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Glaciotectonic deformation of till-covered glaciofluvial deposits in Oulu region, Finland

Antti Pasanen* and Juha Pekka Lunkka
Department of Geosciences, University of Oulu. Post-box 3000, FI-90014 University of Oulu, Finland

Abstract
Sedimentary sequences in Isoniemi and Hangaskangas in the Oulu area of Finland have been studied using conventional sedimentological techniques including structural and clast-fabric measurements on fold and fault structures and till units. Four different facies were identified from the sequence in the Isoniemi area and three in the Hangaskangas area. In the Isoniemi area, the measurements of glaciotectonic deformation and till clast-fabric analyses can be related to the ice movement from the south-west and the subsequent ice front oscillation from the north-west. These ice movement phases are thought to have taken place during the Late Weichselian. In the Hangaskangas area, the south-western shear-stress direction crosscuts the sediment strata indicating that the latest ice movement came from that direction during the Late Weichselian. However, there is also indication of an earlier shear-stress in the Hangaskangas area indicating the north-western ice movement. The age of this ice movement phase is thought to be older than the Late-Weichselian.

Key words: glaciofluvial features, sediments, till, lithostratigraphy, deformation, glaciotectonics, ice movement, Pleistocene, Weichselian, Isoniemi, Hangaskangas, Oulu Province, Finland

*Corresponding author email: antti.pasanen@oulu.fi

1. Introduction

The Oulu region (Fig. 1) is situated in a crucial area considering the behaviour of the Scandinavian Ice Sheet (SIS) during the Weichselian Stage. The SIS advanced across Finland into North-western Russia several times during the Late Pleistocene. Based on till stratigraphical investigations, it is thought that three till beds were accumulated by three separate ice advances in Finnish Lapland and the area north of Oulu during the Weichselian Stage (*ca.* 116 000 – 11 500 years ago). Lapland was covered by ice during the Early Weichselian, the early Middle Weichselian and during the Late Weichselian (Hirvas, 1991; Lunkka et al., 2004; Johansson & Kujansuu, 2005; Helmens et al., 2007). Stratigraphical investigations south of the Pudasjärvi-Hossa line (Fig. 1), however, suggest that the SIS advanced into central and Southern Finland only during the early Middle Weichselian and the Late Weichselian (Lunkka et al., 2004; Salonen et al., 2007). It has been hypothesised that the series of till-covered glaciofluvial ridges in the Pudasjärvi end-moraine zone (Fig. 1), including the Isoniemi complex, represent the Early Weichselian ice limit (Sutinen, 1992; Nenonen, 1995). It has also been suggested that a number of till-covered glaciofluvial complexes in the Oulu region were deposited prior to the Late Weichselian Sub-stage (Bargel et al.,

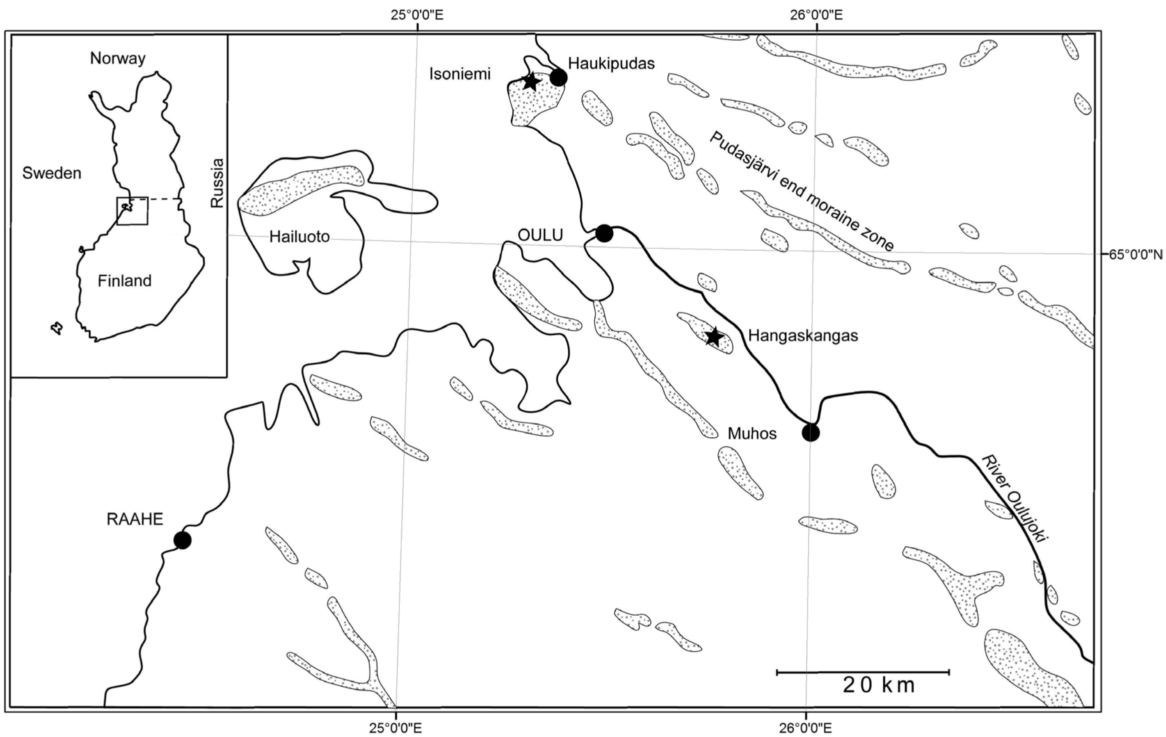

Fig. 1. Map of glaciofluvial deposits in the Oulu region. The circles indicate selected towns and villages, the stars indicate study sites and the dotted areas indicate a simplified distribution of glaciofluvial deposits. The dotted line in the small map indicates the Pudasjärvi-Hossa line mentioned in the text.

1999; Johansson & Kujansuu, 2005). Both the Isoniemi and Hangaskangas sites (Fig. 1) discussed here are glaciofluvial sediment sequences overlain by till which has been intensively deformed by the overriding ice. Borehole data from the Runteli ridge shows almost 90 m of glacial and glaciofluvial sediment above the Muhos Formation sedimentary bedrock. (K. Mäkinen, pers. comm. 2005). The glacial striation measurements taken from the bedrock exposures north of Isoniemi and south-east of Hangaskangas indicate two separate ice flow phases, the first from the north-west and the latter movement from the west (Hirvas & Nenonen, 1987; Bargel et al., 1999). However, the age of these ice flow events and the age of the glaciofluvial sediment beneath the till unit are not known.

Previous work from the Oulu region has noted the till-covered glaciofluvial areas of Isoniemi, Hangaskangas and Muhos (Helle & Ylinen, 1965; Gibbard, 1979; Vehkaperä, 1988; Eronen et al., 1995; Bargel et al., 1999). Gibbard (1979) carried out a detailed litho- and biostratigraphical study of the Oulujoki River banks at Muhos *ca.* 10 km south-east of the till-covered glaciofluvial formation of Hangaskangas and established the stratigraphy of the area around Muhos. Gibbard (1979) concluded that the lowermost Hietaniemi Sand beneath the Pohjola Till most likely represents Late Weichselian esker deposits. The Late Weichselian Pohjola Till was laid down during the last deglaciation as a result of minor ice front oscillations, while the Montanlampi Varved Clay and Montanniemi Silt above the till were deposited into the Ancylus Lake and Litorina Sea of the Baltic Basin. The sequence is capped by Halokangas Sands that is thought to represent beach sand.

According to a stratigraphical map composed by the Mid-Norden Project (Bargel et al., 1999), there are pre-Late Weichselian sediments beneath the top-

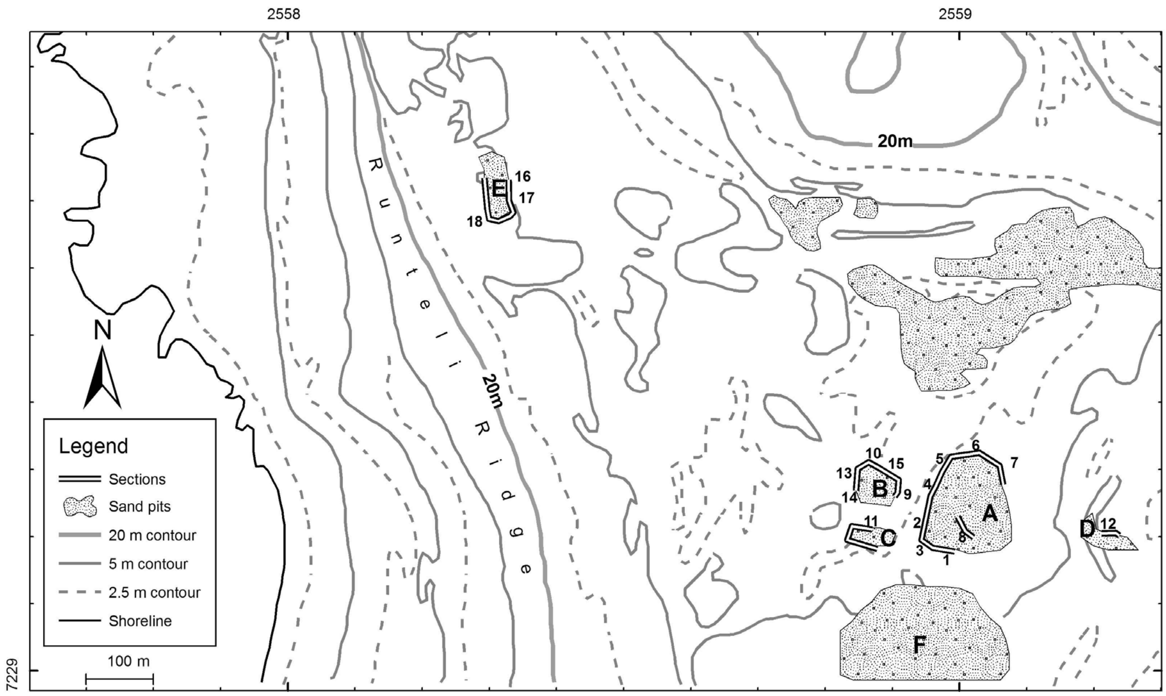

Fig. 2. Map of the Isoniemi area showing the location of the sand pits (A–F) and the sections studied (1–18). Coordinates refer to the Finnish KKJ coordinate system (zone 2).

most till in the Hangaskangas area. The sediment succession from the base of the sequence consists of 1) silt and clay, 2) interstadial sediments with organic remnants (C-14 dated to 41.6 ka BP), 3) sand and gravel, 4) till and 5) sand. However, no description has been published detailing the type of sediments assigned to represent pre-Late Weichselian interstadial deposits. In addition, Helle & Ylinen (1965) and Eronen et al. (1995) described the upper part of the Holocene sequence at Hangaskangas and described and dated the molluscs and kelp found in the Litorina sediments (silt and beach sand) above the uppermost Weichselian till unit. Vehkaperä (1988) studied the Quaternary sediments and the underlying bedrock in the Haukipudas-Kiiminki area, including the Isoniemi area discussed here, in his unpublished licentiate study. The author interpreted the Runteli ridge, the ridge that runs north to south along the eastern side of Isoniemi, as an ice marginal deposit. Vehkaperä (1988) also noted that on the distal side of the Isoniemi area, at least three km from the Runteli ridge, lenses and layers of till at several different depths below the ground surface occur separated by thick units of glaciofluvial sediment. Apart from Vehkaperä's (1988) studies, there are no detailed site investigations of the Isoniemi complex.

In this paper the authors describe the sediment exposures in two till-covered glaciofluvial formations in the Oulu region. The aim of the paper is to establish the lithostratigraphy and deformation style of till-covered glaciofluvial sequences at the Isoniemi and Hangaskangas sites in order to understand the behaviour of the SIS at its marginal zone and to shed light on the depositional environments that existed in the area during the Late Weichselian.

2. Study area and methods

The two study areas discussed herein are situated in the vicinity of the city of Oulu (Fig. 1). The Isoniemi area (N65°09' E25°15', Fig. 2), which is part of the larger (approximately 25 km²) glaciofluvial Iso-

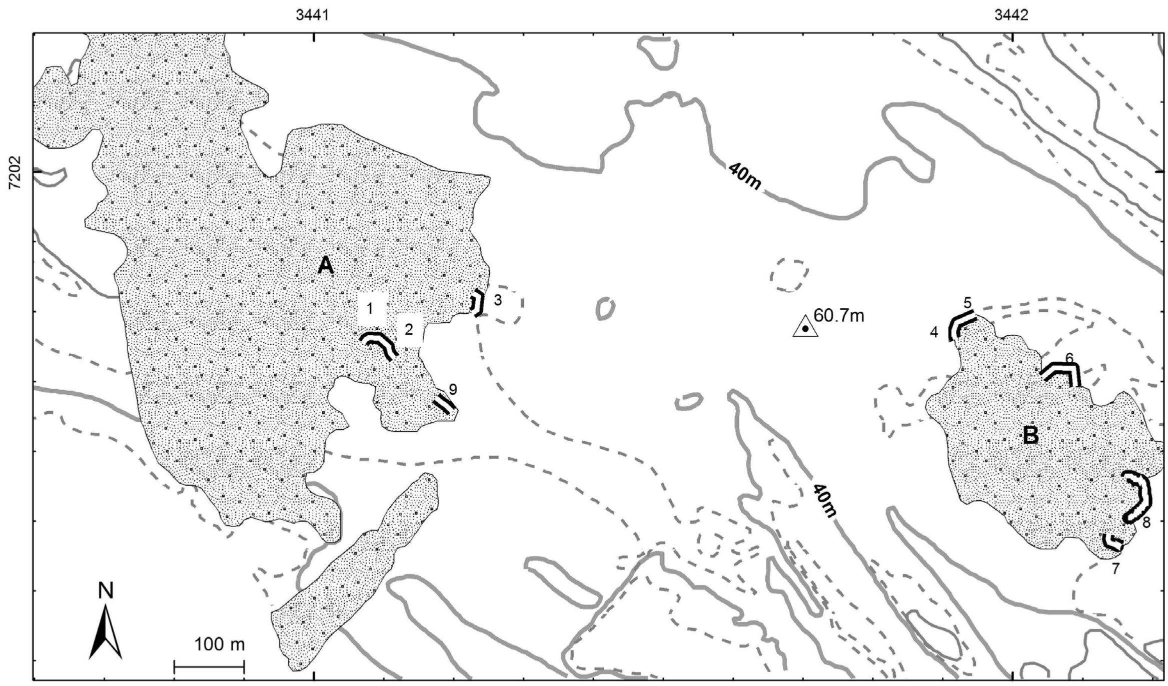

Fig. 3. Map of the Hangaskangas area showing the location of the sand pits (A-B) and the sections studied (1–9). Coordinates refer to the Finnish KKJ coordinate system (zone 3). The triangle indicates the highest point in the area. See Fig. 2 for the legend.

niemi-Virpiniemi complex, is located on the coast of the Gulf of Bothnia 6 km north-west of the village of Kello in Haukipudas Commune. The highest geomorphological feature in the area is the Runteli ridge which reaches over 25 m above sea level (asl). The sea is approximately 500 m west of the Runteli ridge. The modern ground surface surrounding the Runteli ridge is at 20 – 25 m asl.

The Hangaskangas area (N63°37' E43°13', Fig. 3) is situated 20 km south-east of Oulu in the suburb of Pikkarala near the border of the Muhos Commune. The highest point of the study area is 60.7 m asl which occurs north-west of Pit B (Fig. 3). The pits are situated at over 40 m asl and the adjacent area lies between 20 – 25 m asl. The Hangaskangas formation is approximately 6 km long and 1.5 km wide. Ancient beach deposits from the Litorina Sea of the Baltic Basin occur on both flanks of the Hangaskangas formation and are covered by aeolian sands in places (Helle & Ylinen, 1965; Eronen et al., 1995).

Sediment exposures in the Isoniemi and Hangaskangas areas were studied using conventional sedimentological techniques, including clast-fabric measurements of till units and structural measurements of fold and fault structures beneath the uppermost till unit. The sedimentological technique adopted consists of measuring the thickness of each sedimentary unit and the textures and structures of the units using lithofacies codes modified after Miall (1977, 1985) and Eyles & Miall (1984) (Table 1). In addition, the lower contacts and lateral extent of each unit were defined. The results were used for the interpretation of the facies and depositional setting. The deformation was studied by measuring the dip angle and direction

Table 1. Facies codes, lithofacies and sedimentary characteristics used in the section descriptions and interpretations. Codes modified after Miall (1977, 1985) and Eyles & Miall (1984).

Facies code	Lithofacies and sedimentary characteristics
Diamict	
Dmm	Matrix supported, massive
Dmm(s)	Matrix supported, massive, sheared
Dmm(d)	Matrix supported, massive, deformed
Dms	Matrix supported, stratified
Sand	
Sd	Soft sediment deformation structures
Sr	Ripple cross-bedding
St	Trough cross-bedding
Sp	Planar cross-bedding
Sh	Horizontal lamination
Gravel	
Gmm	Massive, matrix supported
Gmc	Massive, clast supported
Gh	Horizontal bedding
Gp	Planar cross-bedding
Gd	Deformation structures
Fine-grained (silt and clay)	
Fm	Massive

of fold axis, planes of fold limbs and fault planes of thrust faults and by defining the fold types. The results were plotted on the lower hemisphere equal area projection net poles to planes and used for the interpretation of the shear-stress direction during the deformation. Clast-fabric analyses were applied to the sections where diamicton was present. The analyses were carried out by measuring 40 – 50 dip angles and directions of the long axis (a-axis) of the pebble-sized clasts, with an axis ratio of 2 to 1. The results were plotted on a lower hemisphere equal area projection net and the statistical significance was tested using the S1/S3 (Eigenvalue 1/Eigenvalue 3) method described in Woodcock & Naylor (1983).

3. Results and facies description

3.1. Isoniemi area

The sections in the Isoniemi area occur in sand pits which are currently being exploited. Exposures in four sand and gravel pits (Pits A, B, C and E) and one diamicton pit (Pit D) were studied in detail (Fig. 2). As shown below, the sediments exposed in the Isoniemi area can be grouped into four facies which from the bottom to the top comprise: 1) deformed sand and gravel facies (FA1), 2) diamicton facies (FA2) which can be found above or within FA1, 3) massive cobble gravel facies (FA3) and 4) pebble gravel and sand facies (FA4).

Deformed sand and gravel facies (FA 1)

Deformed sand and gravel facies FA 1 can be seen in all exposures in the area except in Pit D (Figs 2 and 4). Facies FA1 is composed mainly of deformed medium to coarse sand and pebble (occasionally cobble) gravel (Fig. 4). In Pit B, Section 15 and Pit C, Section 11 facies FA1 consists mainly of fine sand with load structures while in Pit E beds of cobble gravel are common (Fig. 4). Although FA1 is deformed, in most of the sections in Pits A, B, C and E, primary, the current induced sedimentary structures have survived deformation within the facies FA1. The primary structures are mainly cross-bedded, horizontally-bedded and ripple-bedded sands and massive matrix-supported gravel. The lower contact of the facies was not found in the exposures but the sediment in the lower parts of Section 15 in Pit B and in Pit F are only slightly glaciotectonically deformed (Fig. 5).

In the Isoniemi area, fold-plane, fold axis and thrust fault plane dip angles and directions were measured from deformed sand and gravel facies (FA1). The deformation structures in facies FA1 consist mainly of tight to isoclinal folds which are normally gently inclined or recumbent and thrust faults (Fig. 5). In some exposures high angle bedding planes represent the fold planes of steeply inclined and upright folds where fold noses have been eroded after the folding

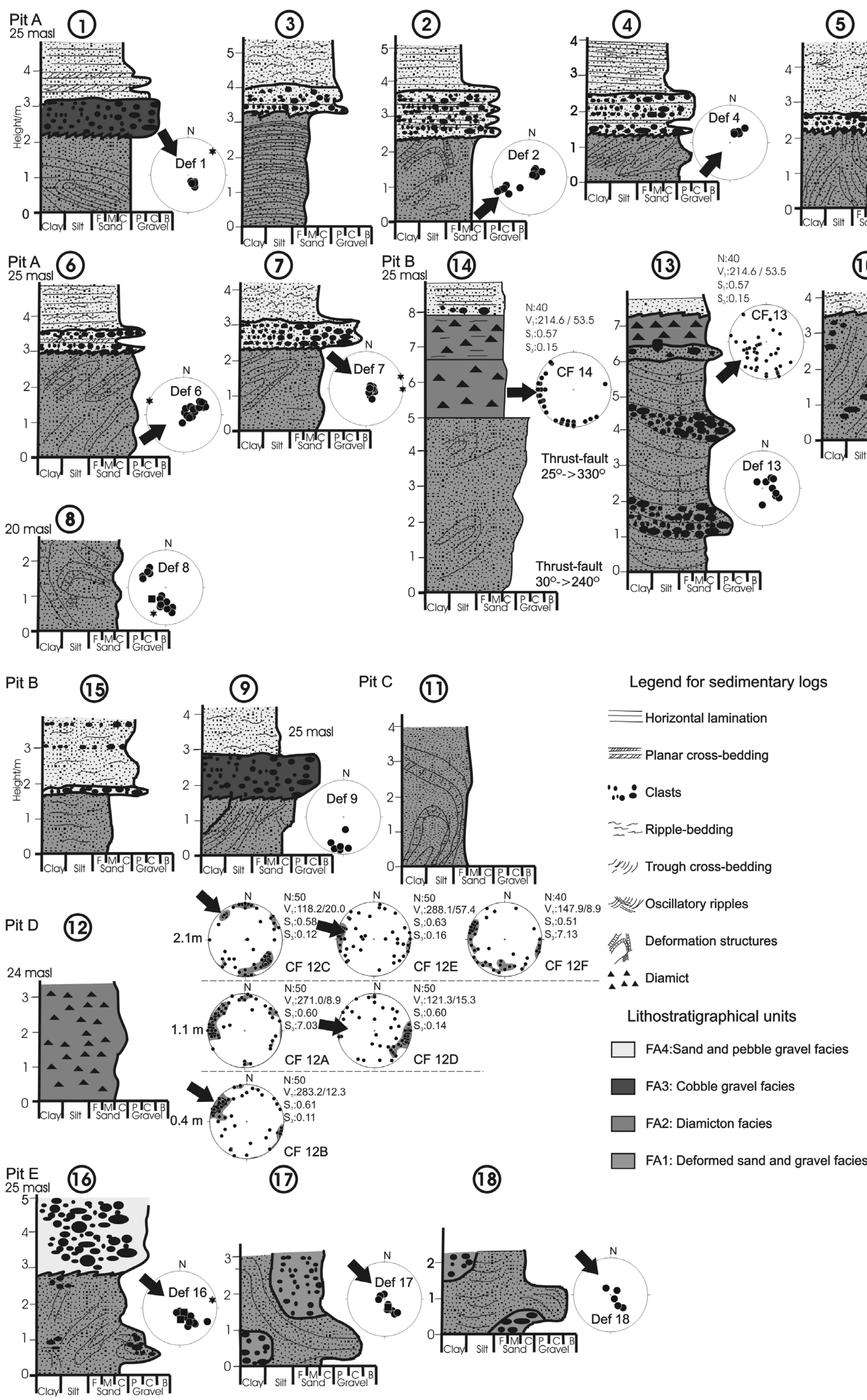
Pit A
25 masl
Height/m
Clay Silt F M C Sand P C B Gravel
Def 1
Def 2
Def 4
Def 5
Def 6
Def 7
20 masl
Def 8
Pit B
25 masl
N:40
V1:214.6 / 53.5
S1:0.57
S3:0.15
CF 14
CF 13
Thrust-fault 25°->330°
Thrust-fault 30°->240°
Def 13
25 masl
Def 9
Pit C
Pit D
24 masl
2.1m
N:50
V1:118.2/20.0
S1:0.58
S3:0.12
CF 12C
N:50
V1:288.1/57.4
S1:0.63
S3:0.16
CF 12E
N:40
V1:147.9/8.9
S1:0.51
S3:7.13
CF 12F
1.1 m
N:50
V1:271.0/8.9
S1:0.60
S3:7.03
CF 12A
N:50
V1:121.3/15.3
S1:0.60
S3:0.14
CF 12D
0.4 m
N:50
V1:283.2/12.3
S1:0.61
S3:0.11
CF 12B
Pit E
25 masl
Def 16
Def 17
Def 18
Legend for sedimentary logs
Horizontal lamination
Planar cross-bedding
Clasts
Ripple-bedding
Trough cross-bedding
Oscillatory ripples
Deformation structures
Diamict
Lithostratigraphical units
FA4:Sand and pebble gravel facies
FA3: Cobble gravel facies
FA2: Diamicton facies
FA1: Deformed sand and gravel facies

Fig. 4. Section logs from the Isoniemi area. Def = stereo plots of the deformation structures found in Facies FA1 (circles = fold planes, squares = thrust fault planes, stars = fold axes). Stereo plots of the clast-fabric measurements (CF) of diamicton (Facies FA 2) are also indicated. Arrows indicate the interpreted shear stress and the ice movement direction. Section numbers are marked above each section. Sand grain sizes below the section logs: F = fine, M = medium, C = coarse and gravel grain sizes: P = Pebble, C = Cobble, B = Boulder. See Fig. 2 for the location of pits and sections.

ISONIEMI PIT F

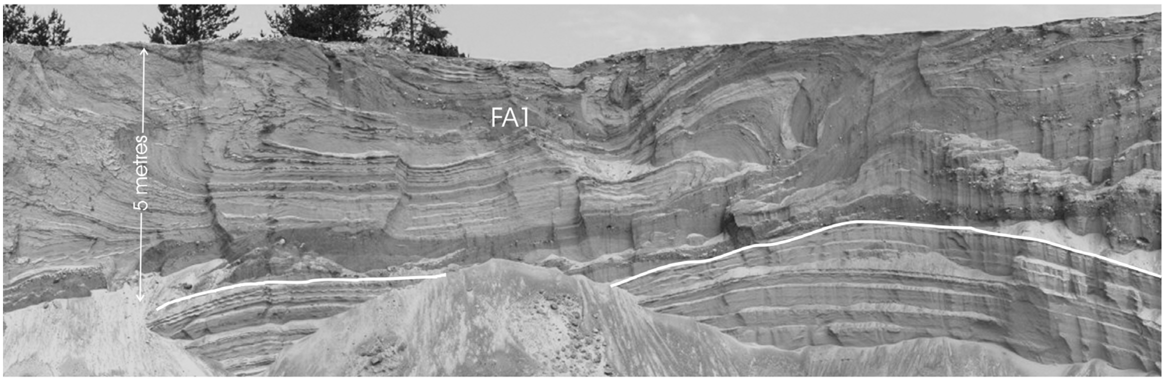

Fig. 5. Pit F in the Isoniemi area showing deformed sand and gravel facies FA1 and slightly deformed, possibly a subaquatic fan-delta facies below the solid line. The fold form on the left is isoclinal and recumbent. A thrust fault cuts the fold form on the right. The view is towards the north-west from the middle of the pit (Fig. 2).

ISONIEMI SECTION 9

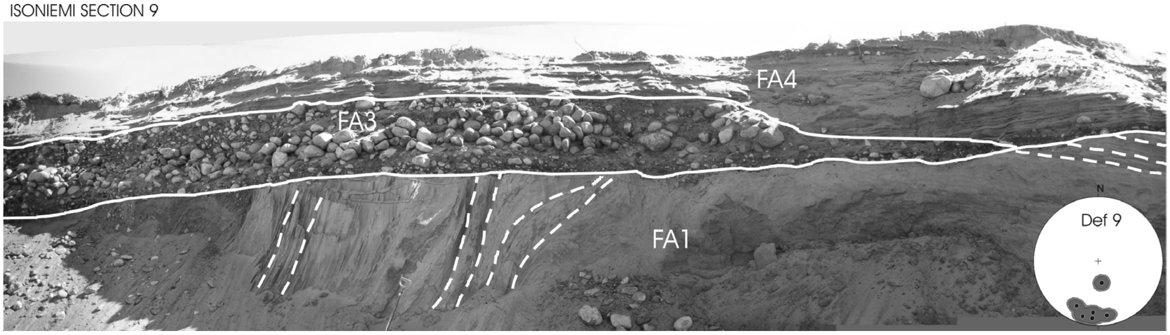

Fig. 6. Facies succession in Section 9 of Pit B in the Isoniemi area showing deformed sand and gravel facies FA1, undeformed cobble gravel facies FA3 and undeformed sand and pebble gravel facies FA4. A stereo plot of fold-planes (dashed lines) in FA1 is also shown. The height of the section is 4.2 m.

events (Fig. 6). The results of the structural measurements of facies FA 1 are briefly presented below.

Thrust faults and folds are best exposed in Pit E, located on the eastern flank of the Runteli Ridge end moraine (Figs. 2 and 7). The thrust fault planes dip towards 310° – 350°, while the fold axis dips towards 70° and the mean dip direction of the fold plane measurements from individual folds range between 305° – 335°. The thrust fault plane measurements together with the fold axis and fold plane measurements clearly indicate that deformation structures in Pit E were formed under shear-stress that was applied

ISONIEMI SECTION 16

Fig. 7. Section 16 in Pit E, in the Isoniemi area showing deformed sand and gravel facies FA1 below facies FA4, and a stereo plot of deformation structure measurements in Facies FA1. The structural measurements from stacked thrust folds indicate a stress direction from the north-west. The height of the section in the middle of the figure is 2.8 m. For symbols in stereo plot see caption in Fig. 4.

from the north-west (Fig. 4, plots Def 16, Def 17 and Def 18).

The measurements of thrust fault planes and fold planes as well as fold axis were also carried out from Sections 9, 13 and 14 in Pit B and extensively from the deformation structures exposed in Pit A. The thrust fault plane measurements at a higher level in Section 14 show thrusting from the north-west, whereas at the lower level thrust fault plane measurements show that the thrusting occurred from the south-west (Fig. 4). Fold plane measurements in Section 9 are scattered but generally the fold planes dip towards the north indicating a shear-stress direction from the north (Fig. 4, plot Def 9). In Section 1, Pit A, fold planes of a tight fold (mean fold plane dip direction 320°) and its fold axis (dip direction 40°) indicate a clear shear-stress from the north-west during the deformation (Fig. 4, plot Def 1). A similar direction is indicated by the fold plane, fold axis and thrust fault plane measurements from the folds in Section 7 (Fig. 4, plot Def 7) and Section 8 (Fig. 4, plot Def 8). In Section 8 a thrust fault plane dipping towards the north-east crosscuts the south-east dipping fold planes. Some of the fold planes also dip towards the north-east. However, in Section 2 (Fig. 4, plot Def 2), Section 4 (Fig. 4, plot Def 4), and Section 6 (Fig. 4, plot Def 6) in Pit A, the folds were formed under a stress that was applied from the south-west while the fold plane measurements in Section 5 are scattered, indicating both the south-western and the north-western distribution of applied shear-stress field during the deformation (Fig. 4, plot Def 5).

Based on the structural measurements of the thrust fault planes and the fold-forms, it can be concluded that the deformation of sand- and gravel-rich sediments in the Isoniemi area was caused by shear-stress applied mainly from the north-west. However, there is also clear indication of a weaker stress field from the south-west.

Diamicton facies FA2

The diamicton unit resting above the deformed sand and gravel (facies FA 1) was observed in Pit B in Sections 13 and 14 (Fig. 4). A thick diamicton unit also occurs in Pit D approximately 350 m east of Pit B (Figs. 2 and 4). Although the lower contact of the diamicton in Pit D was not seen, ground penetrating radar observations confirmed that the diamicton unit overlies the deformed sand and gravel facies.

In Pit B, facies FA 2 occurs on top of facies FA1 and inside a large fold in Section 13 (Fig. 8). Facies FA2 consists of matrix-supported, massive sandy diamicton. The maximum clast size in this facies is approximately 40 cm in diameter. The lower contact of facies FA2 appears to be deformed but relatively sharp. The lateral extent of facies FA2 in the section is approximately 10 m. Clast-fabric analysis carried out from the diamicton unit in Section 13 on top of FA1 indicates strong (confidence level over 99 %) a-axis

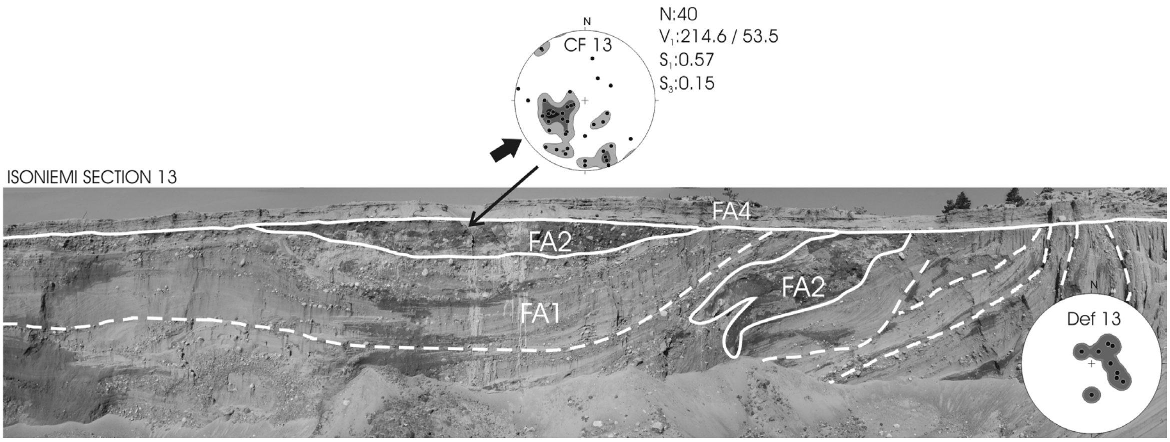

Fig. 8. Section 13 in Pit B, in the Isoniemi area showing Facies FA1, Facies FA2 and Facies FA4. Fold plane (Def 13) and clast-fabric (CF13) measurements are also shown. The height of the section is 7.8 m. For symbols in stereo plots see caption in Fig. 4.

orientation of clasts dipping towards the south-west (plot CF 13 in Figs. 4 and 8). However, the average dip of the clasts is high (37.5°). This is interpreted to have resulted from the shear-stress or ice-movement from the south-west. The statistically significant a-axis dip direction distribution in Section 14 shows that the clasts dip towards the west and the south-west and it is thought to represent the same shear-stress or ice-movement direction as in Section 13.

In Pit D, Section 12, a 3.5 m thick diamicton unit is well exposed throughout the pit. The lower 1.2 m of the unit are composed of matrix-supported stratified sandy diamicton (Fig. 4). The diamicton becomes more massive towards the top of the sequence but sand lenses and so-called tectonic 'dropstones' (sinking and rolling of the clasts during the deformation) (Hart & Roberts, 1994) also occur in places.

Clast-fabric analyses were carried out at three levels of the exposure (Fig. 4, Section 12). The clast-fabric analysis at the lowest level, 0.4 m from the base of Section 12, indicates a statistically significant (over 99 % confidence level) orientation of clast a-axis (Fig. 4, plot CF 12B) that dips towards the north-west. A clast-fabric analysis (Fig. 4, plot CF 12D) 10 m west of Section 12, 1.1 m above the base of the section, shows a statistically significant orientation of clast a-axis dipping towards east-south-east. However, at the same level in Section 12 (Fig. 4, plot CF 12A) the clasts in diamicton are randomly orientated. Two out of three clast-fabric analyses at 2.1 metre-level above the base of the section show statistically significant west-north-west (Fig. 4, CF 12E) and east-south-east (Fig, 4. CF 12C) clast a-axis mean vector orientations, while one clast-fabric analysis (Fig. 4, CF 12F) shows a random distribution. It is also noteworthy that the dip of the measured clast a-axis is relatively high. The results of the clast-fabric analysis suggest that clasts in the diamicton are relatively well orientated and, therefore, it is assumed that the stratified and massive sand diamicton probably represents subglacial deformation till that was deposited by ice moving or, in the case of deformation till, shear-stress was applied approximately from the north-west. But as shown above, the south-western shear-stress or ice-movement direction is also clearly visible.

Cobble gravel facies FA3

A cobble gravel facies overlies the deformed sand and gravel facies (FA 1). It is well exposed in Pit A, Section 1 (Fig. 4) and in Pit B, Section 9 (Figs. 4 and 6). In Pit A, Section 1 the one-metre-thick cobble gravel facies, which extends laterally *ca.* 20 m, is massive, granular gravel-supported. The cobble-sized clasts are mostly subangular and the clast surfaces are occasionally striated. The unit pinches out laterally into pebble gravel where occasional cobble- to boulder-sized clasts occur at the top of the deformed sand and gravel facies.

In Pit B, Section 9 the cobble gravel facies is 1.3 m thick including a thin pebble gravel layer with a fine, poorly sorted matrix at the base of the unit that passes into matrix-supported and partially clast-supported cobble gravel (Fig. 6). Laterally, this unit pinches out into a thin layer of pebble gravel. The clasts in this unit, which extends 25 m along the section, are mostly sub-rounded to well-rounded.

In Pit A, the 'lag' horizon including the cobble gravel unit can be seen in all exposures above facies FA1. The angular clasts, with striations on some of the clasts, suggest that it represents a remnant of diamicton that has been washed subsequently by littoral processes. It may also be that the cobble gravel unit in Pit B, Section 14 represents a beach bar since this unit changes laterally into a diamicton.

Sand and pebble gravel facies FA 4

In every pit where the uppermost part of the exposure has not been artificially removed there is a pebble gravel and sand facies at the top of the sections. In Pits A and B it is up to 2.7 m thick (Fig. 4). The lower part, up to 0.8 m, is normally stratified pebble gravel, and horizontally-bedded and cross-bedded sand that passes in the upper part of the unit into cross-bedded, horizontally-bedded and ripple-bedded fine to medium sand. Occasionally, this unit, particularly in its upper part, includes shell material (*Mytilus edulis*).

This sand and pebble gravel facies is a very common tabular sand sheet that covers large areas in the study area. The facies is interpreted as beach sand that was formed as the area emerged following the glacioisostatic uplift from the Baltic Sea.

3.2. Hangaskangas area

In the Hangaskangas area nine sections were logged in two sand pits (Fig. 3). Also in this area, as in the Isoniemi area, the uppermost parts of the exposures have been excavated during the past few decades. The sediments exposed can be grouped into three different facies which from the bottom to the top are: 1) deformed sand facies (FA1) 2) diamicton facies (FA2) and 3) sand and gravel facies (FA4). A cobble gravel facies, FA3, observed in the Isoniemi area was not found in the Hangaskangas area.

Deformed sand facies, FA1

A deformed fine to coarse sand facies occurs in all sections in Pits A and B except in Pit B, Section 6 (Fig. 9). The primary structures that have escaped deformation within facies FA1 are mainly trough and planar cross-bedded and horizontally-bedded medium and coarse sand and ripple- and horizontally-bedded fine sand. The deformation structures consist mainly of tight to isoclinal and gently inclined to recumbent folds, and thrust faults. Large deformed sand rafts have also been injected into the overlying diamicton in places.

In Pit A, where four sections were logged (Sections 1 – 3 and 9, Figs. 3 and 9), the thickness of the exposed sediment was up to 6.5 m. In the lowermost fold forms in Section 1, the fold plane measurements indicate an applied shear-stress field from the north (plot Def 1A in Figs 9 and 10). However, fold axis measurement in one fold-nose indicates a fold axis dip towards the north (10°) suggesting shear-stress from the west. Another fold axis from a second fold at the same level dips towards the north-west (300°) implying shear-stress from the south-west. Further up in Section 1 (plot Def 1B in Figs 9 and 10) and Section 9, thrust fault plane measurements indicate that thrusting occurred from the south-west (thrust fault plane dip directions 190° and 210°). In other fold-forms in Section 3 (Fig. 9, plots Def 3A and Def 3B), fold plane and fold axis measurements suggest that a stress from the north-west was applied when the deformation took place. Fold plane measurements in Section 2 show both north-western and south-western shear stress directions (Fig. 9, plot Def 2)

In Pit B, thrust-plane measurements and fold plane and fold axis measurements indicate a shear-stress di-

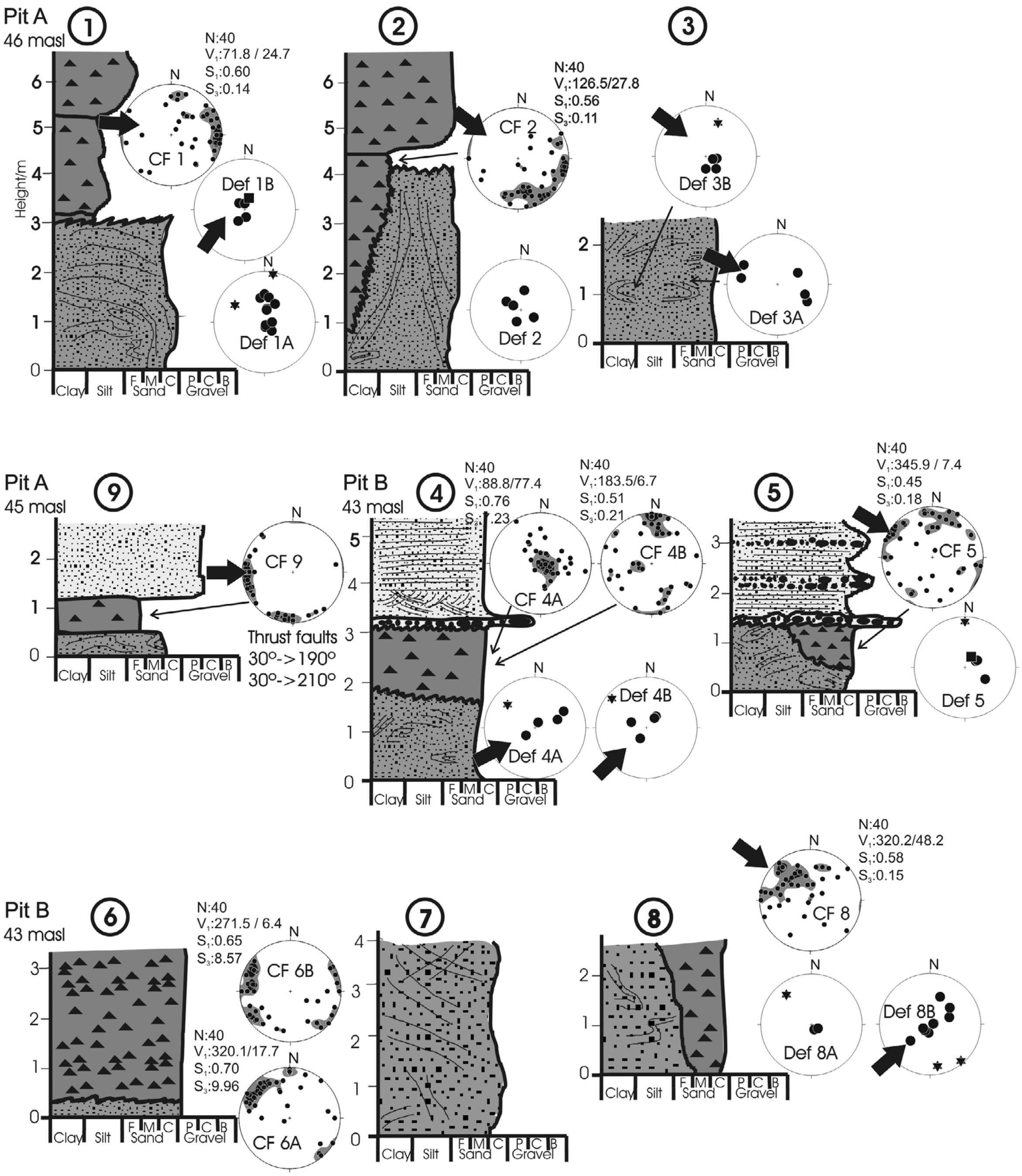

Fig. 9. Section logs from the Hangaskangas area. For a full key see Fig. 4. See Fig. 3 for the location of pits and sections.

rection from the south-west (Fig. 9, plots Def 4A, Def 4B, Def 5 and Def 8B). Nevertheless, in some folds a shear-stress direction from the north-west can also be seen in the fold-plane measurements.

Based solely on the measurements of thrust fault- and fold planes combined with the fold axis measurements and the attitude of fold-forms in the Hangaskangas area, it seems that the deformed sand facies have undergone a complex deformation history including plastic and brittle deformation. Two main stress fields applied first from the north-west and subsequently from the south-west were observed. It is noteworthy that the thrusting from the south-west is the latest stress field direction since these thrust-planes cut the sediment strata.

Diamicton facies FA2

Diamicton overlies the deformed sand facies in most of the sections in the Hangaskangas area, except in Section 3 in Pit A and Section 7 in Pit B (Fig. 9) where the top part of the exposure has been removed during the exploitation of sand. The thickness of the diamicton unit is over 6 m in places (Figs. 9 and 10). In Pit A, the lower part of the diamicton unit is clay-rich and massive (Figs. 9 and 10, Sections 1 and 2). In Section 1, the diamicton overlies a clay silt layer, 0.1 m thick, but in most sites clay-rich diamicton overlies the deformed sand facies FA1 and the contact between the deformed sand and the clay-rich diamicton is erosional but undulating (Fig. 10). At most sites the lower contact of the diamicton unit conforms with the fold forms in the deformed sand facies FA 1.

The top part of Facies FA2 in Pit A, Sections 1 and 2 consists of matrix supported, massive sandy diamicton (Figs. 9 and 10) which is occasionally silt-rich. The contact between two diamicton units is sharp. In Pit A, Section 9 and Pit B, clay-rich diamicton is absent and the matrix-supported sandy diamicton overlies a deformed sand facies, except in Pit B, Section 8 where sand and gravel have been thrust over the diamicton unit.

Clast-fabric measurements from the diamicton facies FA2 were carried out in six sections. In Pit A, Sections 1 and 2 the clast-fabric analyses from the clay-rich diamicton indicate a statistically significant orientation of clast a-axis (over 99 % confidence level) with a relatively high mean dip angle (24°) towards the east and the south-east (plots CF 1 and CF 2 in Figs. 9 and 10). Statistically significant clast-fabric orientation (over 99 % confidence level) was also obtained from the sandy diamicton in Pit B, Section 8, where clast a-axes have a very high mean dip angle (35°) towards the north-west (Fig. 9, plot CF 8).

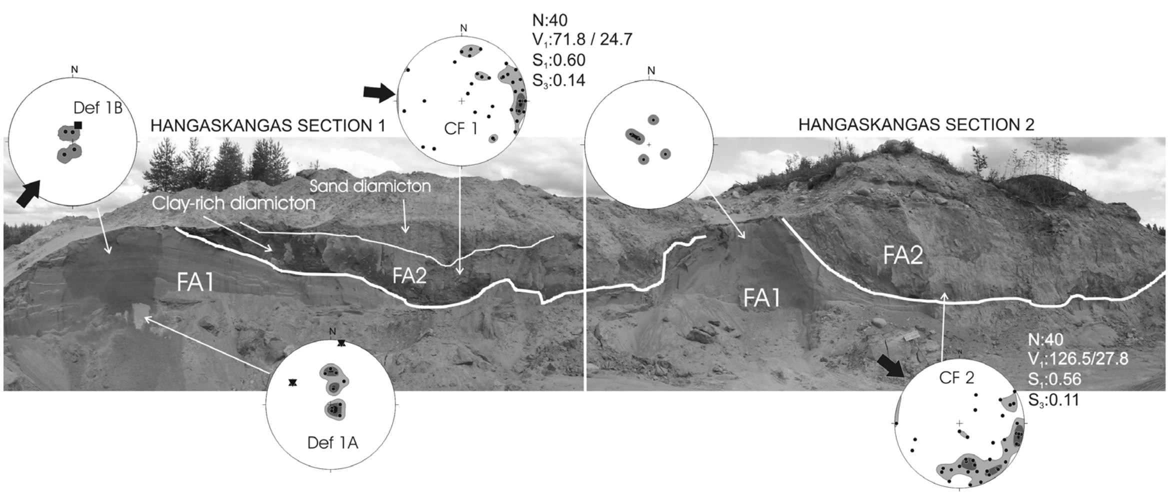

Fig. 10. Sections 1 and 2 in Pit A, in the Hangaskangas area showing deformed sand and gravel facies FA1 and diamicton facies FA2. Stereo plots Def 1A, Def 1B and Def 2 show the fold plane, fold axis and thrust fault plane measurements from Facies FA1 and stereo plots CF1 and CF2 clast fabric measurements from the clay-rich diamicton in Facies FA2. The height of the section is 6.5 m. Thick solid lines mark the boundary between Facies FA1 and Facies FA2 and the thin solid line marks the sharp contact between clay-rich diamicton and sandy diamicton. For symbols in stereo plots see caption in Fig. 4.

In Pit B, Section 4 (Fig. 9, plots CF 4A and CF 4B) and Section 6 (Fig. 9, plots CF 6A and CF 6B) four clast-fabric analyses indicate random orientation of clasts in the sandy diamicton, while in Section 5 (Fig. 9, plot CF 5) the clast-fabric is relatively well oriented (confidence level 97 %) dipping towards the north-west. In Pit A, Section 9 the clast-fabric measurements carried out from the sandy diamicton indicate a significant dip of clast a-axes towards the west and the south indicating ice-movement or shear-stress from the south (Fig. 4, plot CF 9).

The clast-fabric data, together with other properties of the diamicton facies exposed in the Hangaskangas area, strongly suggest that there is a very weak orientation of clasts in diamicton at most sites studied. In addition, it is typical that the clast a-axes dip angles are normally very high, for example over 77° in Section 4. However, the clast-fabrics of the sandy diamicton in Section 9, together with thrust-plane orientations in the underlying deformed sand facies (FA1), indicate that this diamicton represents subglacial till that entered the area from the west or the south-west. It is not possible to draw any conclusion on the ice movement direction or genesis of the diamicton unit in the Hangaskangas area based only on the clast-fabric evidence from other sites. On the other hand, the massive clay-rich diamicton and massive sandy diamicton are compact and over-consolidated showing foliation and shear structures within the unit. Taking this together with the lower contact of the diamicton facies, which is conformable to the fold-forms in the deformed sand and gravel facies (FA 1) beneath, it is most likely that originally the diamicton was deposited by glacial ice but simultaneously or subsequently deformed at the same time as the underlying sand facies.

Sand and gravel facies (FA4)

The sand and gravel facies (FA 4), up to 2 m thick, occurs only in Sections 4 and 5 in Pit B (Fig. 9) where it overlies the diamicton facies (FA 2). The lower part of the facies consists of clast-supported pebble to cobble gravel, 0.1 – 0.2 m thick. The cobble gravel unit is overlain with sets of planar cross-bedded medium sand, 1 to 5 cm thick sets of horizontally-bedded medium to coarse sand and granule gravel.

The sand and pebble gravel facies at the top of the Hangaskangas area represents typical beach deposits. This sand facies is common also in adjacent areas surrounding the sand pits studied here. Based on borehole and ground penetrating radar studies, the topmost sand and gravel facies gets very thick (over 15 m) and includes shell material just a few hundred metres east of the sand pits.

4. Discussion and conclusions

In the Isoniemi and Hangaskangas areas the two lowermost facies, the deformed sand and gravel facies FA 1 and the diamicton facies FA 2, are of special interest for the glaciotectonic and ice movement history in the Oulu region. The exposures in the Isoniemi area are extensive enough to reconstruct a relatively coherent picture of the events that took place during the deposition and deformation of sediments. However, the information gathered from the exposures in the Hangaskangas area is relatively sparse since the upper part of the sequences has been removed during sand exploitation at this site.

The evidence obtained from the deformed sand and gravel facies, FA 1, in the Isoniemi area indicates that two main stress directions, one from the south-west and the other from the north-west, were applied by overriding ice when the sediments were deformed. In the lower part of the facies deformation structures are rare and, for example in Pit F (Fig. 5), the basal sediments are almost undeformed sub-aquatic fan-type deposits. Higher in the sequence the deformation structures become more abundant including fold structures and stacked folds separated by thrust faults. Measurements of the fold structures indicate that the shear-stress field was applied from the south-west and from the north-west but a clear time relationship between these folding events is difficult to determine. However, the exposures in the Runteli ridge *i.e.* Pit E, and Pit B, Section 14, located at the highest point of the study area clearly indicate that the thrusting took place from the north-west. Thrusting from the south-west was also noted in the lower part of Section 14. In Pit A, folds indicate that folding took place under the applied stress field from the north-west and from the south-west. Most of the statistically significant clast-fabric measurements from till overlying deformed sand in the Isoniemi area indicate a preferred clast a-axis orientation from the north-west to the south-east. The conclusion is that the main ice movement direction into the Isoniemi area came from the north-west and the stress field applied by ice from the south-west predates the north-western ice movement.

In the Hangaskangas area, structural measurements from thrust fault planes and clast-fabric analyses from the sand-rich till in Pit A, section 9 indicate that the latest ice movement, most probably related to the deposition of the sand-rich till unit in the area, was from the west or the south-west. The north-western shear-stress direction was also recognised from the Hangaskangas study area in fold-forms in Section 3 and in clast-fabric analyses in Sections 2, 5 and 8. The western and the north-western clast-fabric direction from Pit A, Sections 1 and 2 was acquired from the clay-rich diamicton overlain by sandy diamicton. The conclusion is that the shear-stress direction that caused the south-west orientated deformation structures and the western clast-fabric orientation postdates the north-western orientation. This matches with the relative age of directions of the crosscutting striae in the Oulu region (Hirvas & Nenonen, 1987; Bargel et al., 1999). On the other hand, in the Isoniemi area the latest shear-stress direction (north-west) is thought to have been induced by oscillation of the ice margin at the final stage of the deglaciation.

The drumlins and other streamlined glaciomorphological features in the Oulu area show ice movement from the north-west (Bargel et al., 1999). The drumlin field with the same orientation occurs also in the South-western Lapland (Mäkinen, 1985; Sutinen, 1992; Sarala, 2005). Gibbard (1979) found a similar direction from till clast-fabric measurements from the last deglaciation Pohjola Till in the Montanlampi section 10 km south-east of the Hangaskangas study area.

The till fabrics measurements from the Late Weichselian deposits in the Hitura pit, in the Pohjanmaa region, show that the first ice movement direction was from the west and the latter from the north-west (Salonen et al., 2007). Nenonen (1995) also recorded the same ice movement pattern from Haapavesi, in the Pohjanmaa region.

The age of the glaciofluvial sediments below the till could not be confirmed in this study. According to Bargel et al. (1999), the glaciofluvial deposits below the till in the Hangaskangas area are older than the Late Weichselian. This suggests that the glaciofluvial deposits in Hangaskangas area were deposited before the Late Weichselian. The age of the glaciofluvial deposits below the till in the Isoniemi area could be similar to those at Hangaskangas, but the possibility that the sediments were deposited in the Late Weichselian prior to the final ice front oscillations from the north-west cannot be ruled out.

The extensive tabular sand sheets (facies FA4), cobble gravel units (facies FA3) and the diamicton unit (facies FA2) changing laterally to the 'lag' horizon between the facies FA1 and FA4 in the Isoniemi area show the subsequent erosion and redeposition of the sediments. The erosion and redeposition took place when the sediments rose to the sea level and were exposed to littoral processes in a beach environment. A comparable succession can be seen in the Hangaskangas area. Other studies from the banks of the Hangaskangas formation (Helle & Ylinen, 1965; Eronen et al., 1995) have identified the beach deposits with remains of kelp (*Focus vesiculosus*) and shells (*Mytilus edulis* and *Macoma baltica)* below the highest shore of the Litorina Sea stage of the Baltic Basin.

The sedimentation history of the Isoniemi and Hangaskangas areas is very complex due to intensively glaciotectonised sediments. However, it seems that the thick accumulation of glaciofluvial sediment interbedded within the several till units that are reported from these areas (Vehkaperä, 1988; Bargel, 1999) were laid down not only during the Late Weichselian, but rather, the majority of the sediments were deposited prior to the Late Weichselian. Based on the results from the upper part of the sequence represent-ed in this study it is suggested that there is indication of pre-Late Weichselian glacial sediments in both the Hangaskangas and Isoniemi areas.

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