The genesis of tills from Åstadalen, southeastern Norway

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Ice movements in Åstadalen originated from the north and later from the northwest. Most of the area is covered by a 1-5 m thick till which does not create independent landforms. In the mountainous areas, this till is local and coarse-grained and interpreted as a subglacial melt-out till. Here the glacier was probably rather passive when the till was formed. A complex till occurs along the eastern valley side. At typical lee-side localities, the local coarse-grained till is most probably of a subglacial melt-out origin. Along the western valley side and western upland area, the till is everywhere rather fine-grained and compact, and cobbles and boulders are abraded. Most parts of this till were formed by a lodgement process. Transverse moraine ridges, mainly occurring along the western part of the valley, are composed of till which is interpreted as subglacial melt-out till. Some probably supraglacial material occurs at the top. Hummocks consisting of diamicton are found, particularly along the eastern side of the valley. These are composed mainly of earlier deposited subglacial till, which was subsequently transported on to the surface of the valley ice from ice-free valley sides. Most of the till material in Åstadalen is therefore believed to originate from basally transported glacial debris.

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The classification of till related to its genesis has been a subject of broad interest for glacial geologists during the last ten years, greatly stimulated by the work of INQUA-Commission on Genesis and Lithology of Quaternary deposits (see Dreimanis 1976, 1979, 1980). The commission has proposed different detailed tentative classification systems for tills (see Dreimanis 1976, Fig. 5).

In Norway, tills have for a long time been divided into two genetical groups; basal till and ablation till (Holtedahl 1953, pp. 754-58, G. Holmsen 1956). The first type refers to deposition of material from the basal part of ice and the second to deposition of supraglacial material. The same division is still used today (e.g. Sørensen 1979a, Sveian 1979, Vorren 1979). In many cases it is difficult to distinguish between these two till types in Scandinavia, because varieties of basal tills may be so similar to varieties of ablation till (see descriptions and discussions in e.g. Hoppe 1963, J. Lundqvist 1969a).

The study described here was carried out in Åstadalen, southeastern Norway. The aim has been to try a detailed genetical interpretation based on morainic morphology, till texture, and till structure. Since there is no single generally accepted genetical classification system of tills, it is necessary to define the terms used in this paper (Fig. 1). They are mainly based on Boulton (1976) and Dreimanis (1976), and on a classification proposed by Shaw (1979a) for the INQUA-Commission on Genesis and Lithology of Quaternary Deposits.

Subglacial till is formed by subglacial deposition of basal debris (Fig. 1). Lodgement till is deposited by lodging of material from basal sliding ice (e.g. Boulton 1976, 1978). Friction against the bed forces the clasts to be lodged one by one, and by a plastering on they are gradually embedded in more fine-grained till matrix. Subglacial melt-out till (Fig. 1) is deposited by a melt-out process. Obviously also the lodgement process involves subglacial melting (Goldthwait 1971) and should logically form one part of the subglacial melt-out tills. However, the processes of lodgement are assumed to form tills with characteristics different from tills deposited by a pure melt-out (see Boulton 1976, 1978). In this paper subglacial melt-out till therefore refers to tills which were deposited where there was no lodging from sliding ice, i.e. from zones where the glacier was totally or basally stagnated (Shaw 1977a, 1979a). Subglacial melt-out till may form beneath frontal parts of mainly cold-based glaciers (Shaw 1977a), beneath thick temperate glaciers in zones of basal stagnation because of friction against the substratum (G. Lundqvist 1940), or by melting of debris-rich basal ice remnants during the final part of a deglaciation phase (Mickelson 1971).

Supraglacial till is formed by debris which oc-
Genetic classification of tills

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<th>Position of transport</th>
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<td>Basal</td>
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![Fig. 1. Classification system for tills. Based on Dreimanis (1976), Boulton (1976) and Shaw (1979a).](image)

...curred at the surface of the ice and was deposited as till by a lowering when the underlying ice melted away (Fig. 1). Supraglacial melt-out till is formed by debris which was mainly transported englacially before it occurred in supraglacial position. In some cases debris has been transported totally in supraglacial position without any incorporation in the glacial ice and has then been deposited by a pure lowering (Fig. 1).

Before and during deposition the supraglacial debris has in most cases slid or slumped and been retransported as sediment flows (Lawson 1979), and the sediment may then be classified as flow till (Fig. 1) (e.g. Boulton 1971).

In cases when till melted out from debris-rich, basal ice remnants, the melting may have occurred both from above and below (e.g. Lawson 1979) and the distinction between sub- and supraglacial melt-out is without significance. The till may then be referred to as basal melt-out till.

It was realized long ago that the properties of tills in Scandinavia are clearly related to the topography of the substratum (G. Lundqvist 1940). There is further a clear relationship between till genesis and the related morainic morphology (see general discussion in Sudgen & John 1976, pp. 235–257). The following descriptions are related to the main topographical position of the tills and to the main morainic morphology. Till genesis is discussed for each topographical or morphological group separately.

Methods

The content of boulders and cobbles in till sections was usually estimated visually. A few sections were thoroughly cleaned and the areas occupied by boulders and cobbles were measured. Both visual and areal methods give rough estimations only.

Material finer than 64 mm was analysed by the sieving and hydrometer method.

Standard samples were applied for field determinations of roundness, and roundness index was calculated according to Krumbein (1941).

Long-axis orientation was measured for particles with a-axis $> 4 \text{ cm} > 2b$-axis. Fabric data were evaluated statistically by eigenvalue method (Mark 1973, Lawson 1979, Haldorsen & Shaw in press). Computer programming was performed at the University of Alberta, Canada.

Regional position

The study was carried out in the Åstadalen area, which lies between the eastern Norwegian main...
Fig. 3. Map of the moraine types, distribution of till and glacial striations in Åstadalen. Partly based on Østeraas (1978, 1982). Sediments other than till cover only a minor area and are omitted.
valleys of Gudbrandsdalen and Østerdalen (Fig. 2). The river Åsta drains into the river Glomma in Østerdalen. The investigation was concentrated in the catchment area of the Åsta north of Bjørnåsbrua (Fig. 2). The valley bottom lies at about 800 m a.s.l. in its upper part and slopes down to 620 m a.s.l. at Bjørnåsbrua, and is thus considerably higher than the floor of Gudbrandsdalen and Østerdalen (see numbers in Fig. 2).

Åstadalen is surrounded by mountain plateaus to the east and northeast with an average elevation of 800–1000 m a.s.l. and peaks up to about 1100 m, to the north by a mountain range with heights from 1000 to 1200 m a.s.l., and to the west by upland areas with mountain peaks up to about 1050 m. The valley is fairly wide with gentle side slopes (Fig. 3), the northeastern valley side being somewhat steeper than the southwestern one.

Bedrock
The bedrock consists of Late Precambrian sedimentary rocks belonging to the Brøttum Formation (Englund 1972, Fig. 17) which in the south is composed of rather homogeneous sandstones, and in the north of sandstone alternating with thin beds of silty shale (Figs. 2 & 4). North of the Brøttum Formation other Late Precambrian sedimentary rocks occur (Fig. 2), predominantly with a composition similar to the Brøttum Formation (J.-O. Englund, pers. comm. 1980). The strike of the bedrock is generally E–W (Fig. 4). The bedding and the main regional fractures in NW-SE and NNE-SSW direction strongly control the morphology.

Above 11–1200 m a.s.l., the bedrock is intensively fractured by postglacial frost cracking, and the surface is here partly covered by boulder
Fig. 5. Typical boulder field at the mountain Himmelkampen.

fields (Fig. 5). Such fields are common in the central part of Scandinavia and have been described by G. Holmsen (1960), G. Lundqvist (1951, pp. 81–82), and J. Lundqvist (1969a, p. 119). In many places the boulders lie in situ and each separate sandstone bed can be traced across the boulder fields.

Ice divides and ice movements

Data of G. Holmsen (1960), P. Holmsen (1951, 1964), and Vorren (1977) indicate that the Åstadalen area lay only a few tens of kilometres south of the ice divide during parts of the Weichselian (Fig. 2). and for some time even beneath the ice divide (P. Holmsen 1951, Vorren 1977, Fig. 3).

The directions of ice movements are interpreted from striations. A north-south direction was found at several places in the mountains (Fig. 3) and the same direction was observed at some other places in the Østerdalen region (Fig. 2) (G. Holmsen 1960, Fig. 2). The dominating striation in the area reflects a glacial movement from the northwest (Fig. 3), which is also dominant other places in the Østerdalen region south of the ice divide (Fig. 2) (G. Holmsen 1960, Fig. 2). Crossing striations in the mountains (Fig. 3) show that this movement is younger than the one from the north.

Morainic morphology and related till types

Cover moraine

Most of the area is covered by till of thickness 1–5 m. No morainic landforms parallel with the older glacial movement from the north were observed. It is difficult to determine if some of the small-scale topography reflects independent moraine forms, but an impression from air photos and field interpretations is that the northwest–southeast trending morphology mainly reflects the bedrock structures (Fig. 4).

Thin till covers like the ones in Åstadalen are common in Norway. The related morphology is classified as ground moraine (see Holtedahl 1960, pp. 389–403, G. Holmsen 1954, p. 50, 1960, p. 62) as, for example, in Finland (Aario 1977, p. 88). However, if the definition given by Flint (1971, p. 199) is applied, where a moraine is defined as ‘possessing initial constructional form independent of the floor beneath it’, then such forms are usually lacking in Åstadalen. The till cover found here does not properly create moraines but is merely a part of a drift sheet. Aario (1977, p. 88) proposed the term ‘cover moraine’ for the morphology within areas where the immediately underlying bedrock is reflected. Although this term is not in accordance with the definition of moraine used by Flint (1971, p. 199), it applies very well to Åstadalen and is therefore used in this paper.

Related to its topographical position, the cover moraine can be divided regionally into three areas: (1) the mountainous areas in the north and east, (2) the northeastern valley side, and (3) the southwestern valley side and the western upland area (Fig. 3).

Mountainous areas. – The mountain areas in the north and east are generally characterized by a thin till cover and frequently exposed bedrock
(Fig. 3) with continuous cover moraine found in depressions only. The bedrock topography is mainly irregular on both stoss and lee sides. Such an irregular topography probably existed even when the ice melted away, but in many places the present surface may also be the result of postglacial frost cracking.

Frost and slope activities have obviously altered the original till characteristics in several places. Boulders from boulder fields may by talus activity have moved onto the moraine surface and may even have been mixed into the till material, as described from Sweden by J. Lundqvist (1969a, p. 119). Frost heave and solifluction have also destroyed the original till structures, degree of compaction, till fabric, and granulometric composition. However, by excluding all localities where such supposed secondary influences have occurred, it is possible to recognize some typical original characteristics of the mountain plateau tills. Both on a regional and vertical scale the till is rich in boulders, cobbles, and gravel (Figs. 6 & 7). The grain-size distribution of tills covering the sandstone/shale bedrock in the north is similar to that of tills covering the more homogeneous sandstone bedrock in the south. This is partly because the content of shale in the bedrock is small compared with sandstones and partly because neither the shale nor the sandstone have been intensively comminuted.

The significant content of silt (~20%) relative to sand (~80%) and the general lack of sand lenses indicate that the low matrix content (sand+silt+clay) is mainly a primary property and not the result of removal of fine-grained material by melt-water. The coarse-grained texture therefore shows that glacial comminution beyond gravel size has been small and that the relative supply of coarse clasts was always great. An important factor here is the deeply and intensively fractured bedrock which certainly also existed prior to the last glaciation. Such material was easily incorporated into the glacier and provided a great supply of coarse material.
Some rounded and striated clasts occur, but generally angular material is quite dominant (Fig. 8). The general lack of abraded clasts even in the deepest part of the till, and the very low roundness index are most certainly primary characteristics of the till material.

The high contents of coarse and angular material (Figs. 7 & 8) indicate a melt-out origin. The clasts could hardly have avoided abrasion if they were overridden by an active sliding glacier from the time they were lodged until they were embedded in till material.

Several characteristics indicate that the glacial debris was carried mainly in a basal position. First, it is of a very local origin. This is, for instance, clearly visible near the boundary between the sandstone with shale in the north and the pure sandstone in the south, where the content of shale ends abruptly at the bedrock boundary. Furthermore, the described till rests directly on the bedrock and except for the effects from frost heave there is no systematic vertical variation in it. Finally, there is general lack of meltwater channels, glaciofluvial material, and dead-ice topography with hummocks and ridges (Østeraas 1978, 1982). Thus there is no indication of a lowering by melting of underlying clean ice or of the presence of great amounts of meltwater.

The till may have been formed in the following way (Fig. 9): Boulders and cobbles from the intensively fractured bedrock were incorporated into the glacier and transported a short distance in basal position. Some internal movement in the ice, because of shearing or plastic deformation, may have caused the clasts to collide or be pressed against the substratum. Matrix material was formed by the grinding of small clasts between bigger ones or between bigger particles and the bedrock. Fine-grained material was also formed by abrasion, but this did not significantly change the degree of roundness. It should be emphasized that the till is rather thin. Its formation may well be related to the period of decreas-
Genesis of tills

During glacial activity, a short time before the final deglaciation.

Zones with more abraded clasts occur mainly along some of the marked depressions, for instance at Lyngen and along the upper part of the river Skolla near Skolfjellet (Fig. 3). In such cases, the abraded particles occur together with quite angular material. One component has been transported along the base of active sliding ice for a relatively long time. Before or during the deposition it has been mixed with very local and angular material.

Northeastern valley side. – The topography along the northeastern valley side is variable. It is relatively steep along the Øyungenfjellet and Hynnlia (Fig. 3), and much more gentle where the tributary valleys join Ástadalen. The exposed bedrock surfaces are in some places irregular and show signs of glacial plucking, in other places there are more abraded surfaces (e.g. the great bedrock exposure SW of Øyungen (Fig. 3)). Along the upper part of the valley side the bedrock exposures are most frequent (Fig. 3), and the till thicknesses, obtained by drilling, do not usually exceed 3 m. The lower parts of the valley side have a more continuous till cover of thickness 2–5 m.

A characteristic till occurs at localities which were in lee-side positions of both the older and younger ice movements (Fig. 3). An excavation down to 1.5 m west of Øyungenfjellet (Fig. 3) exposed a loose and nearly structureless till. Two fabric measurements carried out at Øyungen (Fig. 3, locality 1) and Bjørnåsen (Fig. 3, locality 2) showed no strong preferred a-axis orientation (Fig. 10A & B). The frequency of surface boulders is usually high at lee-side localities, and sections and numerous drillings indicate that boulders and cobbles are also abundant deep in the till (Fig. 7). The content of gravel is usually comparable with that of sand, and the content of silt + clay is very low (Fig. 7B). The total clast material has a high degree of angularity (Fig. 8). The lee-side till shows clear evidence of a local source; in particular the angular clasts can in most cases be traced directly to the nearest bedrock exposure.

At one locality southeast of Øyungenfjellet (Fig. 3, locality 1), this till type was studied in more

Fig. 9. Models of till formation in Ástadalen.
Cover moraine, eastern valley side

Fig. 10. Long-axis fabric of clasts from the eastern valley side. The site of localities 1, 2 and 4 is shown in Fig. 3. \( n \) = number of particles, \( A \) and \( P \) give the azimuth and dip of the eigenvector \( V_1 \) in degrees, \( S_1 \) gives the strength of clustering around the mean axis. Projection: Schmidt’s net, lower hemisphere.

detail (Fig. 11). Close to a steep and irregular bedrock wall there was an abundance of big angular boulders of which most had been glacially transported. About 50–100 m further south, the material was gravelly and sandy and appeared structureless. Some big angular boulders occurred at the surface (Fig. 12). At several other lee-side localities there was a similar distribution of material. In some cases the till was very gravelly for some distance from the headwall, where-

Fig. 11. A. Sketch of the lee-side locality 1 south of Øyungenfjellet (Fig. 3). 1: just south of the headwall, 2: 50 m further towards south. B. Grain-size distribution, 1 m depth. C. Roundness of gravel, 1 m depth.
as at other places, as for instance near Skvaldra (Fig. 3, locality 3), it was more sandy. The sandy or gravelly till is not believed to be the result of removal of silt + clay by melt-water. The samples were taken some distance from the visible melt-water channels, and the till was homogeneous without lenses of sorted material.

The till texture at the lee-side localities is concluded to be the result of local glacial erosion, transport, and deposition. The coarse material has been eroded by the steep parts of hill sides, where the fractured bedrock was exposed to glacial plucking. Afterwards, when the big boulders were transported a short distance away from their source area, they might have been pressed against bedrock or underlying drift material to form effective grinding tools. In most cases this results in a gravelly material, but in some cases also in a sandy one.

In this way the lee-side till has the same characteristics as the mountain plateau till. Its coarseness and its angular clasts indicate that it is a melt-out till. The lack of melt-water sorting and a local provenance indicate a basal transport.

It is difficult to determine whether a comminution like that described above occurred before, during, or after deposition. The pressure from big lee-side boulders incorporated in the ice may have gradually crushed the already deposited underlying material. Such a crushing may explain why the particles in the till have a rather broad scatter of a-axis orientation. The big boulders on the top then represent the last, uncrushed material which was finally deposited when the ice melted away.

The typical lee-side till is regarded as representative for the initial stage in till formation along the northeastern valley side (Fig. 9).

Along most parts of the valley side, particularly along its lower parts, a much more silty, compact till type occurs with abraded boulders and cobbles. At some localities there is a marked a-axis orientation parallel with the last direction of ice movement (Fig. 10C). These characteristics indicate a significant transport along the base of an active glacier and the deposition has probably mainly been by a lodgement. In areas where such material dominates there are local occurrences of coarse till with angular clasts (Fig. 13). In many cases there is also a mixture of quite angular and abraded clasts. It is very difficult to find the boundary between the different types in the field and to classify them genetically.

Southwestern valley side and western upland area.

- The topography along the southwestern valley side and the western upland area is rather smooth, and the valley side is gently sloping towards the northeast. There are no marked tributary valleys or any steep mountain sides which have a lee-side position during either of the two ice movements (Fig. 3). The few exposed bedrock surfaces are smooth and striated. Based on drilling, the till thickness is estimated to be on average 3–5 m.

The road cuts show a compact till with a distinct fissility. The till is massive except for some thin silt-rich horizons, which occur in particular at the distal sides of boulders.

At most localities there is a strong a-axis orientation parallel to the last direction of ice movements (see locality 5–8, Figs. 3 & 14). The dip is towards northwest (Fig. 14 A–D) and is easily

Fig. 12. Local lee-side boulders south of Øyungenfjellet, at locality 2, Fig. 11A.

Fig. 13. Local, coarse till with angular clasts from an area where much more abraded material dominates. Photo taken south-east of Øyungenfjellet.
Recognized in sections (Fig. 15). At two localities (locality 7 & 8, Fig. 3) the clasts in the lowermost part of the till show an a-axis orientation in N-S direction with a dip towards north (Fig. 14 E & F). This probably reflects the early direction of ice movement. The upper part of these tills contains particles with the regular NW-SE orientation.

On average the content of silt is considerably higher in the till along the western valley side
than in other till types (Fig. 7). The gravel is more rounded than in the two other cover moraine types (Fig. 8), and the boulders and cobbles are generally more abraded and striated. Many of the boulders have a typical bullet-nosed shape (Fig. 16).

The till characteristics prove that the material has been transported in a zone with intensive glacial abrasion and crushing and indicate that the ice was debris-rich. The particles have been in frequent contact during the transport. As the till seems in all places to rest directly on the bedrock, the transport has been interpreted as a basal one.

A marked fissility, strong a-axis orientation, abraded clasts, a high proportion of fine-grained material, and bullet-nosed boulders with sharp truncated distal end (Fig. 16) as described above, are characteristics which for instance Boulton (1976, 1978) and Dreimanis (1976) regarded as typical for a lodgement till. In the present case they reflect a transport along the base of a sliding glacier, during which it is reasonable that lodgment was the dominating way of deposition. There is, however, a question of whether these characteristics are diagnostic of the lodgement process, as it was defined in the introduction.

The bullet-nosed boulders may have been shaped and orientated before they were deposited. Boulders in the area commonly have a triangular shape with a distinct long axis even in their primary stage. During the glacial transport such boulders were probably rapidly orientated so that they afforded the smallest possible resistance to glacial movement: that is, with their snout pointing upstream. The proximal part may have been abraded and become bullet-nosed during transport. The distal, angular end is then not necessarily the result of a lee-side excavation as described by Boulton (1978), but rather the
Fig. 18. A. Sketch of the transverse moraine ridges at Åkerøseter. B. The degree of roundness of gravel fraction 16–32 mm from site 1 in the lateral part of the valley and site 2 in the middle of the valley.

original surface of the boulder which pointed downstream and therefore avoided abrasion.

The fine-grained till texture does not prove that lodgement took place. Most of the matrix material (sand + silt + clay) was probably formed by intensive glacial comminution of the clasts during the transport. Boulton (1978) described some characteristics which are diagnostic of the lodgement till alone. One of these was that the lodged boulders have an upper surface which is significantly more abraded than other surfaces. Commonly also the upper surface is more uniformly striated, in a manner which clearly reflects the last direction of ice movement. Similar characteristics are found several places along the southwestern valley side.

In some cases, the till just above, and at the lee-side of boulders, is particularly rich in silt (Fig. 17). This may be explained as a deposition of fine-grained material formed by abrasion of the boulders. Such a concentration of silt could hardly occur during the transport.

As the diagnostic characteristics described above are only observed in special cases, they do not prove that the entire till was deposited by a lodgement. However, as pointed out above and also in the introduction, deposition of lodgement till must have predominated as long as the glacier in the valley was active. A pure melt-out process was then probably only of more local occurrence. During the final part of the deglaciation a melt-out till may have been deposited from remnants of debris-rich basal ice. This may form the uppermost part of the till. In that case it has been strongly influenced by secondary soil processes and is no longer readily identifiable. Therefore, as the till in the west is so uniform, the total till has here been interpreted as a lodgement till (Haldorsen 1981).

A comparison between the northeastern and the southwestern valley side. – The till is generally thicker and much more continuous along the southwestern than along the northeastern valley side (Fig. 3). This applies even for the rather gentle parts of the northeastern valley side. The difference may be explained in the following way: During the early glacial phase with movement from the north, the northeastern valley side was a lee-side area while the southwestern side was a stoss-side area (Fig. 3). The step-wise local topography along parts of the northeastern valley side promoted entrainment of material by glacial plucking and regelation. Part of this material was transported across the valley and upwards along the southwestern stoss side, where a basal melting dominated. Material originating from the northeastern valley side was in time lowered to the zone of traction, and parts of it may have been deposited as a lodgement till. Net erosion
probably occurred along the northeastern valley side and less till was deposited there than to the west.

During the late glacial phase, material was no longer transported from the northeastern to the southwestern valley side because the flow was then parallel with the valley. New till material was certainly formed and deposited along both valley sides. However, the initial difference between the two valley sides may explain why there is more till in the west today.

Melt-water activity is another important factor in this connection. Much more melt-water occurred along the northeastern than along the southwestern valley side. A great amount of deposited till and glacial drift was eroded and redeposited as glaciofluvial material in the vicinity of the northeastern slope.

The bedrock structures have strongly controlled the behaviour of the glacier in Åstadalen. The strike of the bedrock is mainly east-west and the dip is towards the north along the central part of the valley (Fig. 4). In combination with the main fracture zones (Fig. 4) this is responsible for the steep and irregular topography along the northeastern valley side. When the glacier flowed from the north and down into the valley it had to pass from one fractured sandstone bed to another along the valley side. A uniform basal sliding was therefore not established. Along the southwestern valley side the ice could more or less follow the surface of one sandstone bed for a long distance. This allowed a more uniform flow. In combination with the lee-side plucking and stoss-side abrasion (Boulton 1970, 1971) it gave favourable conditions for formation of lodgment till in some places and subglacial melt-out till in others.

**Ridges transverse to the direction of ice movement**

Several places along the valley bottom, particularly west of Åsta, there are moraine ridges which are oriented more or less transverse to the last direction of ice movement (Fig. 3). The ridges are partly curved with the convex side downstream. The length varies from 20 to 60 m and height from 2 to 10 m. The distal slopes are generally steeper than the proximal. The ridges are arranged in groups in a fish-scale-like pattern (Fig. 18A).

The till is everywhere loose and sandy with lenses and beds of sorted sediments, indicating influence from melt-water. The roundness of gravel is some places similar to that of the lodgment till (Figs. 8, 18A, site 1 & 18B, curve 1). Towards the centre of the valley the roundness index is higher (Figs. 18A, site 2 & 18B, curve 2) indicating a fluvial prehistory for some of the material (cf. Fig. 19).

The long-axis orientation is mainly parallel to the last direction of ice movement, indicating a basal formation (Haldorsen & Shaw in press). The undisturbed internal structures and absence of drumlinization show that the ridges were not overridden by active ice after the formation.

The total situation, structure, and texture imply a formation just before the ice became stagnant, and a deposition by a subglacial melt-out (Fig. 9). The history is believed to be similar to that of the Rogen moraines in Sweden (G. Lundqvist 1943, p. 21, J. Lundqvist 1969b and Shaw 1979b).

The uppermost parts of the ridges – above the zone of proper melt-out till – locally consist of sorted stratified material and sandy diamicton (Fig. 20). The layering is irregular, and the fabric
Fig. 20. Section in a transverse moraine ridge at Åkerseter (site 1, Fig. 18), 1–2 m below the surface. To the right, fabric diagrams. Maximum of a-axis orientations is given by the azimuth \( A' \) and by the average dip \( P' \). Magnitude of the resultant vector in relation to the number of observations \( n \) gives the strength of orientation (values \( R \)). \( A' \), \( P' \), and \( R \) are calculated by the method described by Steinmetz (1962).

*significant orientation at a 5% level of significance.

A. Subglacial melt-out till with a preferred long-axis orientation of clasts parallel with the valley. B. Coarse-grained diamicton of supposed supraglacial origin. A broad scatter of long-axis orientation of clasts is found. The boundary between A and B is defined by a layer of fine sand and silt.

Hummocks

Hummocks containing diamictons are mainly found along the valley floor. They are most frequent in the east (Fig. 3). The hummocks are from 2 to 8 m high. Irregular ridges also occur.

There are several small gravel pits and road cuts in the hummocks, which show an abundance of sorted zones, mainly as irregular bands and lenses. The diamictons are commonly rich in gravel and have a sandy and loose matrix. They are several places overlain or underlain by sorted, stratified material. There is in most cases no correlation between the directions of ice movement and the long-axis orientation of clasts.

The hummocks are mainly found in areas where eskers and kames are frequent. Drilling showed that they occasionally rest on a homogeneous silty diamicton, probably a till of the same type as that of the cover moraine. In some places the hummocks are found on eskers. This, and the fact that they are clearly influenced by melt-water and have disturbed internal structure, indicate a supraglacial origin.
A section through the upper part of a hummock at Kattugletjern is shown in Fig. 21 B. The lower part of this consists of a sandy, gravelly diamicton. (Fig. 21 B & C: 1) with irregular lenses of fine sand (Fig. 21 B & C: 2). The upper part consists of a diamicton with a low content of sand and silt (Fig. 21 B & C: 3). Part 1 is rather massive while part 3 has a diffuse stratification. There is no sharp boundary between part 1 and part 3. The gravel has the same degree of roundness in both parts (Fig. 21 D).

The long-axis is roughly parallel with the local
surface slope (Fig. 21 E) but with slightly less dip than the surface gradient.

The presence of sorted material (Fig. 21 B: 2) and the fabric in the diamicton indicate a deposition by flow. The cap of coarse material according to Nemec et al. (1980) is typical for subaerial debris flows. The lower part of the section (Fig. 20 B: 1) could represent a true debris flow, with a high concentration of solids. The upward movement of pore water may have given an increased concentration of water towards the top of the flow. The material here has been totally liquified and a syndepositional removal of fines thereby occurred. This facies may be represented by the upper, gravelly part (Fig. 21 B: 3).

At Myrbakken (Fig. 3) a section in an irregular ridge shows a lowermost part (Fig. 22 A: 1) consisting of stratified sediments with a variable gravel content. The material finer than 2 mm contains <10% silt + clay (Fig. 22 B). The stratification is partly disturbed.

Above, there is a sandy, gravelly diamicton
(Fig. 22 A: 2) with a silt content of about 10\% (Fig. 22 B), poorly developed stratification and irregular lenses of coarse sand (Fig. 22 A). There is no sharp boundary between the diamicton and the underlying stratified sediments or between the diamicton and the sand lenses.

At the top of the sequence there are sorted and stratified sand and gravel beds (Fig. 22 A: 3) with a silt content below 5\% (Fig. 22 B) and with a well defined and probably erosional contact to the underlying diamicton.

The gravel has similar roundness through the whole section (Fig. 22 C) and is considerably more rounded than the gravel of the diamicton (see also Fig. 19). The long axes of clasts in the diamicton lie in the whole section close to the horizontal plane (Fig. 22 D), but compared with the bedding planes there is a distinct dip towards northeast (Fig. 22 E). If the long-axis orientation was parallel with the movement of the diamicton during its deposition, this implies a transport from northeast.

The low silt content and the roundness of gravel indicate that all the material has undergone a short glaciofluvial transport. Part 1 was probably deposited in a crevasse with a northeast-southwest direction. Later part of these deposits – or other sediments with the same composition – flowed by gravity along the crevasse, in a southwestern direction, forming the diamicton. The top of the diamicton was probably eroded by melt-water before the glaciofluvial sediment unit 3 was deposited.

The deformation of the sediment 1 may result from the melting of underlying ice. It is reasonable that the processes which caused the deformation also caused the sediments to flow. The undisturbed stratified sediments at the top indicate on the other hand that no significant lowering occurred after the deposition of part 3.

Alternative sources of the supraglacial sediments are shown in Fig. 23. The eastern valley side and the eastern mountainous areas were probably nearly deglaciated while the valley bottom was still filled with ice, and may be the source for much of the supraglacial material (Fig. 23 C). This is indicated by the clast abrasion which is similar to that of the lodgement till and by the concentration of hummocks in areas where melt-water channels are frequent along the upper part of the valley side.

Basal drift may have been lifted to an englacial position along the eastern valley side where the topography is variable (Fig. 23 B). However, during the last part of the glaciation there was certainly an overall net melting along the base of the glacier and most of the basal drift was deposited at subglacial till.

The supraglacial sediments may have had a complex history also after their introduction to a supraglacial position.

This is well demonstrated by the two studied sections and also illustrated in Fig. 23 D-E-F. All the supraglacial diamictons which have been studied in sections bear evidence of flow. None of them are, therefore, supraglacial melt-out tills or lowered supraglacial tills (Fig. 1). In fact, the active processes in the supraglacial position were either flow or running water. The only till type which was formed from original tills in this environment was consequently a flow till (Fig. 23). The debris-flow sediments at Kattugletjern (Fig. 21), is of this kind. The diamicton at Myrbakken (Fig. 22), on the other hand, should not be classified as a till. At other localities an original glacial till may have been mixed with glaciofluvial sediments during flow. This is indicated along Skolla (Fig. 3) where the diamictons include gravel with a bimodal roundness distribution (Fig. 24), and a rapid variation in grain-size distribution. Zones with silty material occur frequently and are inter-
interpreted as fine-grained material from the original till. Diamictons of this kind are not true tills.

There may be several reasons why the hummocks are more common along the eastern than along the western valley side. The eastern valley side is steeper and the mountain area east of the valley is generally higher. These areas were probably free of ice before the western upland area (Fig. 3). In addition, the eastern side is the sunny side of the valley (Fig. 3), and therefore a greater melting rate occurred here than in the west. The surface of the ice may for a time have sloped towards northeast. Possible supraglacial material along the western valley side could have been transported towards the east and there contributed to the supraglacial sediments.

_Till genesis – concluding remarks_

Fig. 9 shows the supposed formation of different till types in Åstadalen. Most of the material is interpreted as basally transported and subglacially deposited.

Lodgement till is probably the predominant till type in the valley. However, this conclusion is based more on general glaciological considerations than on diagnostic characteristics of the till itself.

Local lee-side till and a significant part of the sparse till cover in the mountain areas have been classified as melt-out till. This interpretation is based on the conclusion that the material could not be identified as lodgement till. In addition the melt-out till may locally constitute parts of the regular till sheet in the valley (Fig. 9). The studies indicate that it is often easier to identify a melt-out till than a lodgement till.

It has been difficult to distinguish between subglacial and supraglacial melt-out till as both are formed from melt-out of basal drift and as the melt-out process was probably mainly related to the final part of the deglaciation phase (Fig. 9).

The relation between tills formed from basal drift and diamictons formed from supraglacial material is in many cases complex. The transverse moraine ridges in Åstadalen (Rogen type moraines) were formed mainly by melt-out of subglacial debris. As shown in Figs. 9 & 20, this material may be covered by a cap of supraglacial sediments. The hummocky moraines, on the other hand, were probably mainly formed from supraglacial sediments. The source of such sediments may in most cases have been subglacial till from the valley slope. The study illustrates that it is often difficult to define what is a "basal till" and what is an "ablation till", and even to determine what is a till.

_Cronology of till formation_

Åstadalen was not swept completely free of sediments before the present tills were formed. At
Øvre Åstbrua (Fig. 3), sorted sand and silt with lumps of clay are found beneath a till from the early glacial phase (Fig. 25). The clay contains remnants of turf and mosses from an ice-free period, and the till contains significant amounts of subrounded gravels which indicate an incorporation of water transported material (Fig. 25).

The organic matter in the sub-till sediments at Øvre Åstbrua has a sparse pollen content, indicating an interstadial origin (R. Sørensen pers. comm. 1980). The material has not been dated, but may for instance be of the same age as the sub-till sediments in Gudbrandsdalen (Bersgeren & Garnes 1981) or the organic material in Brunmunddal (Helle et al. 1981). These are related to Early Weichselian interstadials, and may represent the last time in the Weichselian that the Åstadal valley was deglaciated.

No defined boundary between the lower till transported from the north and the upper till transported from the northwest has been recognized. The difference between them is only reflected in the fabric. There is therefore no indication of an ice-free period after the deposition of the lower till, which is obviously younger than the organic material at Øvre Åstbrua.

The early glacial phase may have started shortly after the last interstadial and thus a long time before the Weichselian maximum. There is, however, no indication of a gap in time between the formations of the lower till and the upper till. On the contrary, sedimentation seems to have been continuous. The early glacial movement from the north could therefore be younger than the Weichselian maximum and represent part of the Late Weichselian (the time after 25 000 B.P., Fig. 26). The change in ice movement was probably caused in a shift of the ice accumulation centre, and the last movement lasted until all glacial activity stopped, as the toponymy also favours a southeastern direction (Figs. 2 & 4).

If both tills were deposited after the Weichselian maximum, there is a gap of many thousand years between the deposition of the organic material at Øvre Åstbrua and the till. A long time was thus available for the removal of old sediments. After the Weichselian maximum there were periods with a great net melting and thus a net deposition. Such periods are therefore not representative for all parts of the last glaciation. The Weichselian might well have included periods with significantly more erosion than during its last parts.

Deposition of lodgement till was probably dominant during an early part of the last glacial phase (Fig. 26). When the ice became more passive, the most important processes became stacking of basal ice and deposition of melt-out till. Such deposition may have continued until the very last of the ice melted (Fig. 26).

It has been postulated that a regional glacial stagnation occurred over many inland parts of southern Norway (Reusch 1901, p. 88, Strøm 1943, Mannerfelt 1945, Holtedahl 1953, p. 753). The mountain area in Åstadal was not ice free before the end of the Preboreal (Sørensen 1979b). The valley bottom lies about 200–300 m below the general level of the mountain plateau, and there was probably some ice movement along the valley until the glacier disintegrated into ice remnants along the valley floor. However, melt-out may have dominated compared with lodgement long before that phase. The Preboreal, and particularly the later part of it, is therefore believed to be dominated by deposition of subglacial melt-out till and supraglacial sediments (Fig. 26).

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