenly to the main valley floor, and there is no indication of deposition at the mouth of the joint valley in the main valley, despite an almost complete lack of drainage in the main valley. The small, eastern valley, which is V-shaped and steep, joins the other two at a considerable angle, its upper part being nearly parallel with the main valley.

Fardal near Almind provides another example of these small valleys. It is situated on the east side of Hald Sø and cuts through the steep, wooded side of the lake. It has a flat bottom, although its sides slope in places at 23 degrees. The gradient of its floor is between 3 and 5 degrees, steepening slightly before it joins the lake, where it becomes narrower. The valley grades out onto a small terrace a little distance above the lake level. A tributary on its south side has a floor gradient of 15 degrees. Like so many of the other valleys of this type, it and its tributary now carry no drainage.

The lack of drainage in these valleys at present indicates that they must have been formed under different conditions when a supply of water of considerable volume was available to cut their steep sides and transversally flat floors. The absence of deposits at the mouths of the valleys shows that when they were being cut the material carried out of them must have been removed by the water flowing in the main valley. The main valleys now have very sluggish drainage and would not be capable of re-



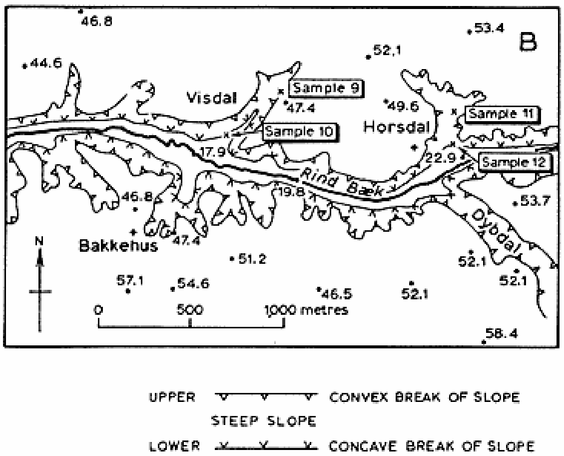


Fig. 6a. Morphological diagram of Dybdal, one of the longer tributary valleys draining north into Nørreå, on the north side of Vinkel parish.
Fig. 6b. Morphological diagram of some of the smaller tributary valleys draining into the Rind Bæk valley on the south side of Vinkel parish.
See figure 1 for the location of the areas shown.
Fig. 6a. Morfologisk diagram over Dybdal, sidedal til Nørreådalen i Vinkel sogns nordlige del.
Fig. 6b. Morfologisk diagram over nogle mindre sidedale til Rind Bæk i Vinkel sogns sydlige del.

moving much material. This evidence points to the contemporaneity of formation of both sets of valleys. If the main valleys were formed as tunnels beneath stagnating ice, it can then be suggested that the side valleys could have been cut by glacial meltwater, flowing beneath the ice, in the form of subglacial chutes. Their alignment with respect to the main valleys, the nature of their often shallow, bowl-like, heads and their steep sides and flat floors, as well as their present lack of drainage, could all be explained by this hypothesis. The sediment sample from the floor of one of the valleys could also support this conclusion.

Conclusions

Both depositional and erosional processes have given to the material and morphology their characteristics, by which the processes can in turn be elucidated. The processes producing the present landforms were associated mainly with the mode of deglaciation in the area. There has probably been relatively little modification of the landscape since the ice melted about 15,000 years ago.

The processes of deposition in much of the area of deposition must have preceded those of erosion, in that the erosional features are cut into the sediments that build the area in the absence of solid rocks. The depositional processes can best be studied by reference to the deposits they laid down. The description of the sediments suggests that the great bulk of them were laid down by water. Their characteristics indicate a great range of depositional environments, from extremely vigorous ones, to those in which fine sediment could accumulate in quiet conditions. The steeply dipping, coarse gravelly deposits were laid down, probably mainly in vigorous braided streams close to and in places beneath a decaying ice sheet. The evenly bedded sands, which are very plentiful and very thick in places suggest more uniform, but still vigorous conditions. The water depositing the sand must have had access to large supplies of sand-sized sediment, hence again supporting the theory of proximity of the ice, especially in view of the contortions in some of the strata. The presence of ice is also confirmed by the frequent occurrence of a thin layer of ablation moraine above the stratified deposits, a characteristic that confirms the depositional nature of the surface.

The incising of the tunnel valleys through these deposits may date from a time when the ice became completely stagnant, so that the local supply of sediment, which had previously been brought by moving ice, was reduced; incision instead of deposition would result. The decaying ice still covered the area and the main meltwater streams became concentrated into the major tunnel valleys, which were then in process of being cut. Smaller subglacial streams drained into the major ones. The smaller subglacial streams were fed by local supplies of meltwater, which flowed down their steep sides. These smaller streams cut the numerous subglacial chutes that incise the margins of the interfluve plateaux. There may have been local exceptions to the stagnant nature of the ice. The arguments for glacial erosion in the Hald Sø valley in conjunction with the elongated mounds in the Vansø valley have already been put forward. The conditions in this area were unique owing to the concentration of ice in this area, where several streams converge into one outlet in the Dollerup hills.

The landforms of the Viborg area can be explained in terms of the glaciation of area. The ice first brought much material to the area, which was mainly laid down by meltwater in the later stages of glaciation. As the ice became largely static and started to decay, large volumes of meltwater were released, and this meltwater redistributed the massive amounts of largely sand-size material across which it flowed. This material was built into the flattish interfluve areas, incorporating masses of dead ice. The melting of these buried dead ice masses created the numerous kettle holes, as well as accounting for the contortions in some of the exposures of the sediments. Locally the ice still remained active and capable of erosion and the shaping of material into drumlins in specially suitable localities.

As the ice became stagnant over a wider area the supply of sediment was reduced, so the meltwaters were able to erode more effectively. Under these conditions the major tunnel valleys were cut by the largest meltwaters streams flowing under the dead ice from far behind the ice front. The small tunnel valleys, such as that of the Rind Baek, were cut by the streams that derived their water more locally. The still smaller tributaries were cut as subglacial chutes by the locally derived meltwaters draining down beneath the ice into the tunnel valleys. The drainage in the loose sandy soils dried up almost completely as the ice finally decayed away, leaving all these signs of deglaciation that have been subsequently little modified, owing to lack of drainage.

The creation of the tunnel valleys of Denmark could possibly be related to the thermal nature of the ice sheet. At its margin, where it was thin, it could have been cold and frozen to its bed, while nearer its centre, where the ice was thicker and the flow faster, its base could have been at the pressure melting point. Meltwater accumulating in this zone could have built up sufficient pressure to eventually overcome the resistance of the outer cold part, and streams of meltwater could have forced their way beneath the outer cold part to cut the subglacial tunnel valleys as they flowed towards the ice margin. Hydrostatic pressure could have been built up under these conditions and the undulating longitudinal profiles of the tunnel valleys cut. The presence of minor faulting in some of the deposits lends some support to this hypothesis, which has been advocated for part of the Laurentide ice sheet by H. E. Wright, (1973). This phase would have had to postdate the deposition of the interfluve sediments, which must have taken place under temperate ice conditions, probably as the ice was advancing in the Weichselian period.

One of the most striking features of the geomorphology of the Viborg area, which does not appear to have been stressed by earlier workers, is the widespread nature of stratified deposits in the New Moraine area. The moraine is not the classic type of ice-deposited material, but rather it is a water-laid deposit, that bears witness to the large amount of meltwater available in the area. In this characteristic it resembles the Salpausselkä moraines of southern Finland. The availability of meltwater in such large volumes would provide support for the theory that most of the tunnel valleys are the product of fluvioglacial erosion by braided streams, cutting into erodible sediments, as suggested by Woodland. This view does not necessarily counter that of the effectiveness of glacial erosion, put forward by Hansen. Evidence for glacial erosion can be found in the Hald Sø valley, supported by the forms in the Vansø valley, and explicable in terms of the local relief that allowed concentration of ice flow in this vicinity. Even if glacial erosion shaped this deep valley, much meltwater must have flowed through it to create the outwash fan, the apex of which lies at its mouth.

RESUMÉ

Viborg området er placeret på det sted af hovedopholdslinien for isen under sidste istid (Würm), hvor isfronten skiftede retning fra N-S til Ø-V. Områdets landskabsformer inkluderer store og små tunneldale, adskilt af flade terrænelementer, der marginalt er dissekeret af små, dybt indskårne dale mod tunneldalene. Sedimentanalyser angiver sandfraktionen som dominerende materiale. Dens karakteristiska indicerer stærkt varierende betingelser for smeltevandsaflejringerne, en konklusion der bekræftes af analysen af sedimentstrukturerne. Fabricanalyser og morfologi antyder, at lokale ismasser kunne have bevæget sig hurtigt nok til at forme de strømliniede aflejringer og til samtidig at erodere effektivt. Erosionen synes at have været koncentreret i Hald Sø-dalen, hvor flere isstrømme har konvergeret og dermed skabt et hoved-trug med omvendte skrænter. Tunneldalene er muligvis udskåret subglacialt af smeltevand, efterhånden som isen blev til dødis, og materialetilførslen som et resultat heraf blev reduceret. De fluvio-glaciale aflejringers eroderbare materiale, i hvilket tunneldalene var nedskåret som braided river strømme, sikrede, at de var brede og flade. De små, stejle sidedale til dem må betragtes som subglaciale render (chutes), nedroderede, samtidig med at tunneldalene blev dannet af aktivt strømmende smeltevandsflomme. Begge typer dale er i dag for størstedelen tørre eller optaget af sekundært dannede strømlejer (misfit streams). Ægte moræneaflejringer fra isen er ikke særlig almindeligt forekommende. Tynde ablationsmoræner kan dække de lagdelte aflejringer visse steder, men hovedmængden af materialet er fluvio-glacialt, aflejret under dødis-betingelser. Denne konklusion ville forklare det flade terræn, der karakteriserer områderne mellem dalene. Disse områder er endvidere forstyrret af jordfaldshuller (kettle holes), de viser, at efterladte dødisklumper sekundært er smeltede.

REFERENCES

Andersen, H. Lykke, (1972): Viborgegnens tunneldale. Miv. 2 Museerne i Viborg amt 10–15.

Hansen, K. (1971): Tunnel valleys in Denmark and northern Germany. Bull. Geol. Soc. Denmark. 20 (3) 295–306.

Jaspersen, P. (1953): Sandurbildung durch subglazialer aufsteigende Schmelzwasser. Eiszeitalter und Gegenwart 3 129–135.

Madsen, V. (1928): Third glacial period. In "Summary of the Geology of Denmark". Danm. geol. Unders. række 5 (4) 107–119.

Milthers, V. (1935): Landskabets udformning mellem Alheden og Limfjorden. Danm. geol. Unders. række 2 56 32 pp.

Nordmann, V. (1958): Beskrivelse til det geologiske kortblad Fredericia. Danm. geol. Unders. række 1 22a 125 pp.

Schou, A. (1949): Landskabsformerne. Atlas over Danmark. København Ed. N. Nielsen. p 31.

Ussing, N. V. (1903): Om Jyllands hedesletter og teorierne for deres dannelse. Overs. o. Det kgl. danske Vid. Selsk. Forh. 2 99–152.

Ussing, N. V. (1904): Danmarks Geologi i almenfattelig omrids. Danm. geol. Unders. række 3 2 358 pp.

Ussing, N. V. (1907): Om floddale og randmoræner i Jylland. Overs. o. Det kgl. danske Vid. Selsk. Forh. 4 161–213.

Weiss, E. M. (1958): Bau und Entstehung der Sander vor der Grenze der Würm. vereisung im Norden Schleswig-Holstein. Meyniana 7 5–60.

Woodland, A. W. (1970): The buried tunnel valleys of East Anglia. Proc. Yorks. Geol. Soc. 37 521–578, Section II. The tunnel valleys of Denmark 523–526, and section IV Comparison between the East Anglian buried channels and the Danish tunnel valleys 555–557.

Wheeler, P. T. (Editor) (1973): Viborg and its region. Geographical Field Group Regional Studies 16, Nottingham, England. Chap. 1. Physical Geography of the Viborg area. 1–19 189 pp.

Wright, H. E. (1973): Tunnel valleys, glacial surges and subglacial hydrology of the Superior Lobe, Minnesota. In The Wisconsinan Stage. Eds. Black, R. F., Goldhwait, R. P. G. and Willman, H. B. (Geol. Soc. Amer. Mem. 136 251–276).

had to postdate the deposition of the interfluve sediments, which must have taken place under temperate ice conditions, probably as the ice was advancing in the Weichselian period.

One of the most striking features of the geomorphology of the Viborg area, which does not appear to have been stressed by earlier workers, is the widespread nature of stratified deposits in the New Moraine area. The moraine is not the classic type of ice-deposited material, but rather it is a water-laid deposit, that bears witness to the large amount of meltwater available in the area. In this characteristic it resembles the Salpausselkä moraines of southern Finland. The availability of meltwater in such large volumes would provide support for the theory that most of the tunnel valleys are the product of fluvioglacial erosion by braided streams, cutting into erodible sediments, as suggested by Woodland. This view does not necessarily counter that of the effectiveness of glacial erosion, put forward by Hansen. Evidence for glacial erosion can be found in the Hald Sø valley, supported by the forms in the Vansø valley, and explicable in terms of the local relief that allowed concentration of ice flow in this vicinity. Even if glacial erosion shaped this deep valley, much meltwater must have flowed through it to create the outwash fan, the apex of which lies at its mouth.

RESUMÉ

Viborg området er placeret på det sted af hovedopholdslinien for isen under sidste istid (Würm), hvor isfronten skiftede retning fra N-S til Ø-V. Områdets landskabsformer inkluderer store og små tunneldale, adskilt af flade terrænelementer, der marginalt er dissekeret af små, dybt indskårne dale mod tunneldalene. Sedimentanalyser angiver sandfraktionen som dominerende materiale. Dens karakteristiska indicerer stærkt varierende betingelser for smeltevandsaflejringerne, en konklusion der bekræftes af analysen af sedimentstrukturerne. Fabricanalyser og morfologi antyder, at lokale ismasser kunne have bevæget sig hurtigt nok til at forme de strømliniede aflejringer og til samtidig at erodere effektivt. Erosionen synes at have været koncentreret i Hald Sø-dalen, hvor flere isstrømme har konvergeret og dermed skabt et hoved-trug med omvendte skrænter. Tunneldalene er muligvis udskåret subglacialt af smeltevand, efterhånden som isen blev til dødis, og materialetilførslen som et resultat heraf blev reduceret. De fluvio-glaciale aflejringers eroderbare materiale, i hvilket tunneldalene var nedskåret som braided river strømme, sikrede, at de var brede og flade. De små, stejle sidedale til dem må betragtes som subglaciale render (chutes), nedroderede, samtidig med at tunneldalene blev dannet af aktivt strømmende smeltevandsflomme. Begge typer dale er i dag for størstedelen tørre eller optaget af sekundært dannede strømlejer (misfit streams). Ægte moræneaflejringer fra isen er ikke særlig almindeligt forekommende. Tynde ablationsmorænener kan dække de lagdelte aflejringer visse steder, men hovedmængden af materialet er fluvio-glacialt, aflejret under dødis-betingelser. Denne konklusion ville forklare det flade terræn, der karakteriserer områderne mellem dalene. Disse områder er endvidere forstyrret af jordfaldshuller (kettle holes), de viser, at efterladte dødisklumper sekundært er smeltede.

REFERENCES

Andersen, H. Lykke, (1972): Viborgegnens tunneldale. Miv. 2 Museerne i Viborg amt 10–15.

Hansen, K. (1971): Tunnel valleys in Denmark and northern Germany. Bull. Geol. Soc. Denmark. 20 (3) 295–306.

Jaspersen, P. (1953): Sandurbildung durch subglazialer aufsteigende Schmelzwasser. Eiszeitalter und Gegenwart 3 129–135.

Madsen, V. (1928): Third glacial period. In "Summary of the Geology of Denmark". Danm. geol. Unders. række 5 (4) 107–119.

Milthers, V. (1935): Landskabets udformning mellem Alheden og Limfjorden. Danm. geol. Unders. række 2 56 32 pp.

Nordmann, V. (1958): Beskrivelse til det geologiske kortblad Fredericia. Danm. geol. Unders. række 1 22a 125 pp.

Schou, A. (1949): Landskabsformerne. Atlas over Danmark. København Ed. N. Nielsen. p 31.

Ussing, N. V. (1903): Om Jyllands hedesletter og teorierne for deres dannelse. Overs. o. Det kgl. danske Vid. Selsk. Forh. 2 99–152.

Ussing, N. V. (1904): Danmarks Geologi i almenfattelig omrids. Danm. geol. Unders. række 3 2 358 pp.

Ussing, N. V. (1907): Om floddale og randmoræner i Jylland. Overs. o. Det kgl. danske Vid. Selsk. Forh. 4 161–213.

Weiss, E. M. (1958): Bau und Entstehung der Sander vor der Grenze der Würm. vereisung im Norden Schleswig-Holstein. Meyniana 7 5–60.

Woodland, A. W. (1970): The buried tunnel valleys of East Anglia. Proc. Yorks. Geol. Soc. 37 521–578, Section II. The tunnel valleys of Denmark 523–526, and section IV Comparison between the East Anglian buried channels and the Danish tunnel valleys 555–557.

Wheeler, P. T. (Editor) (1973): Viborg and its region. Geographical Field Group Regional Studies 16, Nottingham, England. Chap. 1. Physical Geography of the Viborg area. 1–19 189 pp.

Wright, H. E. (1973): Tunnel valleys, glacial surges and subglacial hydrology of the Superior Lobe, Minnesota. In The Wisconsinan Stage. Eds. Black, R. F., Goldhwait, R. P. G. and Willman, H. B. (Geol. Soc. Amer. Mem. 136 251–276).