Late Pleistocene glacial-deglacial facies successions and geologic history at Vuolgamasjåkka, Finnmarksvidda, Norway

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A 50 m high river section at Vuolgamasjåkka, Finnmarksvidda, Norway, has been studied with regard to lithofacies, glaciotectonics and geologic history. Six formations reveal a history of four glacial events and two deglacial events spanning the Weichselian back to the Saalian. Ice-free conditions are represented by deglacial sediments consisting of proximal to distal outwash facies and, at one horizon, delta foreset beds deposited in an ice-dammed lake. These sediments occur together with tills in stacked glacial-deglacial successions. Four kinetostratigraphic units are recognized on the basis of glaciotectonic structures, till fabrics and palaeocurrent directions. Glaciotectonic structures were formed in both frozen and unfrozen sediments during successive glacier advances.

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Thick till sheets and subtill and intertill sorted sediments on the inner Finnmark plateau (Finnmarksvidda) of northern Norway (Fig. 1) record a history of multiple glacial phases and intervening ice-free periods extending back through the Weichselian and earlier (Olsen & Hamborg 1983, 1984; Olsen 1988, 1989). One of the longest and most complete succession of till-intertill sediments occurs in a 50 m high river section at Vuolgamasjåkka

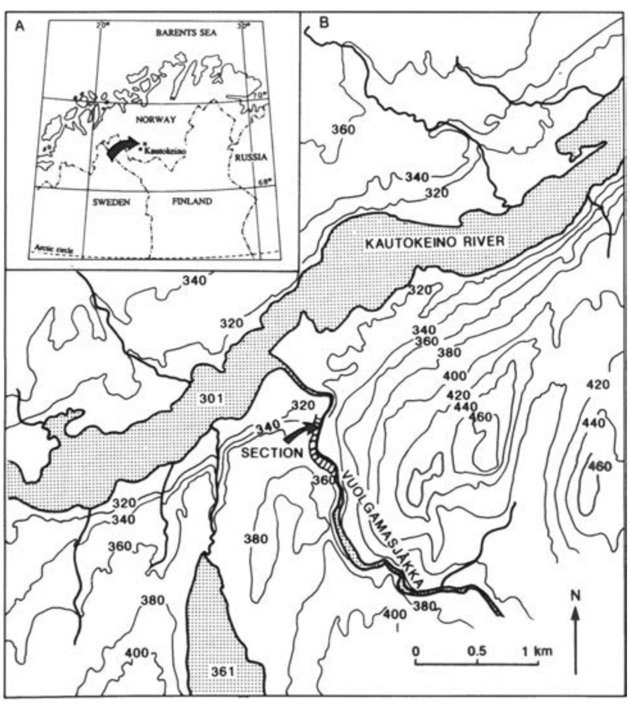

Fig. 1. Map showing the location of (A) Vuolgamasjåkka area on Finnmarksvidda, 18 km northeast of Kautokeino, northern Norway, (B) the section at Vuolgamasjåkka river. The Kautokeino river drains towards the northeast. Elevations in meters.

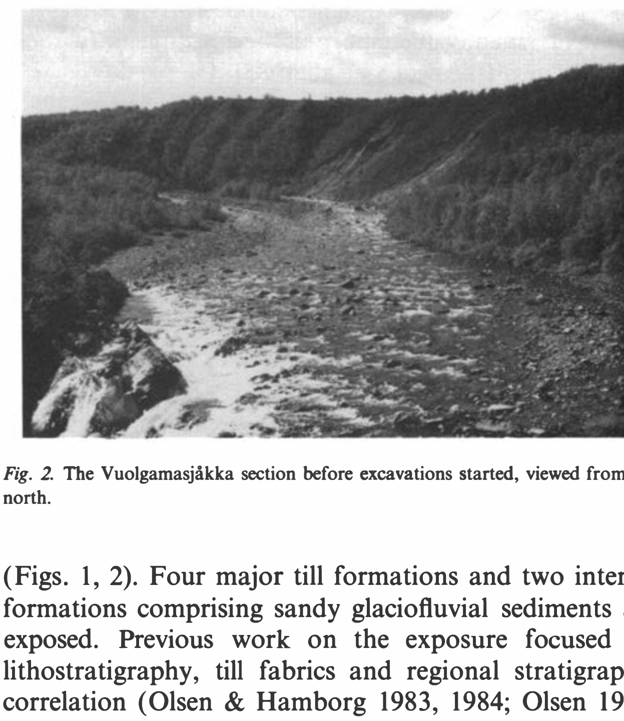

Fig. 2. The Vuolgamasjåkka section before excavations started, viewed from the north.

(Figs. 1, 2). Four major till formations and two intertill formations comprising sandy glaciofluvial sediments are exposed. Previous work on the exposure focused on lithostratigraphy, till fabrics and regional stratigraphic correlation (Olsen & Hamborg 1983, 1984; Olsen 1988, 1989). The present article presents the results of a detailed study of the sedimentary succession at Vuolgamasjåkka, with emphasis on lithofacies, interpretation of depositional environment, glaciotectonic structures and till fabrics. The results show that the lithostratigraphic units can be grouped into two major glacial-deglacial successions, capped by a multiple till succession (Figs. 3, 4).

Location and setting

Vuolgamasjåkka is a tributary stream of the Kautokeino river (Fig. 1). The topography consists of a low-relief

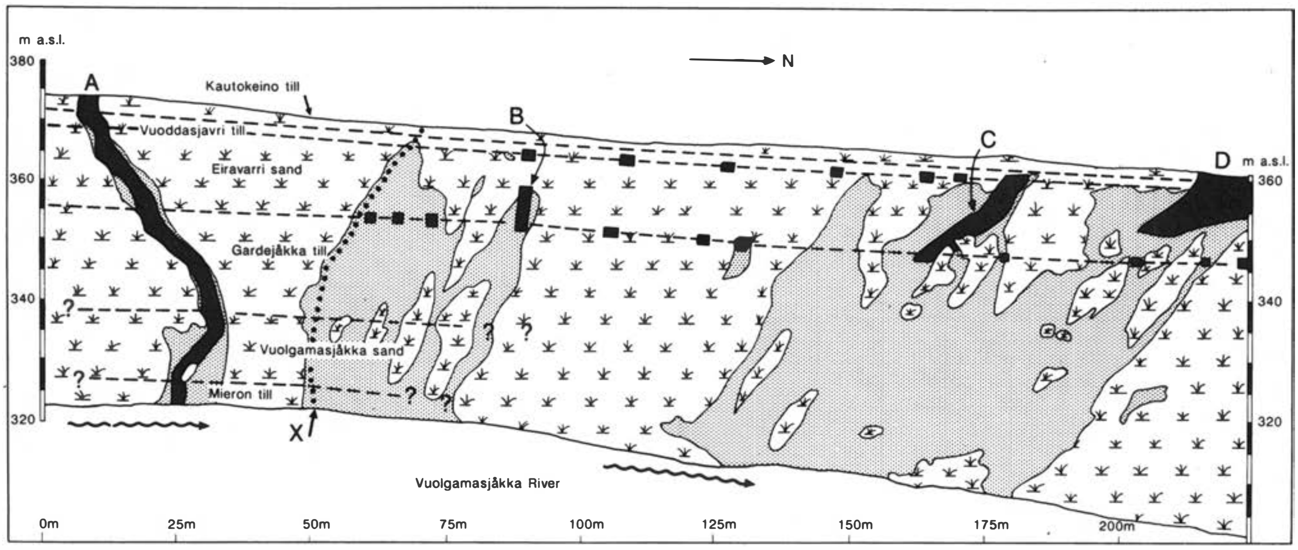

Fig. 3. Sketch of the Vuolgamasjåkka section showing formation boundaries. Black areas represent investigated profiles. The main profiles (A–D) are indicated. The profile line (X) studied by Olsen & Hamborg (1983, 1984) is shown dotted. The shaded area is covered with colluvium, the remainder vegetated.

undulating moraine plateau, 300–400 m a.s.l. Bedrock, exposed only on promontories and in incised valleys (Fig. 2), consists of Archaean and Early Proterozoic basement (mainly metamorphic and sedimentary rocks and granites) (Siedlecka et al. 1985).

The partly exposed, partly vegetated 50 m high, 225 m long exposure was studied at 4 main sections (profiles A–D, Fig. 3). The sections are located close to sections 1–4 of Olsen (1989) and include a continuous vertical profile (A) situated 25 m south of a comparable profile studied by Olsen and Hamborg (1983). In addition, numerous small sections were studied in order to trace major lithological boundaries laterally.

Stratigraphic framework

The sedimentary succession at Vuolgamasjåkka is divided into six informally named formations (Olsen 1988). These are, from bottom to top (Figs. 3, 4): Mieron till, Vuolgamasjåkka sand, Gardejåkka till, Eiravarri sand, Vuoddasjavri till and Kautokeino till. Based on local TL-dates and regional lithostratigraphic and till fabric correlations of younger tills, the Mieron till and Vuolgamasjåkka sand are thought to be of pre-Eemian and Eemian age, respectively, while the overlying Gardejåkka till and Eiravarri sand are thought to be of Early Weichselian age (Olsen 1988, 1989). An interstadial of possible Middle Weichselian age (Sargejåk interstadial) is thought to separate deposition of the two uppermost formations, the Vuoddasjavri till and the Kautokeino till (Olsen 1988, 1989).

Methods

Sediment texture was recorded in the field using a modified Udden–Wentworth–Krumbein scale (Shea 1973) and a facies code to denote all main fractions comprising >5% (Table 1). Grain-size analysis was carried out in the laboratory using pipette analysis for the <63 μm fraction, and wet or dry sieving for the >63 μm fraction. In the field, sieving was carried out on some samples for fractions 16 mm to 128 mm using sample weights of 25–100 kg.

Orientation measurements are given uncorrected for the local declination deviation (2° in 1992). Fabric analysis was carried out on clasts having an a/b axis ratio >1.5. The results are plotted and contoured on a Schmidt net (lower hemisphere) and statistical eigenvalues S_1, S_3, and eigenvector V_1 calculated. Till fabrics generally show a strong orientation and all are statistically significant at the 99% confidence level (Woodcock & Naylor 1983).

Table 1. Lithofacies codes for sorted sediments at Vuolgamasjåkka based on texture (adapted from Washburn et al. 1963 and Corner 1977).

Facies code	Description	Constituent fractions (>5% in total) in order of amount	Occurrence (no. of beds in section)
bG	bouldery gravel	cbsG	1
cG	cobbly gravel	scG	7
sG	sandy gravel	sG, csG	3
cS	cobbly sand	gcS	3
gS	gravelly sand	gS	23
S	sand	S	50
pS	pelitic sand	pS	15
qS	gravelly pelitic sand	gpS	7

Sediment type and texture

Sorted sediments and diamictons are subdivided into lithofacies types based on grain size and sedimentary structures (Tables 1–3).

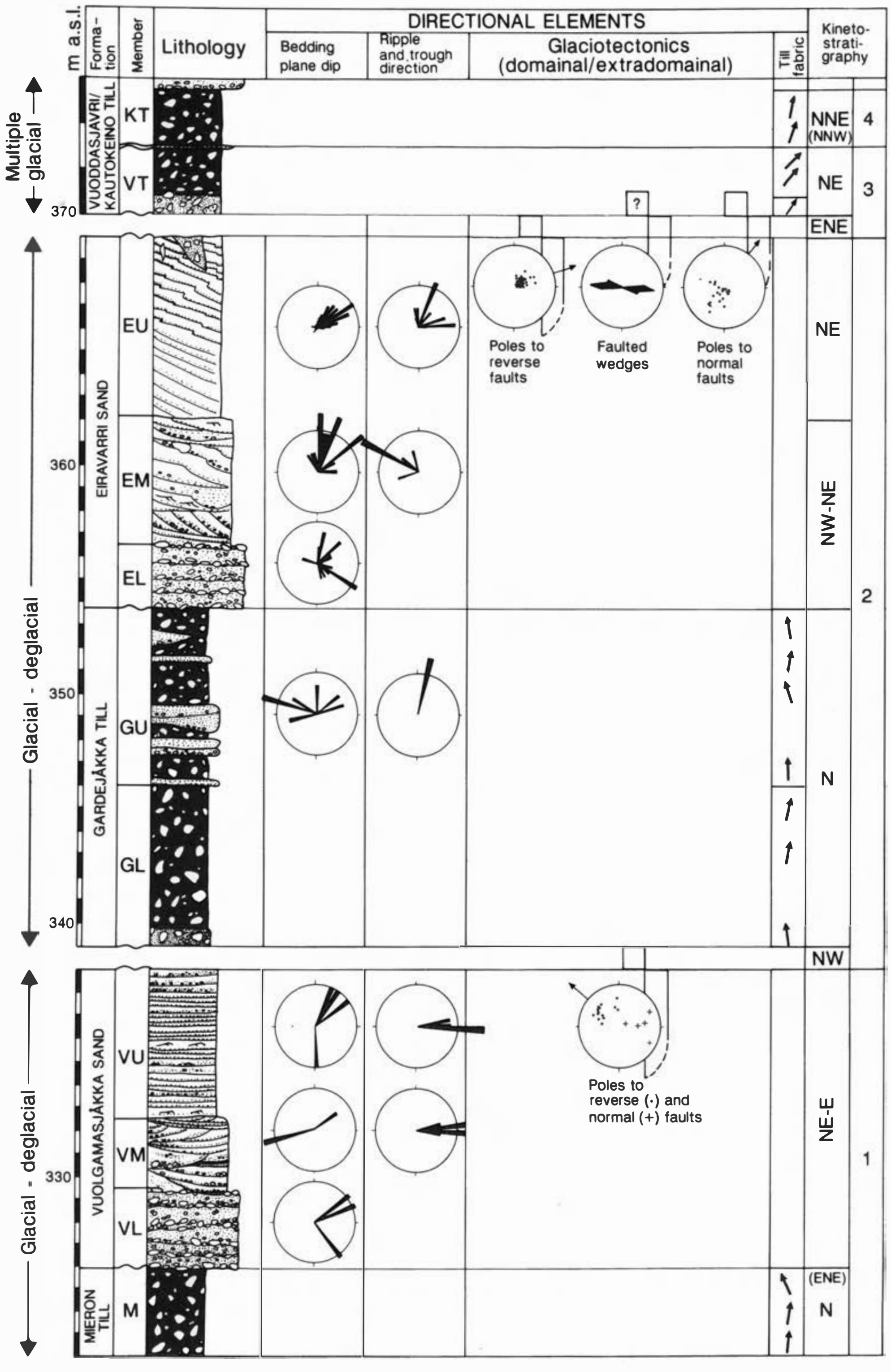

Fig. 4. Composite litho- and kinetostratigraphy at Vuolgamasjåkka. For details on lithofacies, palaeocurrent and till fabrics, see Figs. 7, 8, 10, 12 and 14. The four kinetostratigraphic units are numbered 1–4. Kinetostratigraphic directions in parentheses are after Olsen (1988).

Sorted sediments show considerable diversity in grain size, sorting and type of bedding structure (Fig. 5). Facies are subdivided primarily on the basis of texture (component main fractions >5%) and secondarily on the basis of structure (Tables 1, 2).

The diamictons are essentially non-sorted sediments comprising tills that have been deposited directly by the glacier or reworked by glacial processes (Table 3). They show a relatively uniform composition, having a matrix mode in the very coarse silt to medium sand fraction, and a subordinate clast mode in the very coarse gravel fraction (Fig. 6). A minor but significant difference is shown between silty sandy tills of the Mieron Till (Fig. 6A) and tills from overlying

Table 2. Lithofacies codes for bedding types among sorted sediments at Vuolgamasjåkka, and their interpretation (based partly on Miall 1977 and Eyles et al. 1983).

Facies code	Description	Occurrence (facies types)	Interpretation
Horizontal/subhorizontal stratification:			
m	massive to crudely bedded	cGm, sGm, gSm, Sm, qSm, pSm	longitudinal bars, debris flow, waning flood deposits
h	horizontal/subhorizontal (parallel bedding)	bGh, cGh, sGh, cSh, gSh, Sh, pSh	longitudinal bars, lag deposits, planar bed flow (lower and upper flow regime)
l	low-angle cross-bedding	gSl, Sl, qSl, pSl	scour fills, waning flood deposits
c	scour-and-fill, crude trough cross-bedding	gSc, Sc, pSc	scour fills, minor channel fills
p	planar cross-bedding	Sp	transverse bars, magaripples
r	ripple cross-bedding	pSr, Sr	ripples
d	deformed bedding	pSd, Sd	slump, liquefied flow
Inclined (large-scale foreset) stratification:			
f	parallel laminated	cSf, gSf, Sf, qSf	grain flow, turbidity current, suspension settling
fm	massive	gSfm, qSfm	turbidity current, debris flow
fl	low-angle cross-bedding	Sfl	turbidity current
fr	ripple cross-bedding	Sfr, pSfr	ripples, turbidity current
fd	deformed beds	Sfd, qSfd, pSfd	slump, liquefied flow

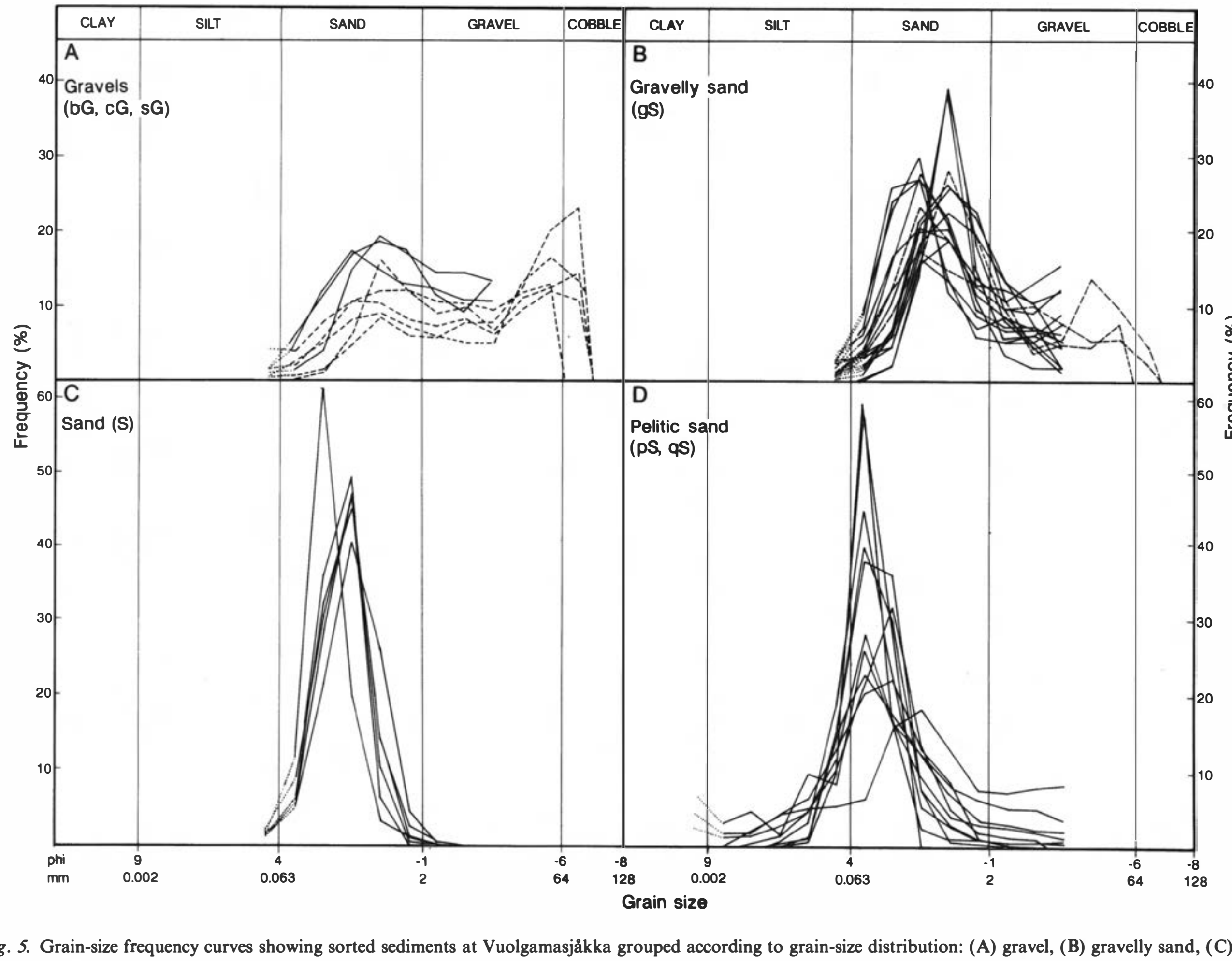

Fig. 5. Grain-size frequency curves showing sorted sediments at Vuolgamasjåkka grouped according to grain-size distribution: (A) gravel, (B) gravelly sand, (C) sand, (D) pelitic sand. Continuous lines represent grain-size distribution for samples < 16 mm. Dashed lines represent grain-size distributions for samples < 128 mm. Dotted lines indicate the total amount of fines (clay) in the unanalysed part of the sample.

Table 3. Lithofacies codes and inferred genesis of glacial diamictons at Vuolgamasjåkka.

Facies code	Description	Interpretation
Dm	Massive diamicton, normal silty-sandy composition	Lodgement and basal melt-out till
Dms	Massive diamicton with thin sand lenses and linings around clasts	Lodgement and basal melt-out till
sDm	Massive, sand-enriched diamicton, occasionally heterogeneous	Deformation till containing sand eroded from local substrate, and melt-out till
gDm	Massive, gravel-enriched diamicton, occasionally heterogeneous	Melt-out till

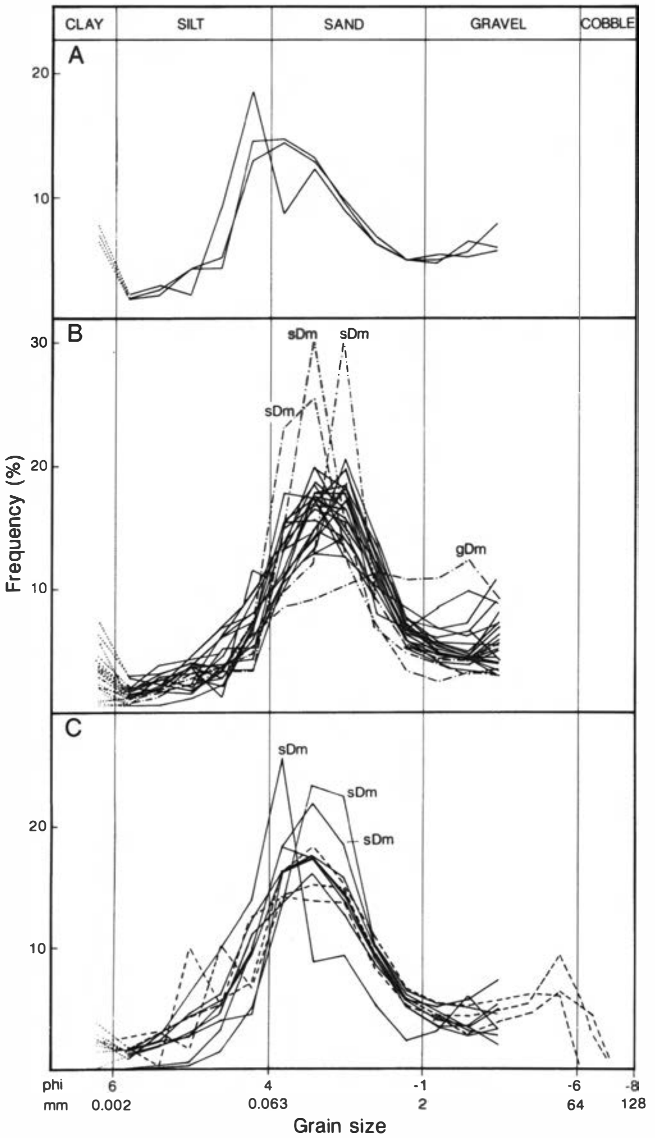

Fig. 6. Grain-size frequency curves of diamictons at Vuolgamasjåkka from (A) the Mieron till formation, (B) Gardejåkka till formation, (C) Vuoddasjavri and Kautokeino till formations. See Fig. 5 for an explanation of the different line types. Dot-dashed lines (labelled with facies code) depict aberrant curves which represent remixed sorted sediment (deformation till).

formations which have a slight coarser, sandier composition.

Lithostratigraphy, facies interpretation and directional elements

Mieron till

The base of the Mieron till (Fig. 7) is not exposed, but bedrock occurs in the stream bed just below profile A (Fig. 3). Mieron till is a well-consolidated, massive, silty sandy diamicton (Dm). It is interpreted as a subglacial till, probably of lodgement origin (Dreimanis 1988). Three clast-fabric analyses (Fig. 7) show N to NNE orientation in the lower and middle part of the formation, and a weak NNW orientation in the upper part, indicating glacier movement generally towards the north.

Vuolgamasjåkka sand

The Vuolgamasjåkka sand is 13 m thick at profile A (Fig. 3) and is divided into three members (VL, VM and VU, Fig. 8). Stratification within the studied section is subhorizontal with major bedding planes generally dipping ca. 5° towards the northeast to east.

Member VL. – The lower member erosively overlies the Mieron till and consists of coarse, poorly sorted, massive to weakly stratified gravel and gravelly sand. Some beds contain intermittent horizons or lenses of fine sand and sandy silt.

The predominantly coarse texture, poor sorting and weakly developed subhorizontal stratification of member VL suggest deposition in an ice-proximal glaciofluvial environment. The weakly stratified gravelly sediment is

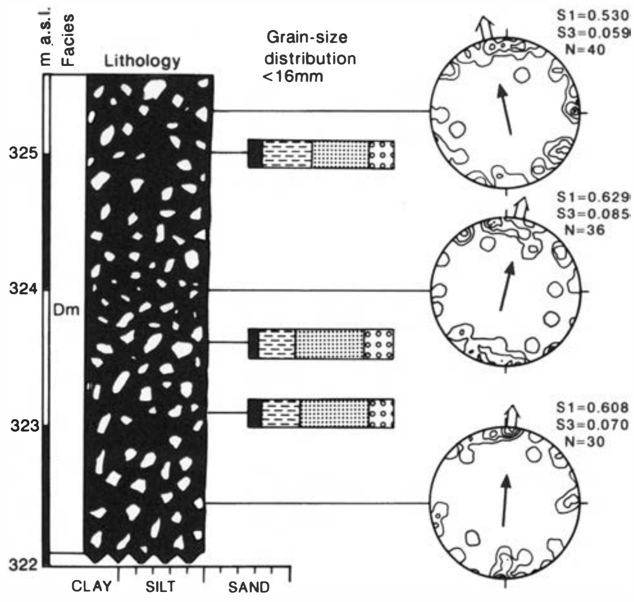

Fig. 7. Lithologic log of the Mieron till. Legend in Fig. 10. The open arrow outside the stereonet is the eigenvector, the single arrow inside is the inferred ice-movement direction.

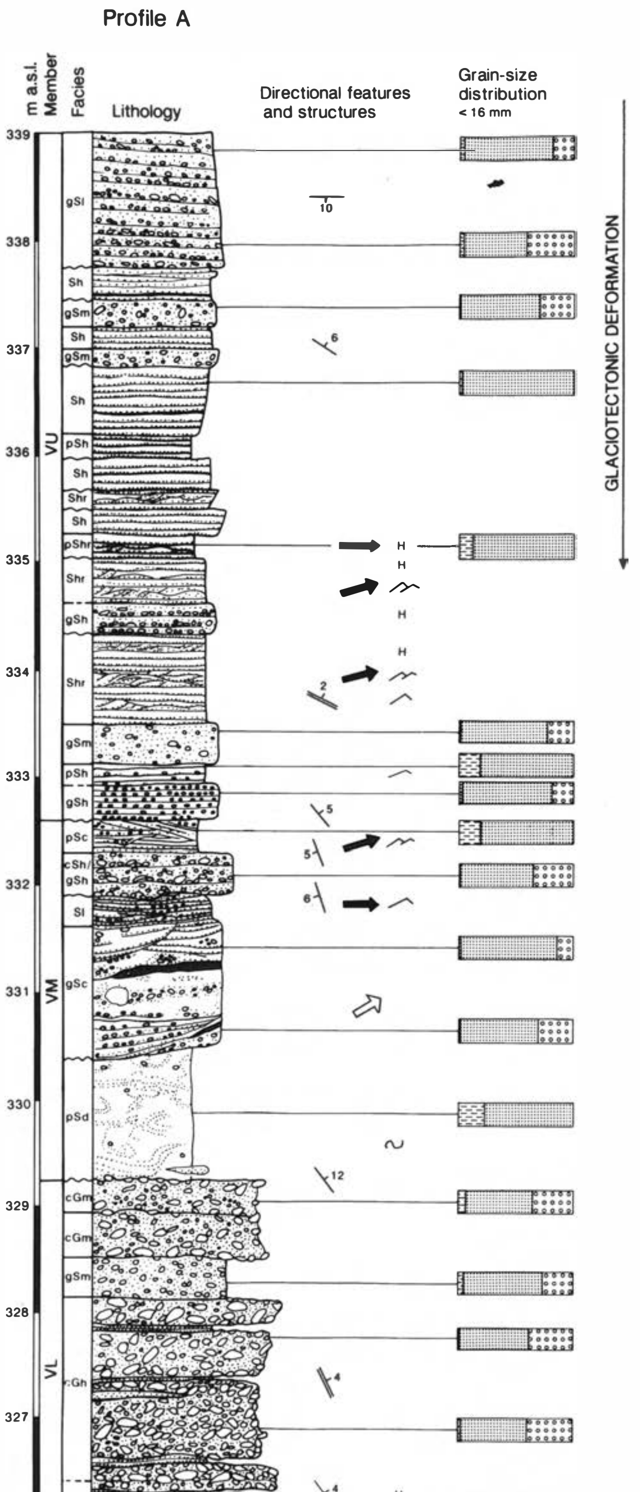

Fig. 8. Lithostratigraphic log of the Vuolgamasjåkka sand formation. The uppermost glaciotectonically faulted part is drawn in its reconstructed undisturbed form. Legend in Fig. 10.

characteristic of longitudinal bar deposits formed predominantly during high flow-stage; finer horizons and lenses represent remnants of low flow-stage deposits (cf. Miall 1977, 1978; Ashley et al. 1985).

Member VM. – This member consists of a heterogeneous assemblage of horizontally bedded, cross-bedded and deformed bedded, gravelly and cobbly sand, sand and pelitic sand (Fig. 9A). In addition to considerable facies diversity, the unit also displays local poor sorting and frequent, scattered, outsized ice-rafted clasts. A liquefaction-deformed bed of pelitic sand occurs at the base. Palaeocurrent directions derived from trough axes and ripple foresets suggest flow towards the east.

The sediments indicate variable energy conditions associated with channel abandonment, fill and partial reactivation in a proximal glaciofluvial outwash environment (cf. Fraser 1982; Fraser & Cobb 1982; Thomas & Connell 1985; Weddle 1992). Slightly finer grain-size than in underlying member VL probably indicates more distal conditions.

Member VU. – Member VU comprises parallel-laminated sand and pelitic sand with subordinate ripple bedding, together with occasional massive or laminated beds of gravelly sand. Heavy-mineral lamination, climbing-ripple cross-lamination, isolated sand lenses and local minor scour surfaces also occur (Fig. 9B). Glaciotectonic faulting pervades the upper 4 m of the member.

The facies indicate fluctuating discharge and sediment supply. Deposition, under upper and lower flow regime conditions and from suspension settling, probably took place on low-relief bars or interchannel flats in a distal glaciofluvial outwash environment (Boothroyd & Ashley 1975; Cant & Walker 1978). Palaeocurrent directions measured on ripple foresets indicate an easterly flow direction.

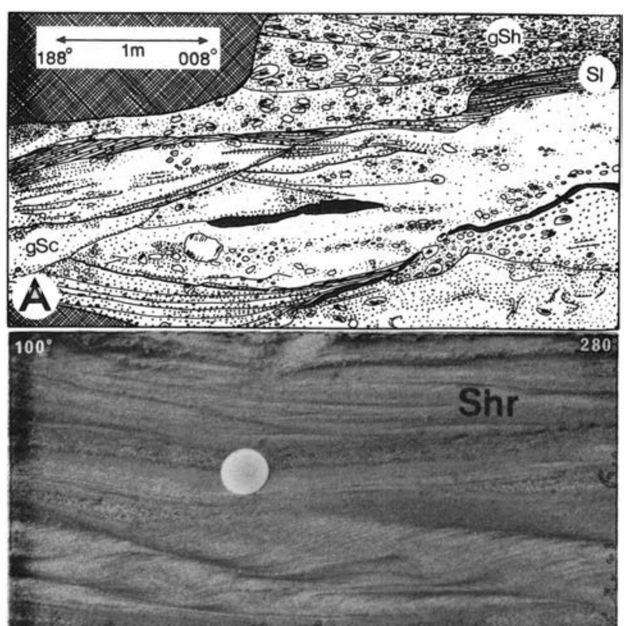

Fig. 9. Selected lithofacies from the Vuolgamasjåkka sand. (A) Sketch from the member VM showing poorly sorted, slightly deformed assemblage of parallel and cross-bedded gravelly sand (gSc, gSh) and sand (Sl) with intermittent pelitic layers. (B) Horizontal and ripple-bedded sand (Shr), member VU.

Depositional environment of the Vuolgamasjåkka sand. – The Vuolgamasjåkka sand is interpreted as a glaciofluvial outwash deposit formed during progressive retreat of the ice margin. Within a sedimentary environment of repeatedly ice advance and retreat, glaciofluvial sedimentation in subglacial conditions may also occur, and may show some similarities with outwash deposits. However, the total thickness of ca. 13 m of upward fining sediments (Figs. 4, 8), in addition to the large lateral extent (Fig. 3), suggest that the Vuolgamasjåkka sand was deposited proglacially rather than subglacially. Palaeocurrent directions towards the northeast to east (Figs. 4, 8) indicate that the formation was deposited during ice-retreat towards the W to SW.

Gardejåkka till

The Gardejåkka till formation is 14.8 m thick at profile A. The upper few meters of the formation were also studied at profiles B and C (Fig. 10). The formation consists of two members: a lower diamicton member (GL) and an upper member comprising alternating beds of diamicton and sorted sediments (GU).

Member GL. – The Gardejåkka till has an irregular, erosional base. The lowermost part consists of a 0.5 m thick sand-rich diamicton containing sand derived from the underlying Vuolgamasjåkka sand (sDm) (cf. Fig. 6B). A fabric analysis shows a N to NNW orientation (Fig. 10). This bed is interpreted as a deformation till (cf. Elson 1988). The remaining 6.5 m of the member consists of texturally homogeneous, fine sandy diamicton having generally massive structure, except for thin (1–2 mm) sand laminae occurring locally either as lenses (up to 35 cm wide) or as cavity linings around clasts (Dms). The degree of consolidation is moderate compared with the Mieron till, and appears to decrease upwards. Two fabric analyses from the upper part show a well-developed N to NNE orientation (Fig. 10). The diamicton is interpreted as a subglacial till, of lodgement or melt-out origin (cf. Dreimanis 1988). The glacier that deposited member GL is considered to have moved generally towards the north.

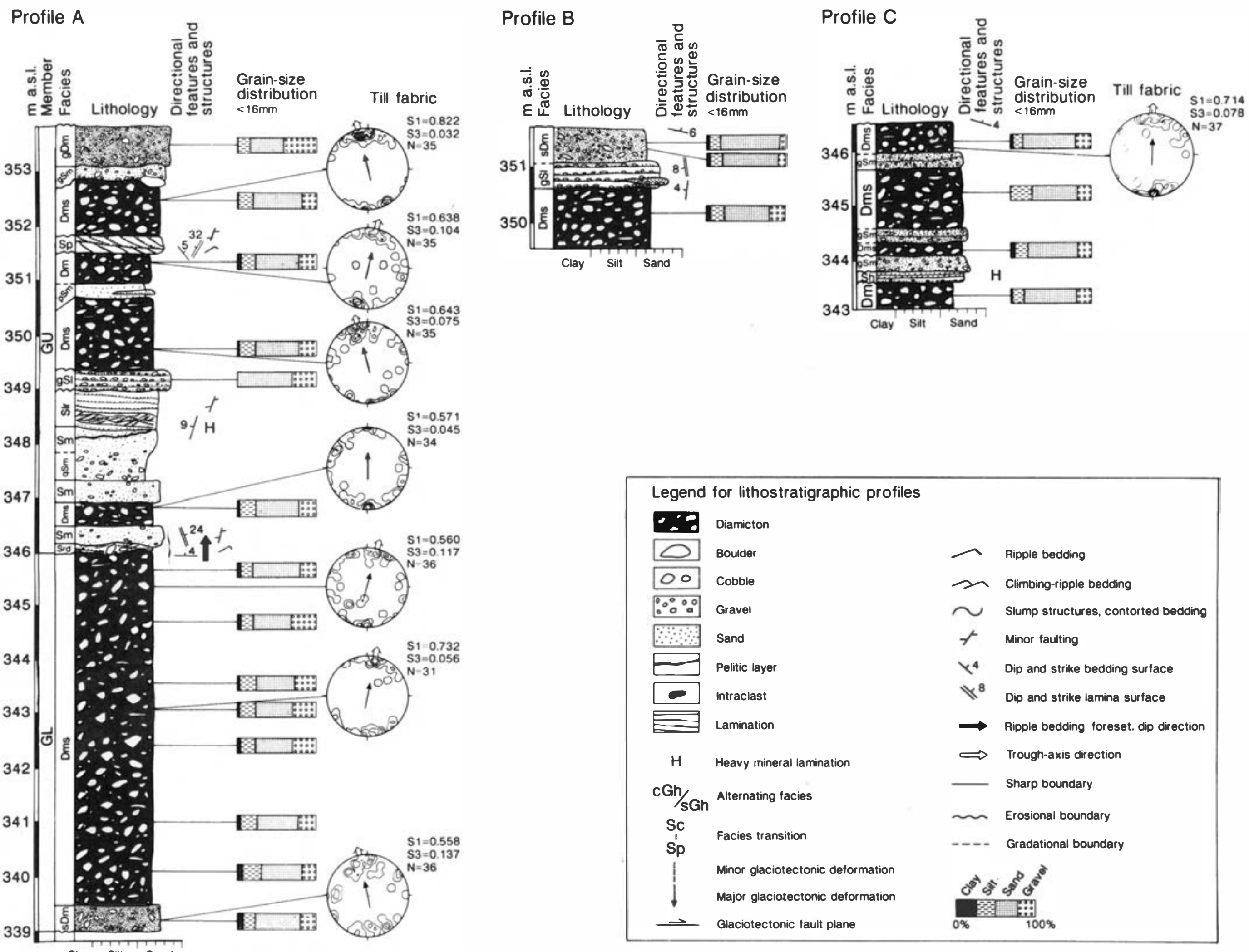

Fig. 10. Lithostratigraphic log of the Gardejåkka till formation at profiles A, B and C. For location of profiles, see Fig. 3. The stereonets are explained in Fig. 7.

Member GU. – The upper member consists of beds of sandy diamicton (up to 1.3 m thick) alternating with beds of sorted sediment (Figs. 10, 11). The diamictons are fairly similar texturally to those in member GL, showing a predominance of Dms facies, except at the very top where sandy (sDm) and gravelly (gDm), heterogeneous diamicton beds occur. The degree of consolidation is less than in the underlying member and decreases upwards. Clast-fabric analyses from the till beds (Fig. 10) show a slightly variable orientation, varying between NNW and NNE.

The sorted sediments consist mostly of sandy and gravelly sandy sediments. Bedding includes massive and horizontal bedding, and medium to small-scale cross-bedding. Some outsized clasts (Fig. 11) show small-scale deformation beneath them. Ripple orientation measured at one horizon indicates a northerly meltwater flow direction.

The facies assemblage indicates alternating subglacial deposition of melt-out till and glaciofluvial sediment. The presence of thick, poorly consolidated beds of Dms-facies till and decreasing-upwards consolidation suggest that deposition took place beneath a debris-rich, down-melting, stagnant body of ice. The uppermost gravelly and sandy diamicton beds (profiles A and B, Fig. 10) may have been deposited as supraglacial melt-out till. The generally northerly direction shown by the till fabrics suggests similar ice-movement direction as for the lower member GL.

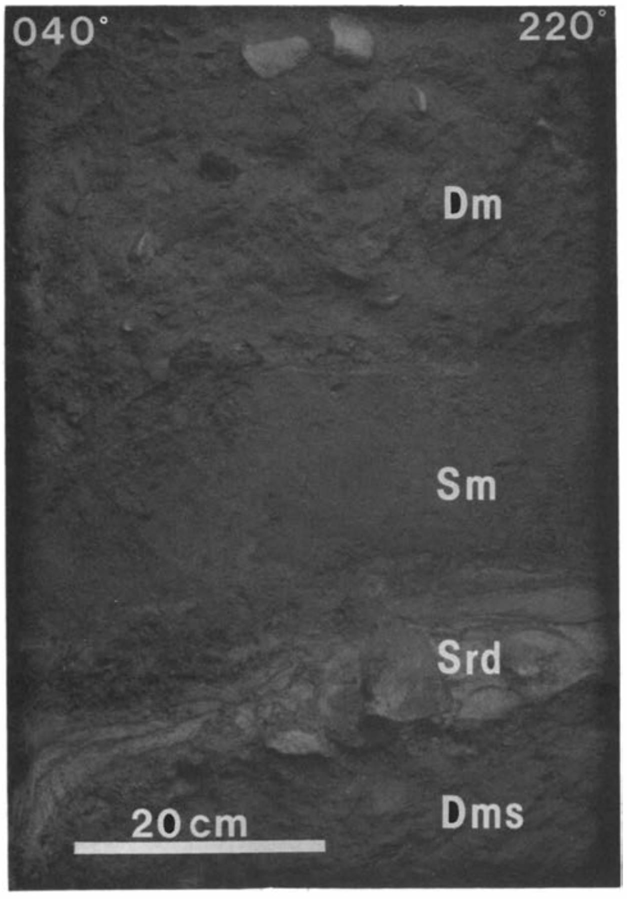

Fig. 11. Lithofacies of the upper Gardejåkka till.

Eiravarri sand

This formation is exposed laterally over a distance of about 225 m (Fig. 3). It was studied in detail at four sections (Fig. 12). The formation rests on the gently inclined (2–4°), north to northeastward sloping surface of the Gardejåkka till. It has an erosional upper boundary and thins distally from 16 m in the south to 11 m in the north. The formation is divided into three members (EL, EM and EU). Stratification in the lower (EL) and middle (EM) members is predominantly subhorizontal, with major bedding planes inclined at between 5 and 10°. The upper member (EU) consists of large-scale foreset beds having primary dip angles of 12–25°. At profiles C and D, the upper 4–5 m of the formation is glaciotectonically deformed.

Member EL. – Member EL rests on the partly channelized surface of the Gardejåkka till. Subhorizontally stratified or massive gravels predominate (Fig. 13A). Mud and diamicton intraclasts are common in the massive beds. The gravels are interbedded with medium to coarse sandy beds of various type, as well as pelitic sands. Scattered outsized clasts and soft-sediment deformation structures are fairly common.

Member EL is interpreted as a succession of glaciofluvial channel and bar deposits formed in an environment of fluctuating discharge, in which major channel erosion and deposition of gravel on longitudinal (braid) bars alternated with deposition of sand and pelitic sand in overbank and channel-marginal areas (cf. Ashley et al. 1985). Deformational structures may have formed owing to channel-margin collapse or liquefaction following depositional loading (Collinson & Thompson 1989). Generally poor sorting and the presence of frequent, outsized, ice-rafted clasts, as well as frequent facies changes, suggest that deposition occurred in an ice-proximal outwash environment (cf. Thomas & Connell 1985; Weddle 1992).

Member EM. – This member consists predominantly of low-angle and large-scale (planar) cross-beds of fine to medium sand, with subordinate ripple-bedded sand, and pebbly and pelitic sand beds. Large-scale cross-bedded sets include simple planar cross-beds as well as compound sets displaying convex upward cross-lamination, reactivation surfaces, and concave upward trough cross-bedding (Fig. 13B). Scattered clasts occur frequently, most noticeably near the top of the member at profile A. Soft-sediment deformation structures caused by partial liquefaction and slumping pervade the upper half of the member (Fig. 12).

The sediments represent deposition on plane beds and transverse or lingouid bars (cf. Ashley et al. 1985).

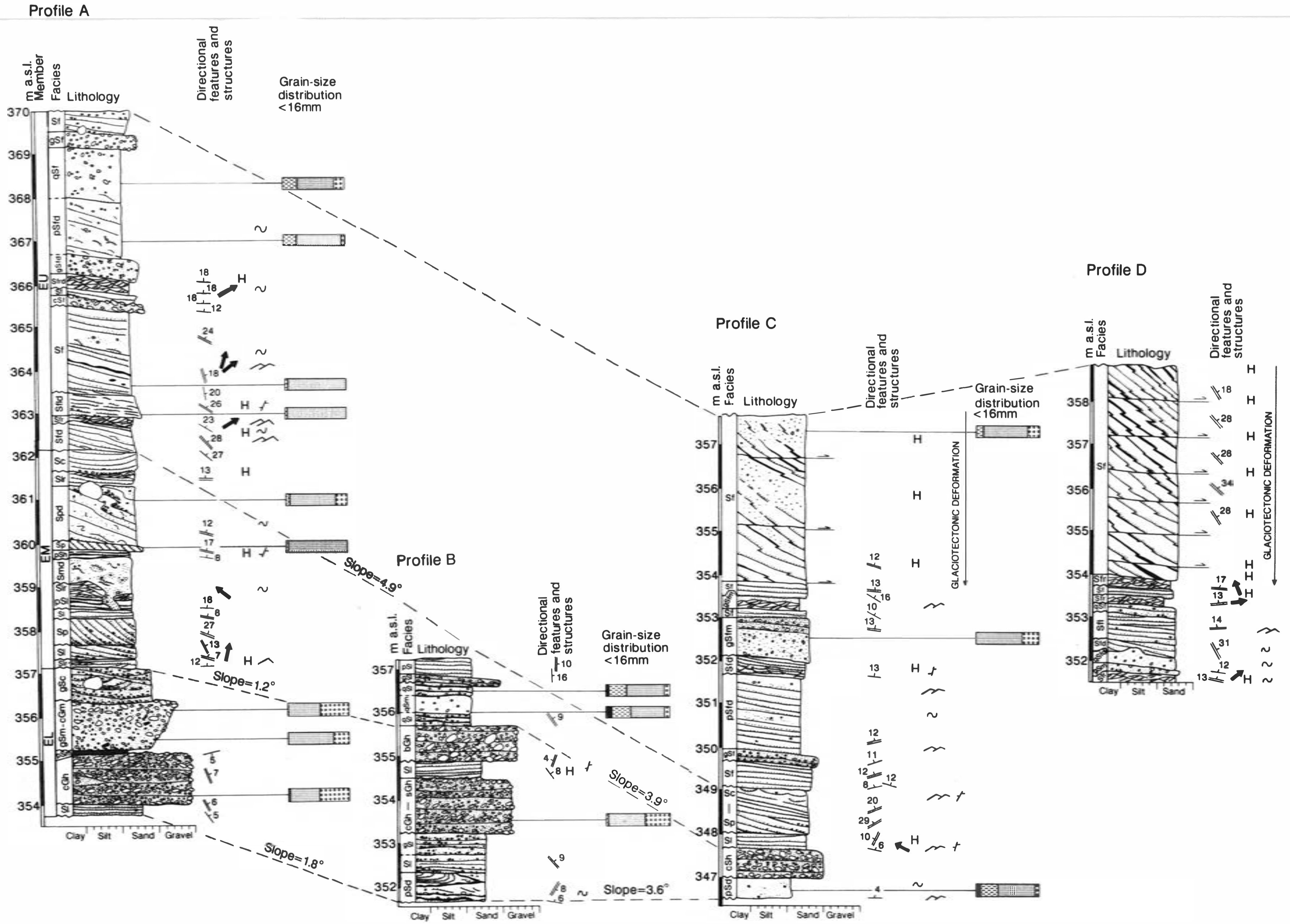

Fig. 12. Lithostratigraphic log of the Eiravarri sand formation. Legend in Fig. 10. Horizontal distance not to scale (see Fig. 3).

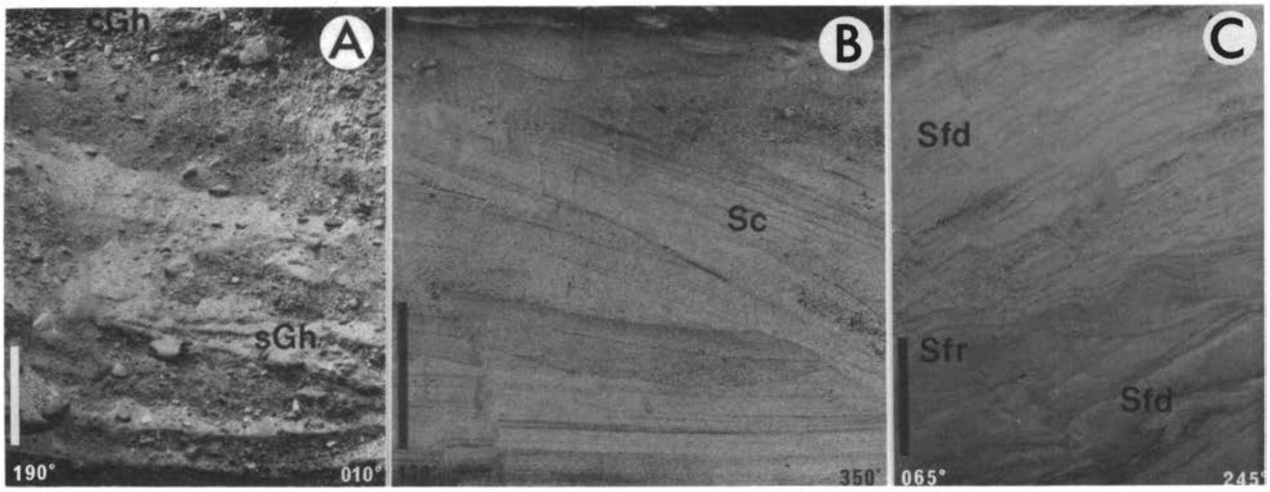

Fig. 13. Facies and structures in the Eiravarri sand. (A) Gravel (cGh/sGh) facies, member EL. (B) Reactivation surfaces and rhythmic graded bedding, member EM, profile C. (C) Delta foreset sands in member EU showing slump folds and climbing-ripple cross-lamination (Sfr) changing upwards into ripple-laminae in-drift to laminae in-phase. Scale bar is 20 cm.

Reactivation and scour surfaces, rhythmic and graded bedding and intermittent pelitic layers reflect fluctuating flow conditions. Locally, poor sorting and the presence of scattered ice-rafted clasts suggest that deposition took place relatively close to the ice-margin.

Member EU. – The upper member of the Eiravarri sand is erosively overlain by the Vuoddasjavri till. At profiles C and D (Fig. 12), severe glaciotectonic deformation has modified or partially obliterated the primary bedding in the upper 4–5 m of the member (Fig. 15), whereas the lower and proximal parts are undisturbed (Fig. 13C).

The sediments consist of inclined, mostly coarse to fine sand parallel beds interpreted as large-scale delta foreset beds. Graded bedding and ripple-bedding, including climbing-ripple cross-lamination (Fig. 13C), are common and suggest rapid deposition from turbidity currents. Slump structures and ice-rafted clasts also occur.

Beds in undeformed parts of the section dip fairly regularly at a moderately steep angle (10–28°, average 19°). Glaciotectonically faulted beds generally dip in a similar direction but at a steeper angle (18–34°). The vertical extent of the foreset unit indicates that the delta slope was at least 20 m high (Fig. 12). The ranges of dip and strike values are similar to those found in modern fjord, glaciolacustrine and marine Gilbert-type deltas (Kostachuk & McCann 1983; Thomas 1984; Corner et al. 1990; Hwang & Chough 1990; Martini 1990). The sedimentary facies and presence of ice-rafted clasts are also typical of features one might expect to form on a glaciolacustrine delta foreset slope (Clemmensen & Houmark-Nielsen 1981; Mastalerz 1990).

Depositional environment of the Eiravarri sand. – The lower (EL) and middle (EM) members are interpreted as glaciofluvial outwash sediments deposited just beyond the ice margin. Ripple-lamination and bedding inclination in these two units suggest a general flow-direction towards NW to NE (Fig. 4). Superposition of the finer, sandy, middle member on the coarser, gravelly, lower member may represent a transition from proximal to more distal facies. However, as discussed below, this change may reflect a rising local depositional base-level caused by ice-lake formation. The depositional environment is envisaged as comprising a moderately sloping, confined outwash fan.

The upper member (EU) represents a markedly different depositional environment in which delta foreset beds, inclined towards the NE, were deposited in what must have been an ice-dammed lake which inundated the outwash fan. The lower and upper altitudinal limits of member EU indicate a local water-level rise of at least 20 m, to an elevation of at least 370 m a.s.l. (Fig. 3). Although the lower boundary of member EU is erosional, the facies change across the boundary is not abrupt, suggesting that there was an essentially conformable transition from deposition by subaerial flows in deepening, barred channels to deposition dominated by sediment gravity flows on a prograding and aggrading delta foreset slope. Some the deformational features seen in member EM may have been caused by this inundation (cf. profile A, Fig. 12). The lake is therefore thought to have formed during the deglacial period as the local ice-margin retreated towards the SW. The lake may have formed in response to blockage of internal drainage channels in a stagnant ice-remnant in the main valley, rather than as a result of a later separate glacier readvance.

Vuoddasjavri till/Kautokeino till

The uppermost 3 m of the section (Fig. 3) consists of two diamictons, the Vuoddasjavri till and the Kautokeino till (Fig. 14), separated in some places by a thin (< 3 cm) sand bed that becomes thinner and indistinct towards the south, where the Kautokeino till/Vuoddasjavri till boundary is erosive. Olsen (1988) correlated this sand bed,

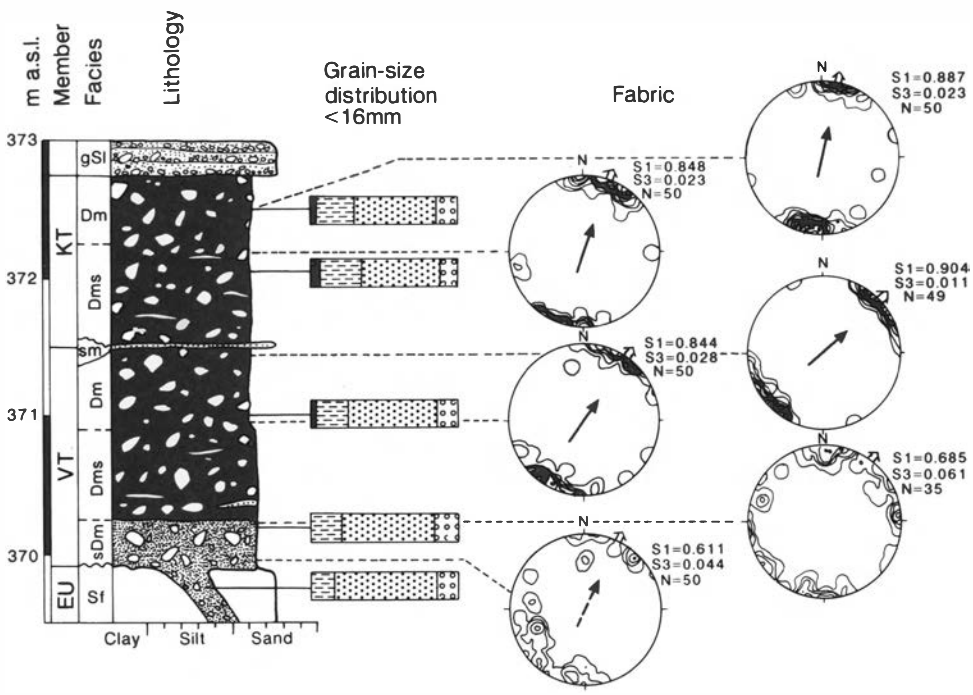

Fig. 14 Lithostratigraphic log of the Vuoddasjavri till and Kautokeino till formations. The log is based on several sections. Legend in Fig. 10. Stereonets explained in Fig. 7.

which may be of glaciofluvial or colluvial origin, with the Sargejåk interstadial (see below). A thin capping bed of gravelly sand probably represents the last deglacial period.

Vuoddasjavri till. – The base of the Vuoddasjavri till is erosive and generally highly irregular. At profile D a till wedge projects into the underlying sands (Fig. 15). The lowermost sandy diamicton (sDm, Fig. 5C) contains angular sandy intraclasts derived from the underlying Eiravarri sand. Overlying this is a massive, fine sandy diamicton containing sand streaks and sandy clast coatings (Dms). This grades in turn, into a slightly finer, more compact diamicton (Dm). The degree of compac-

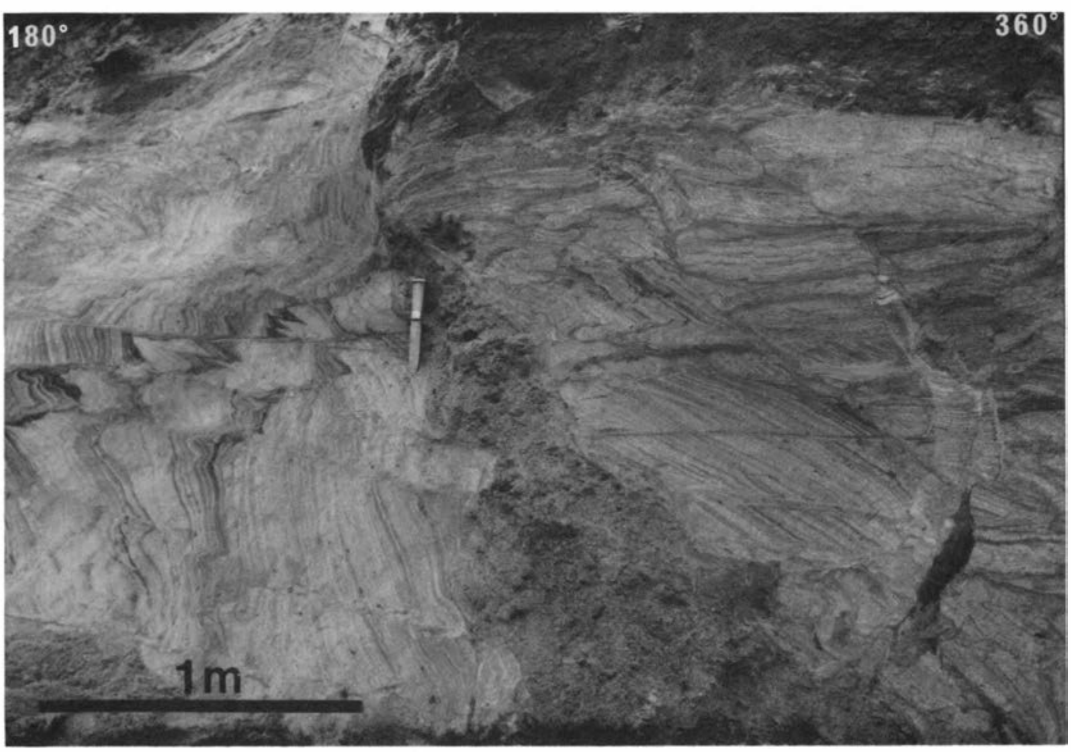

Fig. 15. Glaciotectonic structures in the upper Eiravarri sand. A till wedge and fault wedges cut low-angle reverse faults.

tion in these beds appears to be related to textural differences. Well-developed clast-fabric towards the northeast is shown in the massive diamicton (Fig. 14). We interpret the Vuoddasjavri till as a subglacial till deposited by a dynamically active glacier moving towards the northeast.

Kautokeino till. – The Kautokeino till overlies the thin sand bed with a sharp, even boundary. It comprises two diamicton beds. The uppermost bed (Dm) is less compact and contains fewer sand streaks than the lowermost bed (Dms). Clast-fabric analyses from the diamicton show a well-developed NNE fabric (Fig. 14). The diamictons are interpreted as subglacial tills of probable lodgement origin (cf. Dreimanis 1988). The glacier that deposited the Kautokeino till is considered to have moved towards the NNE.

Glaciotectonic structures

A variety of glaciotectonic structures are found in the upper part of the Vuolgamasjåkka sand and Eiravarri sand and provide additional evidence on ice-movement directions and the thermal regime beneath the overriding glacier (cf. Broster & Clague 1987; Aber et al. 1989).

Glaciotectonic structures in the Vuolgamasjåkka sand

Reverse faults are common, and normal faults and minor conjugate faults also occur in the uppermost part of this formation. Nearly all the fault planes dip >45°, and throw-heights vary from a few centimeters to about 50 cm. Drag folds occur along several fault planes. In some places sediments appear to be amorphously deformed, having a crushed appearance without visible fault planes. This style of deformation suggests that the sediments were unfrozen during deformation. Measurements on reverse faults show a stress direction towards the NW. Normal faults show a more dispersed orientation (Fig. 4).

Glaciotectonic structures in the Eiravarri sand

The uppermost 4–5 m of the Eiravarri Sand is glaciotectonically highly deformed in the northern part of the section over a lateral distance of at least 45 m. Deformational structures include low-angle reverse faults, normal faults, clastic veins and a till wedge (Fig. 15), as well as more chaotic deformation and bedding disaggregation. The deformational structures can be divided into three groups based on type and relative age.

1. The oldest and most common type consists of a system of low-angle reverse faults which form a striking zig-zag pattern in the steeply dipping heavy-mineral laminated sands (Fig. 15). The faulting is mostly concentrated along subparallel planes or thin zones spaced a few decimeters apart. Offsets along these fault planes vary from a few centimeters to at least a meter in some cases. Minor drag folds also occur.

2. Thin veins and wedges cutting the low-angle faults belong to a second deformational phase. Two types occur: (a) fault wedges consisting of thin (mostly <10 cm), vertical or steeply inclined (>50°), straight to crooked veins or wedges, a few centimeters to almost a meter long, wedging out at either end as seen in the plane of section (Fig. 15); (b) sandy pelitic veins up to 5 cm thick and 1 m long, horizontal to vertical, having an undulating, braided and branched morphology and subparallel internal lamination. The fault wedges, in most cases, contain horizontally laminated sediment which represents dislocated slices of the Eiravarri sand. Lamination parallel to the sides of the wedges indicates that fluid injection also occurred (cf. Larsen & Mangerud 1992). The sandy pelitic veins, on the other hand, represent normal clastic dikes formed by fluid injection (Lowe 1975). Some of them extend downward from the base of the Vuoddasjavri till, suggesting that they formed during till deposition.

3. A large till wedge, up to 1.5 m wide, extending 2 m down from the base of the Vuoddasjavri till (Fig. 15) cuts the fault wedges and represents the youngest deformational structure in the Eiravarri sand. A system of local, moderately dipping normal faults, having offsets of a few to 50 centimeters, are associated with it (Fig. 4).

The low-angle reverse faults cutting the primary foreset stratification represent brittle deformation under compressive conditions, suggesting that the faulting occurred in frozen sediments (Broster & Clague 1987).This interpretation is supported by the presence of undeformed intraclasts in the lower part of the overlying Vuoddasjavri till and in the fault wedges. However, lamination parallel to the sides of the fault wedges and the pelitic veins indicate the presence of some water in the system, probably while the fault wedges were being formed.

To summarize, the complex suite of deformational features in the Eiravarri sand are interpreted as follows. First, low-angle reverse faults were formed in frozen sediment in a compressional stress field caused by an overriding glacier that later deposited the Vuoddasjavri till. Wedges and veins were then formed in frozen sediment by faulting and fluid injection from unfrozen overlying till. The deformation probably occurred during an initial erosive glacier advance, whereas the till wedge formed during a subsequent depositional phase.

Geologic history and depositional successions

The stratigraphy and geologic history at Vuolgamasjåkka can be summarized within a framework of depositional successions and kinetostratigraphic units (Fig. 4). The depositional successions comprise two superposed glacial-deglacial succession and a capping multiple glacial succession, each separated by a major unconformity. Kinetostratigraphic units (Berthelsen 1978), indicating the directional characteristics of major ice-movement phases and thier associated deglacial sediments, are defined on the basis of directional elements such as till fabrics, glaciotectonic structures and palaeocurrent indicators within the sediments. Four kinetostratigraphic units and ice-directional phases are recognized (1–4, Fig. 4). Rudimentary dating control is provided by local TL-dates and regional correlation (Olsen 1988, 1989).

Glacial-deglacial succession: Mieron till and Vuolgamasjåkka sand

The lowermost succession of glacial-deglacial sediments represents the deposition of Mieron till by ice moving towards the N and the NNW, with subsequent deposition of thick outwash sands and gravels (Vuolgamasjåkka sand) by NE flowing meltwater streams (kinetostratigraphic unit 1, Fig. 4). Olsen (1988) also recognized a NNE ice-movement direction in the uppermost part of the till, in addition to an ENE direction.

Two TL-dates from the Vuolgamasjåkka sand gave average ages of 120 ± 10 ka (Olsen 1988). This formation, representing the 'Vuolgamasjåkka thermometer', has been correlated on the basis of the TL-ages and lithostratigraphic correlation of overlying tills in northern Norway and northern Finland, with the Eemian interglaciation (Olsen 1988, 1989; Larsen et al. 1991). If this correlation is correct, the Mieron till may represent part of the Saalian glaciation, while the Vuolgamasjåkka sand represents the deglacial phase at the end of this glaciation. However, recent studies by Mejdahl et al. (1992) suggest that earlier TL-dates have been underestimated because sediments absorb more irradiation under laboratory conditions than in nature. Based only on the two TL-dates, a correlation with an older ice-free period is also possible. Evidence of ice-free periods on Finnmarksvidda older than the Eemian are reported by L. Olsen (pers. comm. 1993). A sparse pollen flora and other microfossils of unknown age have been found in a thin silty sand bed of inferred non-glacial origin at the top of the Vuolgamasjåkka sand, as well as in the overlying till (Olsen 1988; cf. also Larsen et al. 1991).

Glacial-deglacial succession: Gardejåkka till and Eiravarri sand

This succession represents a glacial phase with basal till deposition (Gardejåkka till) followed by deposition of thick outwash sands and gravels (Eiravarri sand) (kinetostratigraphic unit 2, Fig. 4).

Glaciotectonic structures in the upper part of the Vuolgamasjåkka sand probably record the oldest ice-movement direction belonging to this phase and indicate initial ice movement towards the NW. No comparable till fabric direction was found immediately in the overlying Gardejåkka till, although Olsen (1988) found a NW fabric at this level in an adjacent section. The Gardejåkka till generally shows somewhat variable, weak to moderately strong till fabric directions as well as bedding structures which indicate a northerly (NNW–NNE) ice-movement direction (Fig. 4). This accords with analyses made by Olsen (1988) in an adjacent section. This glacial period was followed first by outwash fan deposition by northerly (NW–NE) flowing meltwater streams and subsequently by delta foreset progradation towards the NE, into an ice-dammed lake. As discussed above, the Eiravarri sand is thought to form part of a continuous depositional succession, indicating that this ice-lake formed during a deglacial phase rather than during a subsequent major glacier readvance.

Three TL-dates from the Eiravarri sand gave an average age of 100 ± 10 ka (Olsen 1988). The formation was correlated with the Peräpohjola and Jämtland interstadials (isotope substage 5c) in northern Finland and northern Sweden, respectively (Olsen 1988, 1989), implying that the underlying Gardejåkka till was deposited earlier during the Early Weichselian. However, as discussed above, recent studies by Mejdahl et al. (1992) suggest that a correlation based only on the TL-dates could give an older age for the Eiravarri sand, and consequently also for the Gardejåkka till.

Multiple glacial succession: Vouddasjavri till and Kautokeino till

Deformational features in the uppermost part of the Eiravarri sand are interpreted as having been caused by a glacier advance and till deposition over frozen deltaic sediments (kinetostratigraphic unit 3, Fig. 4). The oldest deformational features, low-angle reverse faults, suggest initial ice movement towards the ENE. This direction is not represented by till fabrics in the overlying till, but accords with regional data on initial ice movement (Olsen 1988). Later formed fault wedges, oriented east–west, and normal faults having a NE orientation may have formed normal-oblique to the principle stress field suggesting a N to NE ice-movement direction (Fig. 4). This deformation probably occurred during formation of the sandy deformation till at the base of Vuoddasjavri till, which has a weak NE fabric (Fig. 14). Till fabrics in the upper part of the Vuoddasjavri till show a strong orientation, indicating a major ice movement towards the NE. A later direction towards the NNE recorded by Olsen (1988) is not apparent in our data, suggesting that younger tills from this phase could have been eroded from the investigated section.

During deposition of the Kautokeino till, NNE ice-movement direction dominated (kinetostratigraphic unit 4, Fig. 4). An initial NNW ice-flow direction during this glacial period (Olsen & Hamborg 1983, 1984; Olsen 1988) is not recorded in our data.

The thin sand layer which separates the Vuoddasjavri till and Kautokeino till in some places probably corresponds to a 2–4 m thick sand bed separating the two tills at a locality 800 m further upstream (Olsen 1988, 1989). This bed contains pollen and freshwater algae and has been correlated with the youngest recorded Weichselian interstadial on Finnmarksvidda, the Sargejåk interstadial (Olsen 1988). ^{14}C- and TL-dates at the type locality and localities nearby suggest a Middle Weichselian (35–40 ka) age, although regional correlation suggests a possible earlier age (Early Weichselian–early Middle Weichselian) as well as relatively long duration for this interstadial and for the hiatus between the Vuoddasjavri and Kautokeino till (Olsen 1988, 1989; Larsen et al. 1991). Accordingly, the Vuoddasjavri till stadial and Kautokeino till stadial are thought to correspond to the late Early Weichselian or Middle Weichselian, and Late Weichselian maximum, respectively.

Conclusions

(1) A succession of interstratified tills and sorted sediments, exposed in a 50 m high river section at Vuolgamasjåkka, Finmarksvidda, consists of four thick (3–15 m) till formations (Mieron till, Gardejåkka till, Vuoddasjavri till, Kautokeino till) and two, thick (13–16 m) glaciofluvial/glaciolacustrine formations (Vuolgamasjåkka sand, Eiravarri sand). They record four glacial events and two deglacial events prior to the last deglaciation.

(2) The lower four formations constitute two successions of glacial-deglacial sediments, each consisting of a till with overlying glaciofluvial outwash. The outwash shows fining upward character indicating a change from proximal to distal deposition during deglacial phases. Distal outwash is overlain conformably by ice-lake delta foreset beds at the top of the uppermost deglacial deposits (Eiravarri sand).

(3) Glaciotectonic structures were formed in the upper part of the Vuolgamasjåkka sand and Eiravarri sand during glacier advance. In the Vuolgamasjåkka sand they include reverse and normal faults as well as amorphous deformation formed in unfrozen sediment during advance of the Gardejåkka till glacier. In the Eiravarri sand they include low-angle reverse faults and normal faults, fault wedges, a till wedge and clastic dikes, all formed in frozen or partly frozen sediment during at least three deformation phases during advance of the Vuoddasjavri till glacier.

(4) Four kinetostratigraphic units, representing major ice-movement phases and their associated deglacial sediments, are recognized based on till fabrics, glaciotectonic structures and palaeodirectional features in the glaciofluvial outwash sediments. The glaciers that deposited the four till formations moved generally towards the N and NE. The associated deglacial sediments suggest palaeocurrent directions similar to the ice-movement directions, though with a more prominent NE component.

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