The Uppsala Esker: The Åsby-Drälinge Exposures

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Detailed field studies of two exposures of the Uppsala esker support the model of subglacial esker formation.

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Among theories of esker formation three models are considered classic:

1. Subglacial formation in tunnels at the bottom of the ice (Strandmark 1885, Olsson 1965, cf. Lindström 1973).
2. Subaerial formation in open channels in the ice (Holst 1876, Tanner 1928).
3. Submarginal deltaic formation at the mouths of ice tunnels (De Geer 1897).

This article will describe and discuss esker sedimentation as exposed in two sections of the Uppsala esker at Åsby-Drälinge in a subaquatic environment.

Just north of Uppsala the Uppsala esker forms short ridges and mounds ("beads"). Connecting eskers passing Jumkil and Husby follow fault lines trending from N.W. and N.E. This influenced the drainage during deglaciation toward the main drainage line now evidenced by the Uppsala esker. Large parts of the esker are covered by glaciolacustrine clay. From Lövsta about 10 km N of Uppsala, the Uppsala esker forms a continuous prominent ridge.

Åsby

The Åsby site is a transverse section in the Uppsala esker, normal to the esker axis, in a gravel pit on the east side of the road (E4) about 14 km N of Uppsala (Figs. 1—8). At Åsby the esker broadens. The crest of the esker is rather level from here to the north with a relative height of about 35 m. Its height a.s.l. is 62.8 m as compared to the highest shore line in this area (the Yoldia Sea) which is ca 160 m and the highest limits of both the Ancylus Lake ca 100 m and the Littorina Sea ca 60 m (Lundegårdh-Lundqvist 1956, p. 90). The esker is modified by subsequent wave action resulting in the development of shore terraces on different levels. The esker is surrounded by clay deposits covered by wavewashed fine sand and sand.

The Åsby exposure is composed of two stratigraphic units, here referred to as units 1 and 2, shown in Figs. 1—8.

Unit 1 is made up of alternating beds of sand, pebbles, cobbles and boulders. Horizons of fine sand with ripple laminations also occur, overlain and underlain by pebble, cobble and boulder beds (Fig. 1).

In central parts of the section the bedding is mainly horizontal. No pronounced longitudinal fining has been observed. Cut-and-fill structures are well exposed. Normal faults occur in central parts of the esker (Figs. 1 and 2).

A horizontal bed of sand and boulders in the central part of the esker (Figs. 1 and 5) has been traced for a distance of about 100 m as the material has been excavated to the north. The boulders in the bed are in a matrix of sand and often not in contact with each other. In places the interstitial sand forms layers over individual boulders extending downstream.

In the bottom section in the east (Fig. 7) a block of cohesive material approx. 10 m in height shows contorted

Fig. 1. Transverse section in the Uppsala esker at Åsby. Stratigraphic units 1 and 2. Unit 2 is the topmost ca 1 m.

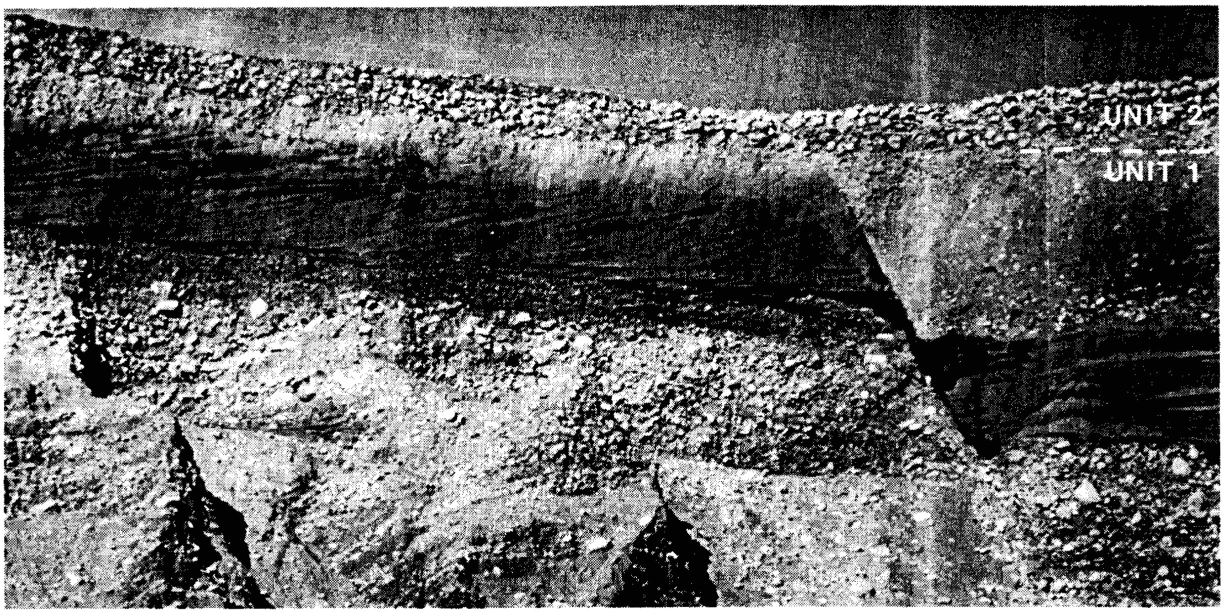

Fig. 2. Detail of Fig. 1.

bedding of clay and silt layers interbedded and folded with sand and coarser rounded material.

At the exposed contact of units 1 and 2, a discontinuous line of boulders is covered by a thin layer of highly consolidated clay (Fig. 3). In some places the clay has been split into laminae interbedded with thin sand horizons. The surface of the underlying block with contorted bedding is marked by the dipping clay layer (Fig. 7).

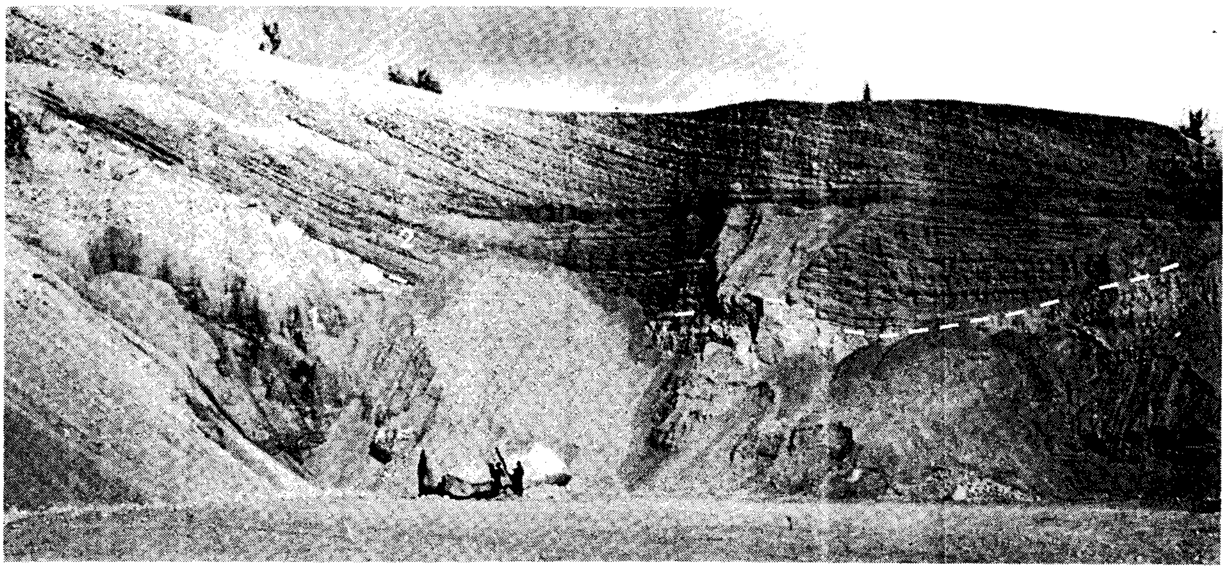

Fig. 3. The eastern part of the exposure at Åsby. Stratigraphic units 1 and 2, separated by a clay layer in the middle of the section.

Fig. 4. Detail of Fig. 3. Clay horizon.

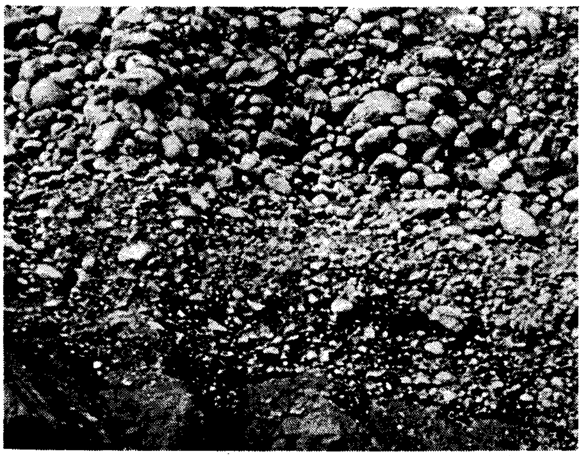

Fig. 5. A bed of boulders and sand in the central part of the esker. Cf. Fig. 1.

Fig. 6. Detail of Fig. 5. Interstitial sand progressively overrides boulders.

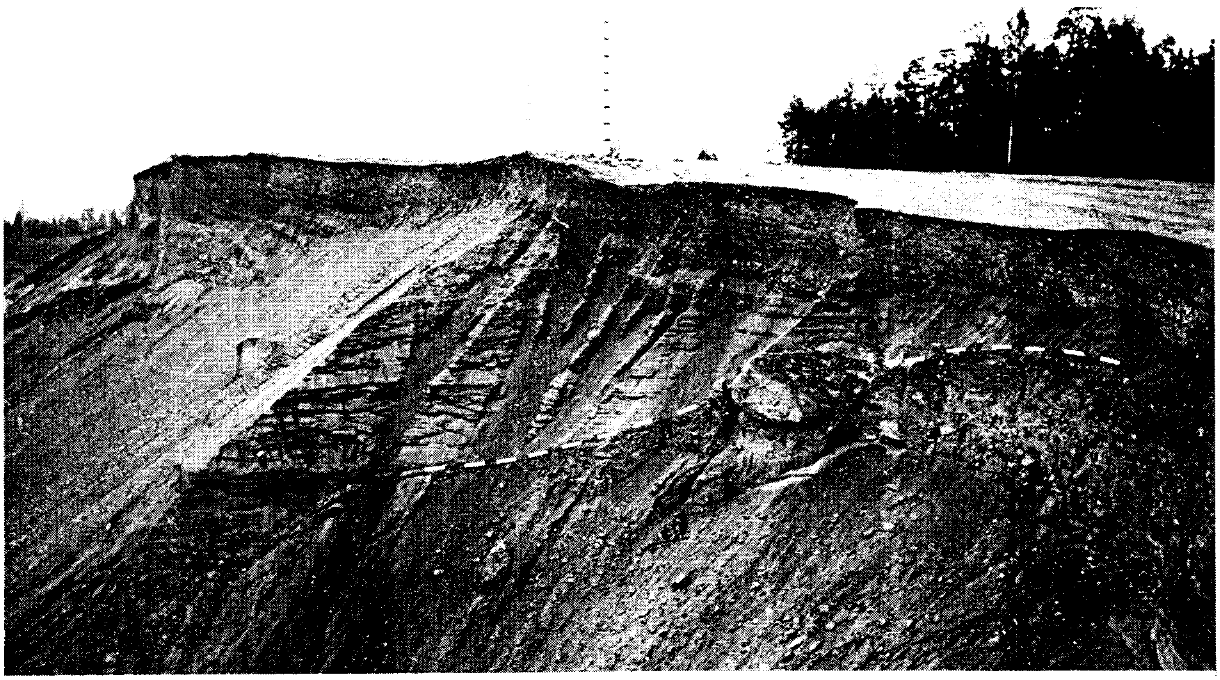

Fig. 7. The eastern part of the exposure at Åsby with the dipping clay layer covering contorted bedding to the left.

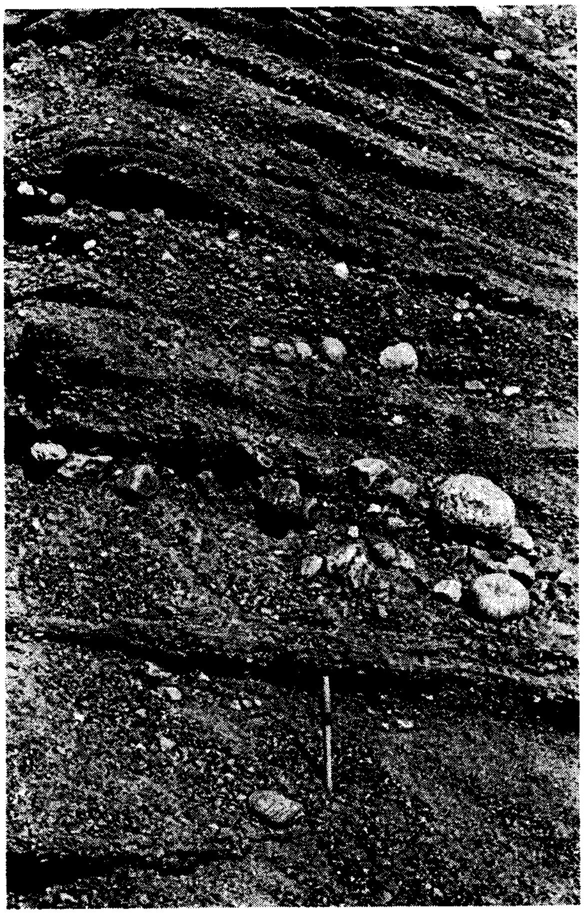

Fig. 8. Cross-beds including clay particles.

The clay layer is overlain by large cross-beds, which compose the bulk of unit 2 (Figs. 3, 7 and 8). The cross-beds include clay particles within the layers of sand and coarser material (Fig. 8). The main part of unit 2 is exposed along the side of the esker. A layer of pebbles, cobbles and boulders on top of the esker is also associated with unit 2. The faults in unit 1 do not affect this layer (Fig. 2).

Drälinge

At Drälinge about 500 m farther to the north, there is another large gravel pit in the central and eastern parts of the esker. With time the two gravel pits will join as the Åsby pit is extended to the north.

Both longitudinal and transverse sections are exposed. A longitudinal section in the central part of the esker shows a zone of rounded imbricated boulders. An exposure of irregularly bedded material also appears in the longitudinal section (Fig. 9).

Interpretation

The sediments of unit 1 at Åsby are primary esker material probably accumulated subglacially by an ice river in a tunnel in the form of beds advancing over each other. The absence of fining downstream would argue against a del-

Fig. 9. Irregularly bedded material in the esker at Drälinge.

taic interpretation. The wide range of particle sizes shows a variety in flow regimes. According to Allen who investigated climbing-ripple cross-lamination at a site in the Uppsala esker near by, Lövstalöt, "the flows depositing the beds appear to have varied in discharge on a time-scale varying between several hours and a few tens of hours" (Allen 1971, p. 157).

The relationships between the boulders and interstitial sand layers at Åsby (Fig. 6) indicate that both the "floating" boulders and the sand were deposited simultaneously. They were probably transported *en bloc* along the channel floor. Similar facies in the Guelph esker have been interpreted by Saunderson (1977, p. 633) as having been deposited "as a sliding bed inside a subglacial tunnel during fullpipe flow".

Cut-and-fill structures are interpreted as filled erosion channels and indicate that the flow was not simultaneous over the whole width of the esker. The normal faults (Fig. 2) may result from the meltout of buried ice in basal parts of the esker or from slumps due to the melting of supporting ice walls (cf. Mc Donald-Shilts 1975, p. 131). The contorted bedding (Fig. 7) may also be interpreted as deformation structures (cf. Reineck-Singh 1973, p. 79) supporting the idea of faulting and slumping.

The discontinuous boulder horizon between units 1 and 2 may have been formed by boulders melting out of the roof of the subglacial tunnel. The existence of ice is also supported by the irregularly bedded material at Drälinge (Fig. 9) which may be interpreted as a kettle caused by the melting of buried ice. The clay horizon at Åsby (Fig. 3) is made up of partly eroded glaciolacustrine sediments.

Unit 2 at Åsby represents a later period of wave-washing and reworking of the glaciofluvial sediments. The stratigraphy in the southern face at Drälinge suggests a deposition of the finer sediments in deeper water with an overlap of coarser shore-line sediments. This sequence regressed down the side of the esker as sealevel fell.

Conclusions

The morphology and stratigraphy of the Uppsala esker at Åsby-Drälinge indicates a subglacial deposition of the esker sediments followed by slumping and burial by glaciolacustrine clays sediments. Subsequent wave-washing and reworking of the glaciofluvial sediments has modified the esker.

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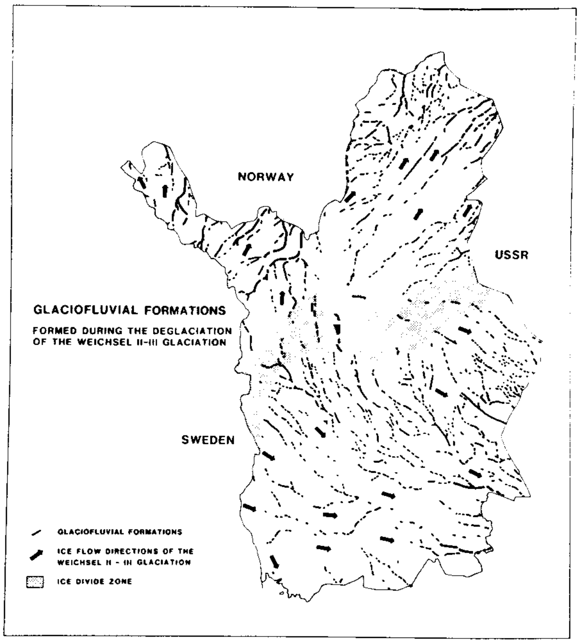

Fig. 1. Map of the glaciofluvial formations formed during the deglaciation of the Late Weichselian glaciation (Weichsel II—III).

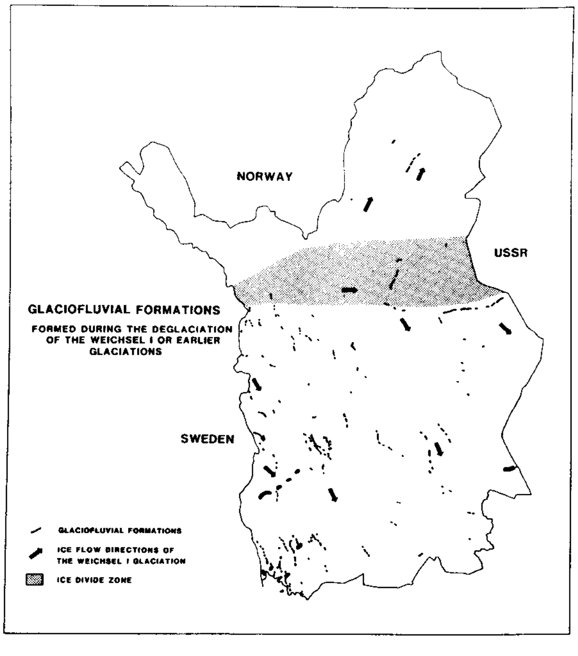

Fig. 2. Map of the glaciofluvial formations formed during the deglaciation of the Early Weichselian glaciation (Weichsel I) or the glaciations preceding it.

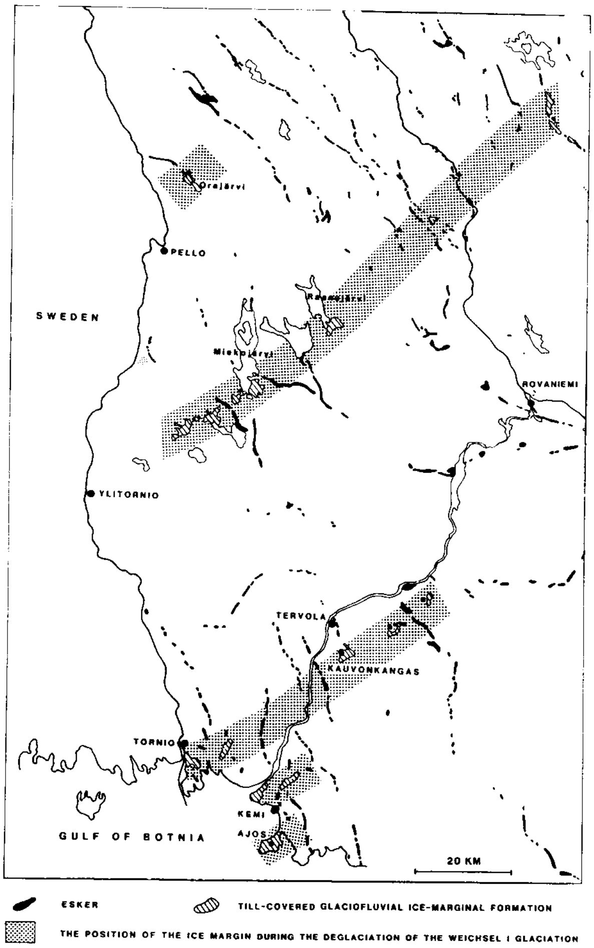

Fig. 3. The till-covered glaciofluvial ice-marginal formations in southwestern Lapland. The shaded zones represent the ice margins of the Early Weichselian glaciation.

elian glaciation flowed from 340°—350° and north of it from 200°—210° (c.f. Hirvas et al. 1977).

The majority of the till-covered glaciofluvial formations are eskers. In addition, till-covered deltas and other glaciofluvial ice-marginal formations, discovered in southern and western Lapland in particular, can be connected with one another to delineate the positions of the margin of the ice sheet during the deglaciation of the Early Weichselian glaciation (Fig. 3). The connecting of the formations to one another is somewhat ambiguous though because the ice-marginal formations were partly obliterated during the Late Weichselian glaciation.

The type of till cover

The till-covered glaciofluvial formations can be divided on the basis of genesis of till overlying them into those covered by ablation till and those covered by basal till. Ablation till (both supraglacial melt-out till and flow till) is met on the glaciofluvial formations that originated during the last deglaciation as a relatively uncompact layer varying in stoniness, especially in the supra-aquatic terrain of northern Finland. In the subaquatic terrain the cover of ablation till is not so common because either it

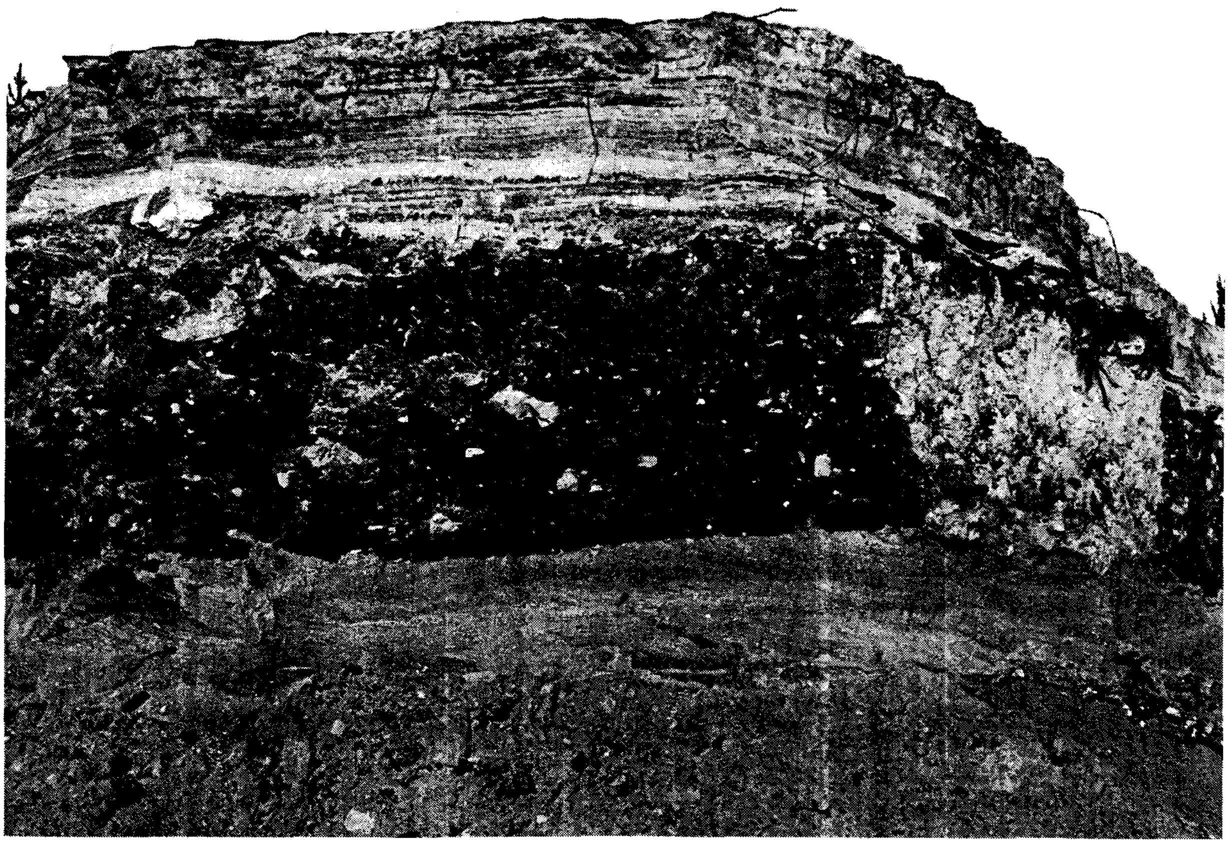

Fig. 4. The till-covered glaciofluvial formation of Sivakkavaara in Kemi. Uppermost lie littoral sediments, then the basal till cover and lowermost the glaciofluvial sand.

has been completely washed away by the action of littoral forces or it has been redeposited as a littoral formation. The formations are usually only partially covered by ablation till varying in thickness from 0.3 to 0.8 m.

The basal till (lodgement, subglacial melt-out and deformation till) covering the glaciofluvial formations (Fig. 4) is from 0.5 to 4.0 m thick, although some markedly higher thickness have been encountered. The basal till cover is typically at its thinnest at the summit of the formations and grows thicker towards the margins. What is more, the till cover is usually thicker on the proximal side than on the distal side of the formation in relation to the ice flow direction (Mäkinen 1981). The basal till overlying the formations is not always continuous, and it may even be altogether absent, especially from the subaquatic areas. Some formations only retain traces of the till cover. Originally the basal till covered the formations everywhere but littoral forces of the Baltic Sea washed away the till cover either partially or completely. Also the Baltic sediments are encountered in subaquatic areas between the basal till that covers the glaciofluvial formation and the overlying littoral deposits.

The flowing ice that produced the basal till bed covering the glaciofluvial formations eroded the underlying formation. The thrust and weight of the ice sheet caused abundant faulting and folding in the sediment layers; this is best seen in the fine-grained sediments. The glacial erosion that affected the glaciofluvial formations also depended on the topographical location of the formations in relation to the direction of the glacier flow. The glacial erosion was relatively slight in those areas in where topographic height differences in elevation are considerable and in which the glaciofluvial formations are located in valleys sheltered in relation to the direction of the ice flow, for example, Meltaus in the valley of the river Ounasjoki, where the eskers deposited in a valley trending NW-SE. The ice sheet flowing from the west only slightly eroded the glaciofluvial formations. The till layer, 0.5—2.0 m thick, covering the formations is not continuous, since in many places the till only covers the western flank of the formation, the eastern flank remaining exposed (Korpela 1969). Because of the weak glacial erosion the original structure of the formations has remained almost untouched.

The age of the glaciofluvial formations

The glaciofluvial formations can be divided into young formations, which originated during the last (Weichsel

Table 1. The age distribution of the glaciofluvial formations in Lapland.

GLACIOFLUVIAL FORMATIONS			
YOUNG FORMATIONS (FORMED DURING THE DEGLACIATION OF WEICHSEL II-III)		OLD FORMATIONS (FORMED DURING THE DEGLACIATION OF WEICHSEL I OR EARLIER)	
NO TILL COVER	TILL-COVERED FORMATIONS	TILL-COVERED FORMATIONS	NO TILL COVER
- ESKERS, DELTAS AND OTHER GLACIOFLUVIAL FORMATIONS.	- ESKERS COVERED BY ABLATION TILL (SUPRAGLACIAL MELT-OUT TILL OR FLOW TILL). - ESKERS, DELTAS AND MARGINAL FORMATIONS COVERED BY OSCILLATION TILL (LODGEMENT TILL, BASAL MELT-OUT TILL OR DEFORMATION TILL). - ESKERS AND DELTAS, WHICH WERE COVERED BY BASAL TILL ACCORDING TO THE SUBGLACIAL SEDIMENTATION.	- ESKERS, DELTAS AND MARGINAL FORMATIONS COVERED BY BASAL TILL (LODGEMENT TILL, BASAL MELT-OUT TILL OR DEFORMATION TILL).	- ESKERS, DELTAS AND MARGINAL FORMATIONS, WHICH WERE AT FIRST COVERED BY BASAL TILL. AFTERWARDS THE TILL COVER WAS WASHED AWAY BY LITTORAL FORCES. - ESKERS, DELTAS AND MARGINAL FORMATIONS, WHICH WERE NEVER COVERED BY TILL.

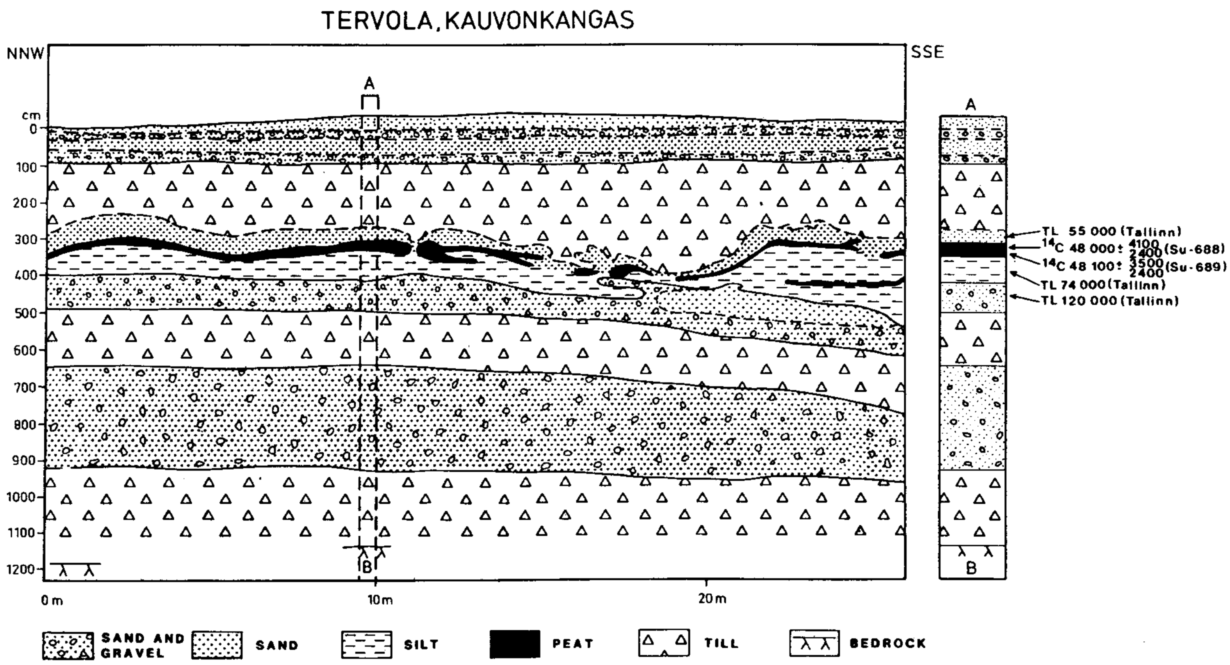

Fig. 5. The stratigraphy, grain-size distribution, thermoluminescence and ^{14}C ages of the till-covered glaciofluvial ice-marginal formation at Kauvonkangas.

II—III) melting stage of the continental ice sheet, and old ones, which formed during the melting stages of the glaciations (Weichsel I or earlier stages) preceding the last glaciation (Table 1). When dating the glaciofluvial formations it is important to take into account their stratigraphic location, sedimentation environment, the type of till covering the formations, the fabric and lithology of the stones in the till and also the age and pollen composition of the organic deposits in the till or between the till and the underlying glaciofluvial formation.

Young formations

The young formations include formations that deposited during the deglaciation of the last glaciation and also formations covered by ablation till that obtained their till cover as soon as the deposition of the glaciofluvial material ended during the last deglaciation. The young formations also include the formations covered by basal till as a result of subglacial sedimentation or oscillation of the ice sheet during the deglaciation of the Late Weichselian glaciation.

Fig. 6. Gyttja sediments at Ajos.

Old formations

After the deposition of the glaciofluvial formations older than the last deglaciation the ice sheet advanced at least once, giving rise to the overlying basal till. Numerous stratigraphic observations and fabric analyses in the till covering the formations have been carried out to date these formations. The fabric analyses indicate that the ice flow direction was from west to east or from west-northwest to east-southeast in southern and central Lapland, corresponding to the directions of ice flow during the Late Weichselian glaciation in these areas (Hirvas et al. 1976).

Organic deposits with Betula-predominant pollen flora indicating a cold interstade have been found in the lower parts of the till bed covering the glaciofluvial formations and between the till and the underlying formation.

The glaciofluvial ice-marginal formation at Kauvonkangas (56 m above sea level), in Tervola, is covered by a till layer 2.5 m thick (Mäkinen 1979). At the base of the till there is a peat layer up to 0.3 m thick (Fig. 5). The peat layer is exposed in a section for 25 to 30 metres, but the same horizon with the organic constituents mixed with the till can be traced north of the section for at least 100 metres. The peat layer has abundant bush-like birch twigs from 0.5 to 2.0 cm thick. The pollen flora of the peat layer is Betula-predominant, representing the flora of a cold interstade (Table 2). The climate was subarctic and the vegetation tundra-like. The peat was dated at 48 000 $^{+4100}_{-2400}$ BP (Su 688) and 48 100 $^{+7200}_{-3800}$ BP (Su 689) by the ^{14}C-method. The sand samples from the ice-marginal formation were submitted to thermoluminescence dating that gave ages 55,000, 74,000 and 120,000 years (Punning and Raukas 1983). The fabric of the covering till is 280° in accordance with the directions of ice flow in the area during the Weichsel II—III glaciation (Hirvas et al. 1977). Another till layer, in which the fabric of the stones (340°) coincides with that of the ice flow during Weichsel I, has been encountered beneath the glaciofluvial sediments in the proximal margin of the formation.

The ice-marginal formation at Ajos (20 m above sea level), near Kemi, is covered by a 0.3—5.0 m thick basal till, in which the fabric of the stones is 310°. This represents the ice flow direction of the Weichsel II—III glaciation in the Kemi area. When the ice advanced over the formation it eroded the topmost portion of the formation. The thrust and weight of the continental ice produced abundant faults and folds in the glaciofluvial sediments. Similar folds were described by Näykki and Vasari from Ajos in 1963.

Organic sediments have been found beneath the till at two sites in the formation. In the northern end of the formation there is gyttja between the glaciofluvial formation and the overlying basal till. The gyttja originally constituted a continuous layer but the Weichsel II—III ice sheet that flowed over it deformed the original structure by faulting and displacing the gyttja to various levels. The preservation of the original layer and the nature of the deformation structures suggest that gyttja has been displaced for only a few meters from its original position.

A glaciolacustrine or glaciomarine deposit containing also gyttja has been encountered in the middle part of the formation between the glaciofluvial sediments and the overlying basal till. The organic deposits are largely undeformed and *in situ* (Fig. 6). Here, as in the northern part of the formation, flowing ice has given rise to the glaciotectonic deformation structures in the western end of the organic deposits, which are in the proximal part of the formation.

The pollen flora in both gyttja deposits at Ajos are Betula-predominant (Table 2), representing the interstadial flora of a cold climate. The ^{14}C ages of the gyttja in the northern part of the formation are 42 800 ± 1 100 BP (Su 1283) and over 53 000 BP (Su 1284). The *in situ* deposit has been dated at 46 000 $^{+2900}_{-2100}$ BP (Su 1188) years.

The ice-marginal delta (140 m above sea level) and the associated esker at Orajärvi, Pello, are covered by a 1.0—4.0 m thick basal till, at the base of which gyttja has been found at several sites intermixed with till. The pollen of the gyttja is Betula-predominant (Table 2) and represents a cold interstadial type of pollen flora. Several ^{14}C datings have been done on the gyttja, the results fluctuating between 42 900 ± 1 600 BP (Su 1186) and >51 700 BP (Su 754) years.

In the late 1970s wedges filled with till were found in the Orajärvi formation at the boundary between the basal till covering the formation and the underlying glaciofluvial sediments. The wedges (Fig. 7), exhibit a network of polygons on the surface of the glaciofluvial formation. Before the Weichsel II—III glaciation, periglacial conditions prevailed in the Orajärvi area and a network of ice wedges developed in the fine-grained glaciofluvial sediments on the surface of the ice-marginal formation. When the ice flowing over the formation started to melt the melting ice wedges were gradually filled with the till that covered the formation. Fabric analyses on the wedges demonstrate that the stones have an almost exclusively vertical orientation. The orientation of the stones in till covering the formation is 270°, in accordance with the directions of ice flow during the Late Weichselian glaciation in the area.

Table 2. The pollen content of the peat and gyttja layers of Kauvonkangas, Ajos and Orajärvi.

SITES	DEPTH m	BETULA %	PINUS %	PICEA %	ALNUS %	OTHERS %	AP %	NAP %	SP %
KAUVONKANGAS	3,6	94,0	4,0		2,0		70,0	28,0	2,0
	3,7	95,0	4,0	1,0			65,0	32,0	3,0
	3,8	98,0	2,0				76,0	21,0	3,0
AJOS	2,93	83,3	12,5		4,2		38,9	58,4	2,7
	2,96	85,0	13,0		2,0		57,5	40,2	2,3
ORAJÄRVI	2,5	97,0	1,0			CORYLUS 1,0 QUERCUS 1,0	19,5	78,7	1,8
	3,2	98,0	2,0				65,1	32,3	2,6
	4,1	95,5	2,0		2.0	CORYLUS 0,5	50,0	48,9	1,1

Organic matter has been found in the Orajärvi formation both in the basal till cover and in the wedges developed in the glaciofluvial sediments. Gyttja was introduced into the wedges during the deglaciation of the last glaciation when the till covering the formation filled the ice wedges. It is also feasible that gyttja got into the wedges before the last glaciation. In that case the ice wedges melted and froze, depending on the season, under periglacial conditions. Gyttja may have moved into partly or completely melted wedges during the summer months.

The pollen flora of the organic deposits in the basal till covering the glaciofluvial formations and between the till and the underlying formation is *Betula*-predominant and reflects the flora of a cold climate. The pollen flora of the formations is equivalent to that of the Peräpohjola interstade by Korpela (1969) and that of the Jämtland interstade by Lundqvist (1967, 1974). The ^{14}C datings of the formations vary between 42 800 ± 1 100 BP (Su 1283) and >53 000 BP (Su 1284) years and are compatible with those of the Peräpohjola interstade by Korpela, i.e. 45 400 ± 2 000 BP years and with that of the Jämtland interstade by Lundqvist, i.e. >40 000 years. Moreover these formations deposited at levels that were distinctly below the surface of the ancient Baltic Sea when the ice withdrew from western Lapland during the Ancylus stage. At that time the surface of the Ancylus lake was at 196 m in the Pello and at c. 215 m in Tervola area.

Since the formations are stratigraphically overlain by basal till generated during the youngest glaciation (Weichsel II—III) and since there are organic layers that deposited during the Peräpohjola interstade on the formations, they were generated before the Peräpohjola interstade.

Summary

The glaciofluvial formations in Lapland can be divided into young ones, i.e. those deposited during the deglaciation of the Weichsel II—III glaciation, and old ones, i.e. those deposited during the melting stage of the Weichsel I glaciation or the glaciations preceding it. In addition to the uncovered formations the young formations also include glaciofluvial sediments covered by ablation till and by basal till due to the subglacial sedimentation or oscillation of the ice margin during the last deglaciation.

The old formations include those covered by basal till, because at least one glaciation giving rise to the layer of basal till overlying the formations took place after deposition. The ^{14}C ages, 42 800 — >53 000 years, of the organic deposits encountered in the lower parts of the basal till and between the till and the underlying formations and also the Betula predominance of their pollen indicate that the organic deposits were formed during the Peräpohjola interstade and the underlying glaciofluvial formations were formed during the deglaciation of the Weichsel I glaciation or the glaciations preceding it.

Fig. 7. Ice wedges filled with the till, which is overlying the glaciofluvial ice-marginal formation at Orajärvi in Pello.

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