A sedimentological and stratigraphical study of Weichselian sediments in the Tvärkroken gravel pit, Idre, west-central Sweden

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Examensarbeten i Geologi vid
Lunds universitet - Kvartärgeologi, nr. 222
(30 ECTS credits)

Geologiska institutionen
Centrum för GeoBiosfärsvetenskap
Lunds universitet
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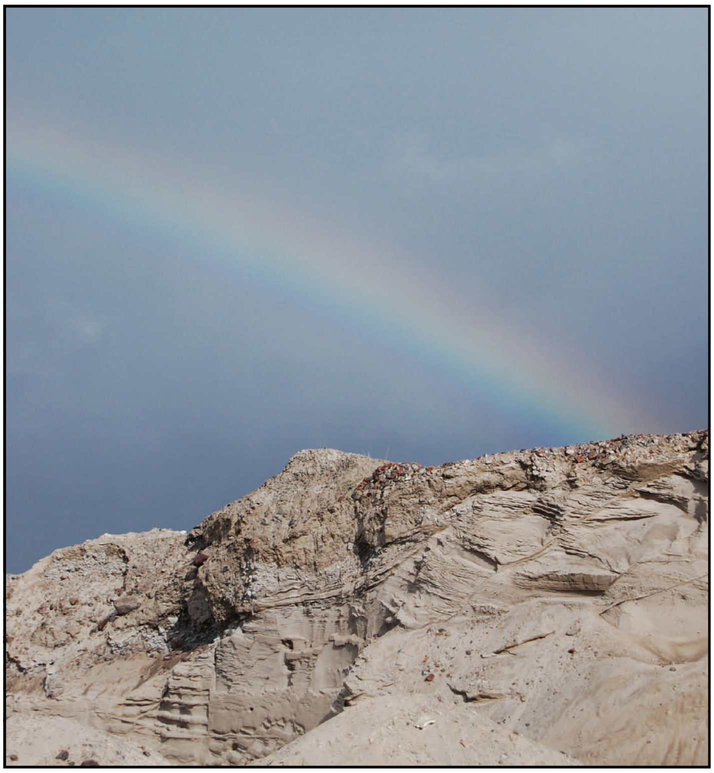

Master Thesis

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Anjar, J. 2008: A sedimentological and stratigraphical study of Weichselian sediments in the Tvärkroken gravel pit, Idre, west-central Sweden. *Examensarbeten i Geologi vid Lunds universitet - Kvartärgeologi*, Nr. 222, 31 pp. 30 credits.

Abstract: A detailed sedimentological study was made on six section walls in the Tvärkroken gravel pit, Idre, west-central Sweden. Based on sediment characteristics, three sedimentary units, units 1-3, were identified. The lowest unit, unit 1, was formed by deposition from sediment-loaded underflows into a stagnant basin. A gradual decrease in water depth is indicated in the upper part of this unit. Post-depositional deformation in the form of an ice wedge cast, normal faults, water-escape structures and silt injections are identified in the unit. Unit 1 is overlain by unit 2 with an erosional contact. Unit 2 is characterized by proximal braided river sediments. A gradational contact separates unit 2 from the subglacially deposited sediments in unit 3. Unit 3 consists of a basal diamict, composed of deformed unit 1 and unit 2 sediments transformed into a subglacial traction till. On top of this is a stacked sequence of deformed sediments derived from unit 1 and 2, transformed into both massive diamicts and glaciotectonites, the latter characterized by boudins. Extensive fluvial erosion occurred in the area after the deposition of units 1-3. Channels were then cut into the sediment successions creating a landscape with flat plateaux, terraces and moraine hummocks, left as erosional remnants and separated by deep channels. Units 1 and 2 are suggested to be of a pre-Late Weichselian age, deposited at a stadial/interstadial transition, whereas unit 3 is suggested to be formed either at the beginning or the end of the last glacial phase of this area. The fluvial down-cutting is presumably due to melt-water erosion from the last deglaciation.

Keywords: Dalarna, interstadial, glaciolacustrine, braided river, till.

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En sedimentologisk och stratigrafisk studie av sediment från weichselistiden i Tvärkrokens grustag, Idre, norra Dalarna

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Sammanfattning: Länge var den allmänna uppfattningen att när en inlandsis täckte ett område så förstördes och försvann alla äldre landformer och sediment. Under de senaste 20 åren har dock den uppfattningen ifrågasatts och fler och fler bevis hittats för att äldre landformer och sediment, det vill säga lösa material som transporterats av vatten, vind eller is, kan bevaras under en inlandsis. Det undersökta grustaget, Tvärkrokens grustag, ligger utanför Idre i ett område med många spår av äldre istider och isavsmältningar. Avsikten med arbetet är avgöra i vilka miljöer som sedimenten avsatts och därigenom få en pusselbit till norra Dalarnas istidshistoria.

Genom att undersöka och beskriva sedimenten med avseende på kornstorleksfördelning och strukturer så kunde tre olika enheter, avsatta i skilda miljöer, identifieras. Dessutom undersöktes landformerna i området med hjälp av flygbilder och fältundersökningar.

Den understa och därmed äldsta enheten består av sand som har avsatts av sedimentrika underströmmar som rört sig längs botten av en lugn bassäng, troligen en sjö. Med tiden så minskade vattendjupet vilket ledde till att strömhastigheterna ökade och grövre sand avsattes. Till sist så torkade sjön ut fullständigt och sjöbotten förvandlades till markyta. Isblock som legat inbäddade i sedimenten smälte bort och orsakade rörelser i de omkringliggande sedimenten.

Enheten ovanför består av lager av sand, grus och sten som transporterats längs botten av ett vattendrag med höga strömhastigheter. Dessa båda understa enheter avsattes troligen under en varmare period av senaste istiden då inlandsisen tillfälligt hade smält bort ifrån området.

Allra överst ligger en enhet som innehåller allt ifrån lera till block. Vissa delar av enheten är massiva medan andra delar består av deformerade bitar av de undre enheterna som brutits loss, dragits ut och veckats. Enheten tolkas som en morän avsatt vid botten av en inlandsis. Isen har plockat upp material från de andra enheterna och blandat eller deformerat dem. Den bildades förmodligen vid slutet av den senaste istiden då inlandsis senast täckte området.

När isen smälte bort ifrån området runt Idre för ungefär 10600-10400 år sedan sköljde smältvattnet bort en del av de avsatta sedimenten, framför allt moränen som låg överst, och skapade ett landskap bestående av flacka platåer separerade av djupa kanaler.

Nyckelord: Dalarna, interstadial, glacilakustrin, flätflod, morän

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1 Introduction

1.1 Glacial history

The glacial history of the area around Idre in west-central Sweden (Fig. 2) is complex and not fully understood. The area was first investigated by Mannerfelt (1938) and Frödin (1925). They both concluded that the last ice divide in the area existed between Städjan and Storvätteshågna, a conclusion that Borgström (1989) shared.

Ljungner (1949) identified two different glacial stages in west-central Sweden. During the first stage, which he called the “Prime Glaciation”, the ice sheet was westerly centered with its ice-divide in the Scandinavian mountain chain. The next stage which he called the “Posterior Glaciation” was separated from the Prime Glaciation by the “Interval”, a period of deglaciation of the foreland and parts of the mountains which Ljungner (1949) interpreted as an interstadial. The Posterior Glaciation began as a mountain-centered ice-sheet with its ice-divide in the west but expanded toward the south and the ice-divide moved eastwards.

The deglaciation history was investigated by Borgström (1989) who used landscape morphology analysis in order to reconstruct the latest stages of the Late Weichselian glaciation in the southern part of the Swedish mountains, from Städjan in the south to Åreskutan in the north. During what he called the “Nunatakk stage”, when only the summits of Nipfjället and Städjan were above the ice, he suggested that there was an ice-divide between Nipfjället and Storvättes-hågnen and an ice-direction from southwest in the Idre area although the evidences for the southwesterly ice-direction during this stage were a bit limited (Fig. 1A). When more of the ice melted away around Nipfjället and Städjan the ice-direction changed to a flow from the west in the area west and south of Hemmeråsen, while the ice came from the north in the Nipfjället area (Fig. 1B and C). During the last stage of the deglaciation, the ice-direction was from the north to northwest in the area north of Nipfjället while the ice in the area west of Idre had probably stagnated (Fig. 1D) (Borgström 1989).

According to the clay varve chronology used by Boulton et al. (2001), the Idre area was deglaciated between cal. yr. 10600 and 10400. According to Lundqvist (1986b) the deglaciation east of the Scandinavian mountains was without re-advances after the Younger Dryas.

The Early and Middle Weichselian history of west-central Sweden is poorly understood. The general agreement seems to be that the area was glaciated during the Early Weichselian (Boulton et al. 2001) and then deglaciated at least once before the end of the Weichselian (Ljungner 1949; Boulton et al. 2001), an ice-free period called the Peräpohjola/Jämtland inter-stadial (Lundqvist 1986a; Donner 1996; Arnold et al. 2002) but when it comes to the timing and number of interstadials the opinions diverge. The Peräpohjola/ Jämtland interstadial is often placed in the Early Weichselian and is usually correlated to the Brørup interstadial in Denmark. However, for some sites a correlation to the Odderade interstadial is suggested (Donner 1996). Correlations to the Middle Weichselian have also been made (Arnold et al. 2002; Andersen and Mangerud 1989). Arnold et al. (2002) and Andersen and Mangerud (1989) propose that most of Fennoscandia might have been deglaciated during Oxygen Isotope Stage 3. This is supported by the radiocarbon dates from central to northern Sweden of 32 and 42 ka BP mentioned by Lundqvist (1986a) but the reliability of these dates is questioned by both Lundqvist (1986a) and Donner (1996). Donner (1996) suggested instead that most parts of Norway, Finland and Sweden were glaciated during all of the Middle Weichselian.

1.2 Pre-Late Weichselian sediments

In the earliest investigations of the area most of the sediments and morphology were assumed to be of Late-Weichselian or Holocene age and older sediments were only described from small areas. Lundquist (1951) describes two sites, at Öje and in the Rättvik delta, where pieces of wood were found below till and below delta sediments respectively. Both findings were interpreted as being of pre-Late Weichselian age. Lundquist (1951) also suggested that the deep weathering of bedrock observed at a few places in Dalarna is of pre-Late Weichselian age, but interprets the main parts of the landscape to be of a Late-Weichselian or Holocene age.

During the 1980s studies from northern Sweden (Lagerbäck 1988a,b; Lagerbäck and Robertsson 1988) challenged the view that most of a pre-existing landscape had to be eroded away when an area became glaciated. Lagerbäck (1998a) concentrated on the Veiki moraines and its most typical feature, the Veiki plateau, which are common in the county of Norrbotten, northernmost Sweden. The Veiki plateaux are more or less circular plateaux, surrounded by one or more rim ridges. ^{14}C-dates of organic material in silty/sandy sediments in the central parts of the plateaux reveal ages ranging from 17 000 BP to infinite with the infinite ages being interpreted as the most reliable. The moraines were concluded to be younger than the first Weichselian glaciation since that was too active in the area for them to survive (Lagerbäck 1988a; Lagerbäck and Robertsson 1988). According to Lagerbäck (1988a) the most likely interpretation is that the sediments were deposited during the deglaciation proceeding the Peräpohjola interstadial, since the Tärendö interstadial is supposed to have been too cold for the amount and types of organic sediments found. The Veiki plateaux are extremely well preserved which means that the erosion and activity of the Middle and Late Weichselian glaciation must have been very low in the area. This condition is further explored in Lagerbäck (1988b) where he describes frost-shattered bedrock, ventifacts abraded by snow or ice, ice-wedge casts and

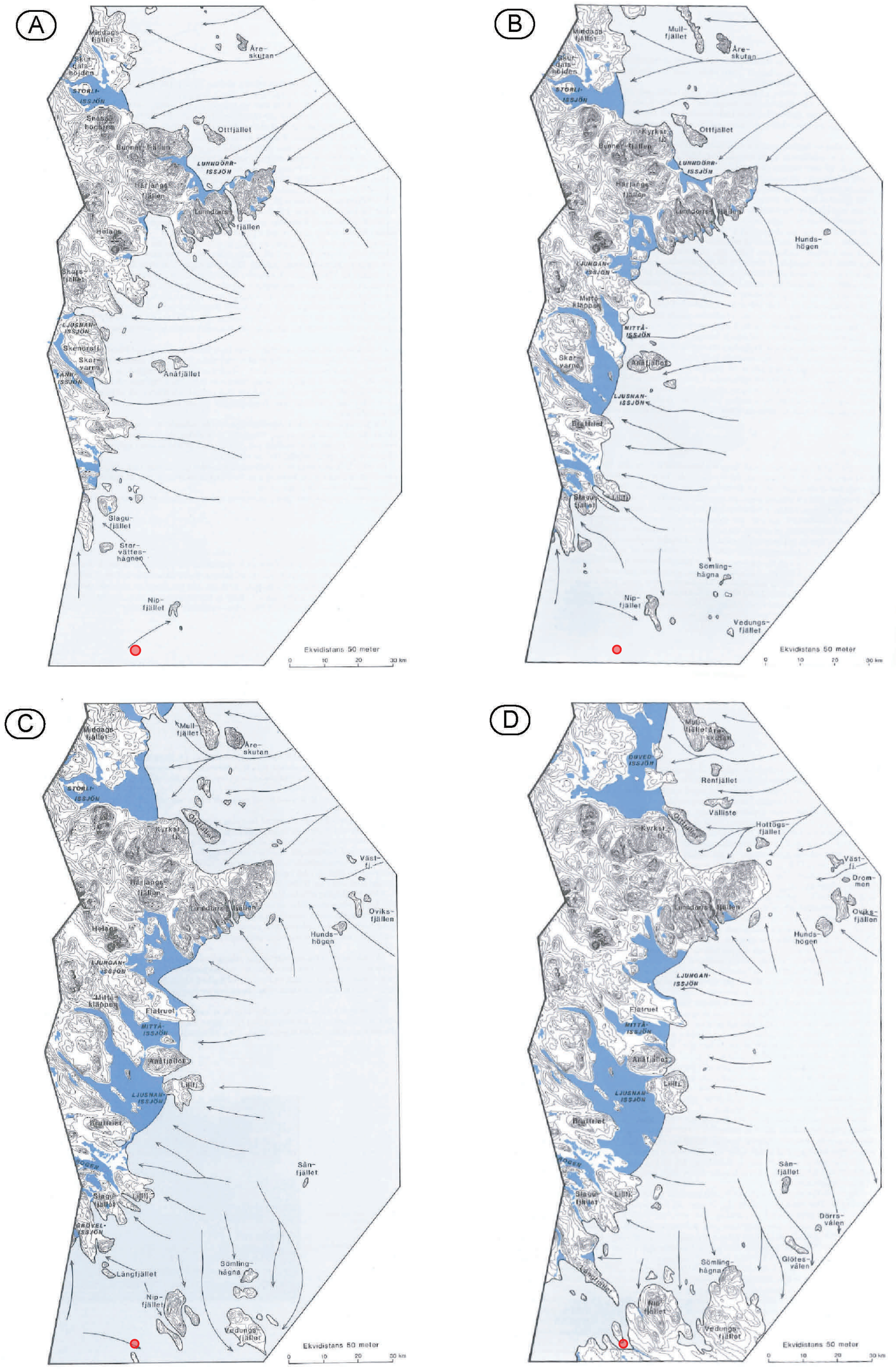


Fig. 1. The deglaciation history of west-central Sweden, reconstructed by Borgström (1989). The red dots mark the position of the Tvärkroken gravel pit. A) The summit of Nipfjället is deglaciated. The ice direction is from southwest in the Idre area. B) An ice-divide exist between Nipfjället och Storvätteshågnen. The ice direction is from the west in the Idre area. C) The ice-divide is further developed. The ice direction is still from the west. D) Only stagnant ice remains in the area around Idre. (Figures from Borgström 1989, slightly modified.)

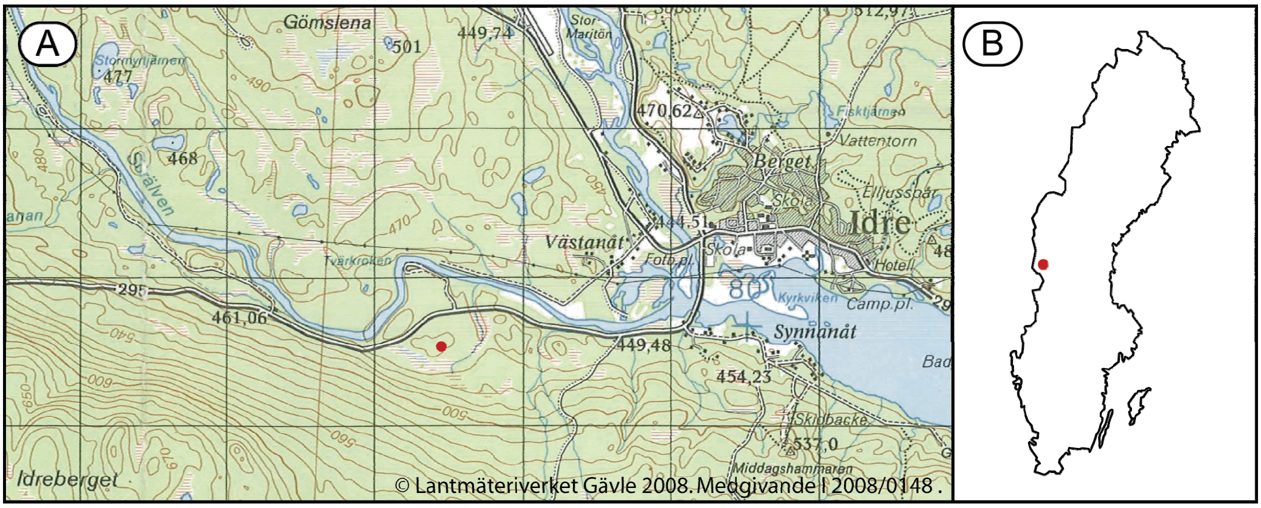


Fig. 2. A) Terrain map over the Sörälven river valley. The red dot marks the position of the Tvärkroken gravel pit. Each square in the terrain map has the side of 1 km (Topografisk karta över Sverige 16C Idre SO Lantmäteriet 1978). B) Overview map over Sweden. The red dot marks the position of Idre.

cryoturbation, some of it as far south as the northern parts of Dalarna. None of these features are likely to occur in the warm climate during Holocene. Instead Lagerbäck (1988b) suggests that they represent the Tärendö interstadial.

Studies in west-central Sweden by Borgström (1989), Kleman et al. (1992) and Möller (2006) suggest that pre-Late Weichselian sediments and landforms could be preserved in this area too.

Borgström (1989) suggested that the glacially transported boulder blankets at Nipfjället, the drumlinized and medial or lateral moraines at Städjan and Nipfjället and possibly also the Rogen moraines in several of the valleys are of pre-Late Weichselian age.

Kleman et al. (1992) studied the morphology and stratigraphy of lateral drainage channels in the Transtrand Mountains, approximately 75 km south of Idre. Their study indicated at least four deglaciation events with formation of lateral channels in the area. The lateral channels from the latest deglaciation indicated an ice-flow from northwest while the ice-flow from the second latest deglaciation came from west-northwest, the third latest glaciation from the east and the oldest deglaciation from the north. The relative dating of the channels from the easterly ice-flow (third latest deglaciation) and north ice-flow (oldest deglaciation) was a bit uncertain. Möller (2006) did sedimentological investigations on Rogen moraines in central Dalarna and concluded that Rogen moraines are reshaped remains of pre-existing transverse ridges at the investigated site, originally formed by controlled moraine formation in a stagnant ice and that the ridges were later overridden and deformed by an active ice sheet. Since no evidence support such a deglaciation and re-advance in the area during the last deglaciation, Möller (2006) concluded that the original transverse ridges are older, presumably Early Weichselian in age.

1.3 Aim and area description

The aim of this study is to determine the genesis of the sediments in an exposure outside Idre in Dalarna, central Sweden (Fig. 2) and to interpret how the formation of the sequence fits into the glacial history of the area.

For the investigation a gravel pit situated 2 km west of Idre was chosen, the Tvärkroken gravel pit Fig. 2 and Fig. 4AB). The area is situated in the eastern fringe of the Scandinavian mountains and is surrounded by relatively low and rounded mountains, only a few of them high enough to reach above the tree line. The area is of great quaternary geological importance due to its occasional position beneath an ice divide (Mannerfelt 1938; Frödin 1925; Borgström 1989) and the evidence for pre-Late Weichselian deposits and landforms (eg. Borgström 1989). The investigated gravel pit is situated in the Sörälven river valley, which is an east-westerly directed valley with the fairly steep mountain Idreberget on its south side and the gentle sloping terrain toward the mountain Höstet in the north. The Sörälven river converges with the Storån river from the north just outside Idre (Fig. 2). Lundqvist (1951) made a map of Quaternary deposits over Kopparbergs Län, the county where the investigated site is situated. For the Idre area he interpreted the most common sediment type to be a boulder-rich, sandy to gravelly sandy diamicton in the higher areas, while the valleys of the Sörälven and Storån rivers were covered with glacifluvial gravel. Peat bogs occur in the lower parts of the terrain and rock outcrops are visible just south of the investigated gravel pit.

The bedrock in the area has been described on a bedrock map in scale 1:250000 by Källberg et al. (1991). The Tvärkroken gravel pit lies in the northern part of a large area with Jotnian sandstone and

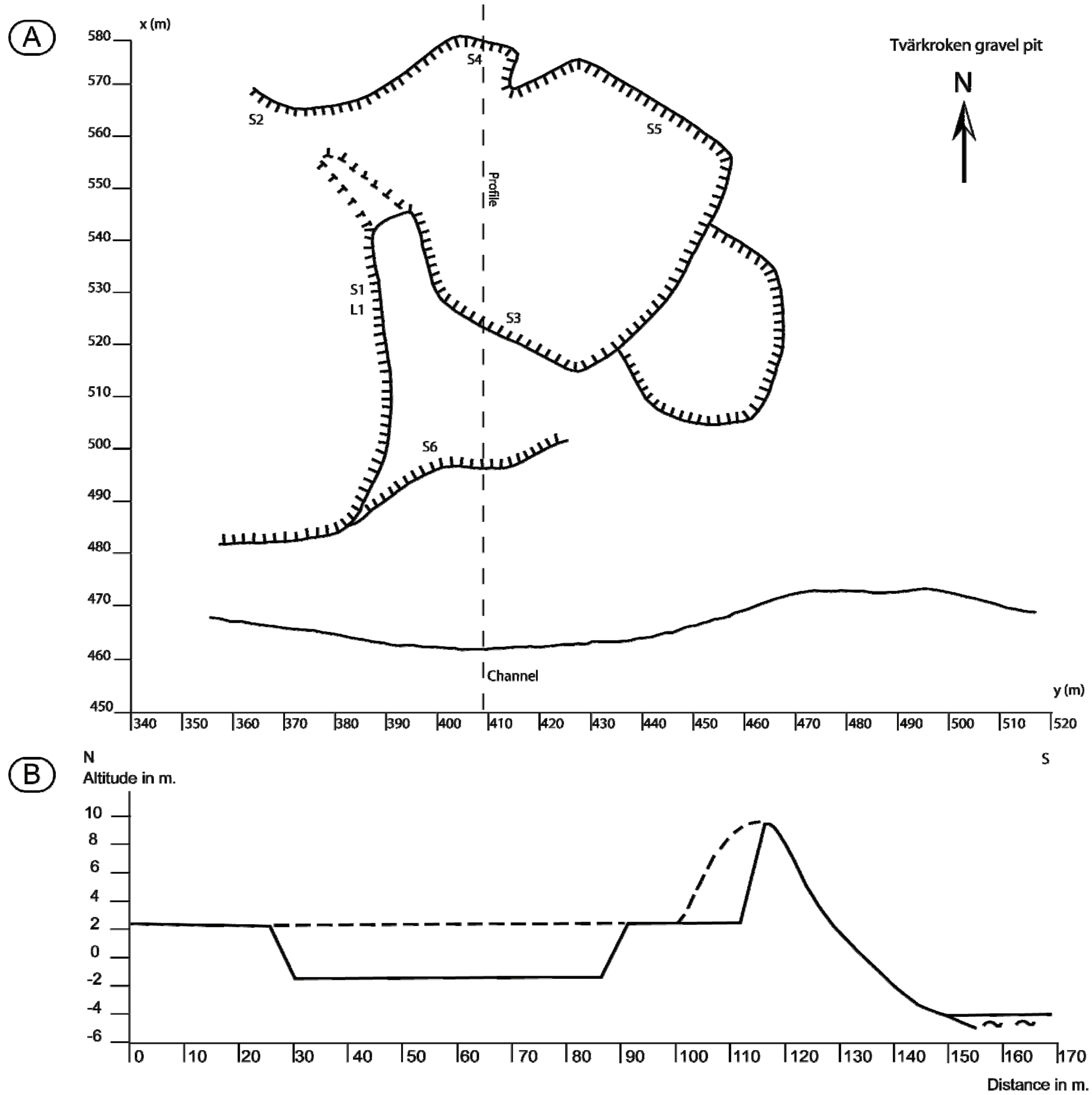


Fig. 3. A) Schematic map over the section walls in the Tvärkroken gravel pit. Sections 1-6 are marked as S1- S6, log 1 is marked L1. The hatched part of the map consists of fill. B) Profile across the gravel pit as marked in A). The hatched part of the profile is the interpreted pre-excavation surface.

dolerite. Further north, at the edge of the mountain chain, is a zone with Cambrian quartzite and alum shale, followed by quartzites, sandstones and areas of augen gneiss and a Precambrian granitoid. Northwest of the Tvärkroken gravel pit is an area with mica schist and quartzite, while Dala porphyry is found in an easte and west direction from the gravel pit.

2 Methods

An overview of the morphology of the area was made by air-photo interpretation. The aerial photos used were panchromatic in the scale 1:30000 covering two lines, one from Hösthån in the north to Mellre Fulusjön in the south and the other from Burusjön in the north to Byggningsjön in the south (x: 6870121-6855136 y: 1332499-1332503 and x: 6874840-6854857 y: 1337435-1337463, coordinates in meters in the coordinate system RT 90). The photos were analysed using Topcon-stereoscope and the interpreted landforms were drawn on an overlaying plastic cover.

The field study was made in the Tvärkroken gravel pit, 2 km west of Idre. The gravel pit configuration was mapped using a GPS (Garmin eTrex) with an accuracy of ± 5 m and a vertical profile across the gravel-pit was constructed from measurements with a Leica Kernlevel (Fig. 3). Six sections, section 1-6 in Fig. 3, in different parts and levels of the gravel pit and representing all the visible sedimentary units, were cleaned and mapped. Two-dimensional section drawings in scale 1:20 were made on section 1, 3, 4, 5 and 6. The sediment beds and larger clasts were drawn on graph paper in the field using horizontal strings and levelling rods at 0.5 (section 1, 3, and 6) or 1 meter distances (section 4 and 5) as scales and reference lines. Due to its height

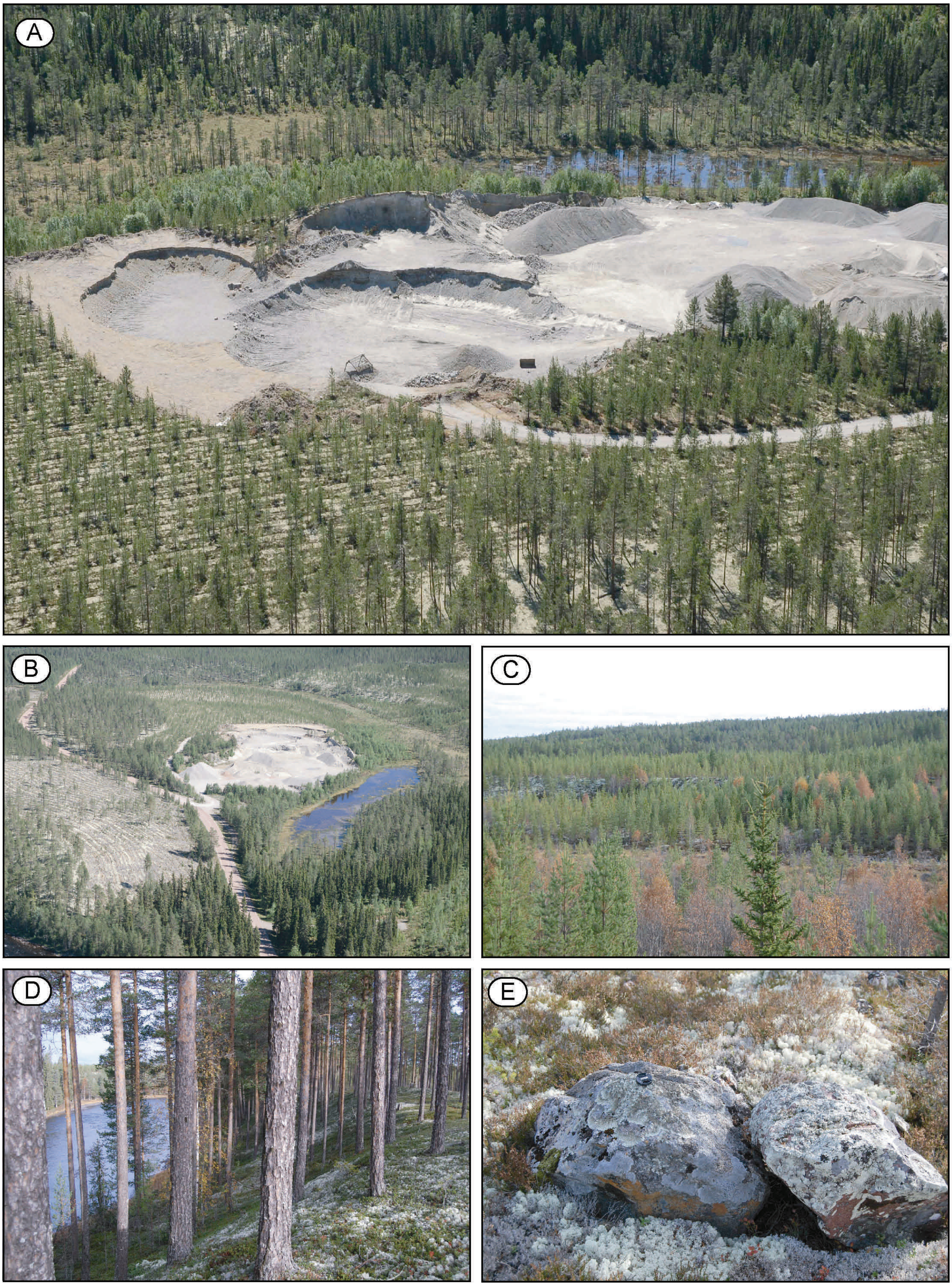


Fig. 4. Tvärkroken gravel pit seen from the north A) and west B). C) View from the top of the Tvärkroken gravel pit plateau (plateau 1 in Fig. 17) and southeast across the channel toward the next plateau (plateau 2 in Fig. 17). D) The slope of the Tvärkroken gravel pit plateau toward the Sörälven river. E) Boulders on top of the Tvärkroken gravel pit plateau. The lens hood is approximately 5 cm in diameter. Photographs 4A and B were taken by Per Möller.

section 6 had to be mapped in two steps: first the lower part was logged after which the upper part was cleaned and logged and the drawings of the two parts were fit together. Photographs were used to add information on the sediment structures when the section drawings were re-drawn.

Sediments in sections 2, 4 and 5 and in log 1, a few meters south of section 1, were also vertically logged at a scale of 1:10. Samples were taken for grain size analyses, clast morphology and OSL dating.

Two samples were taken in section 6 (Fig. 12) for analyses of clast roundness and morphology. From the lower unit, 34 clasts with a-axis ranging from 5 to 11 cm, and from the unit above 45 clasts with a-axis ranging from 3.8 to 10.3 cm were taken. The roundness of each clast was classified to the six classes: very angular, angular, subangular, subrounded, rounded and well rounded, proposed by Powers (1953) and a, b and c-axis of each clast was measured and plotted in a general shape triangle (Sneed and Folk 1958) using the TRI-PLOT spreadsheet described by Graham and Midgley (2000) (Fig. 13).

Six samples (sample 1.1 in Fig. 7, sample 2.1 in Fig. 6, sample 3.1 in Fig. 8, and samples 6.1, 6.2 and 6.3 in Fig. 12) were taken for grain size analyses. The samples were dried in 105˚C for between 12 and 16 hours. Clasts larger than -4.5 phi (22.4 mm) were taken away from each sample and the weight of the sample was measured before all the grains smaller than 3.5 phi (0.063 mm) were washed away, after which the samples were dried again. The new dry-weights were measured and the samples shaken through a series of sieves, with mesh openings in 0.5 phi intervals. The weight of the sediment in each sieve was measured and plotted in Appendix 1.

Hydrometer analyses were made on the samples where sediment grain sizes less than 0.063 mm composed more than 5% of the total sample (samples 3.1 and 6.1-6.3). Approximately 50 g of the fractions less than 2 mm was used from the unwashed remains of each sample. The weights were measured with two decimals and the samples were rotated together with 300 ml distilled water and 100 ml 0.05M $Na_4P_2O_7$ for 15 min. Distilled water was added until the volume of the sediment and the liquid together was 990 ml and the mixture was then stirred for one minute. The hydrometer was then put into the mixture and 10 more ml of distilled water was added in order to clean the walls of the 1000 ml cylinder. Time was taken from the moment the stirring ceased. The hydrometer was read after 0.5, 1, 2, 5, 10, 20, 50, 100, 200, 400 and 1440 min and the mixture was then restirred and the first 20 min of measurements were performed once again.

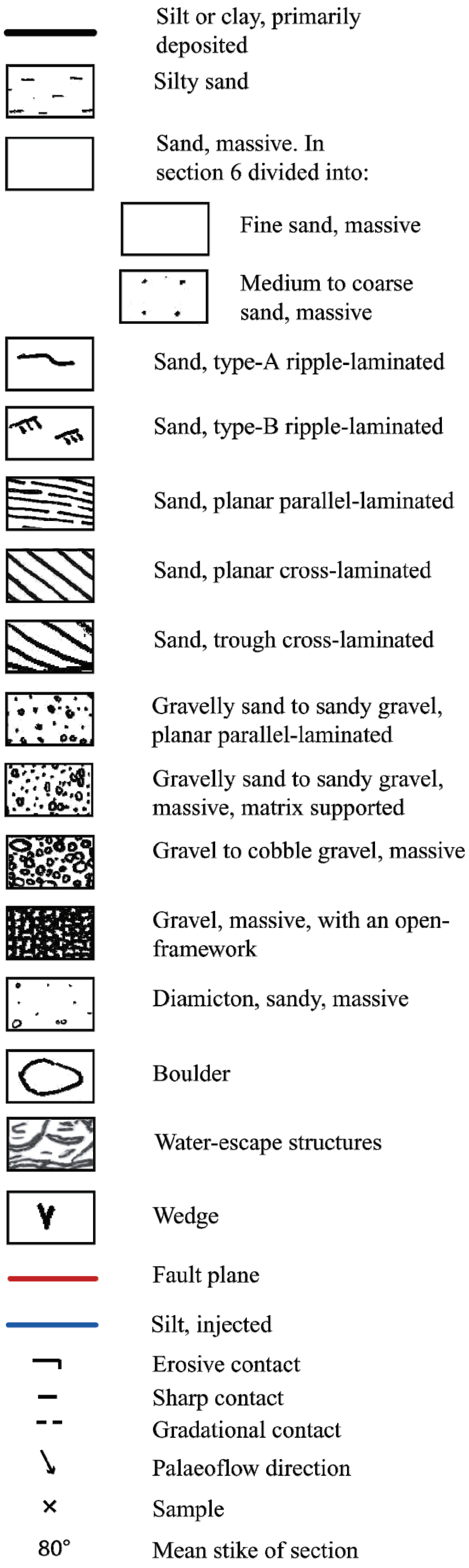
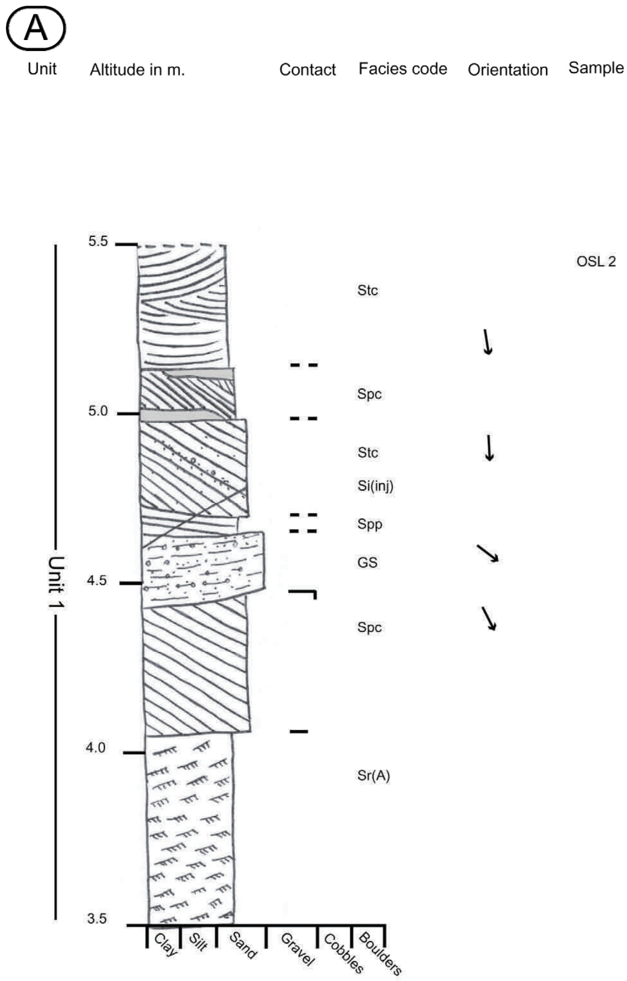
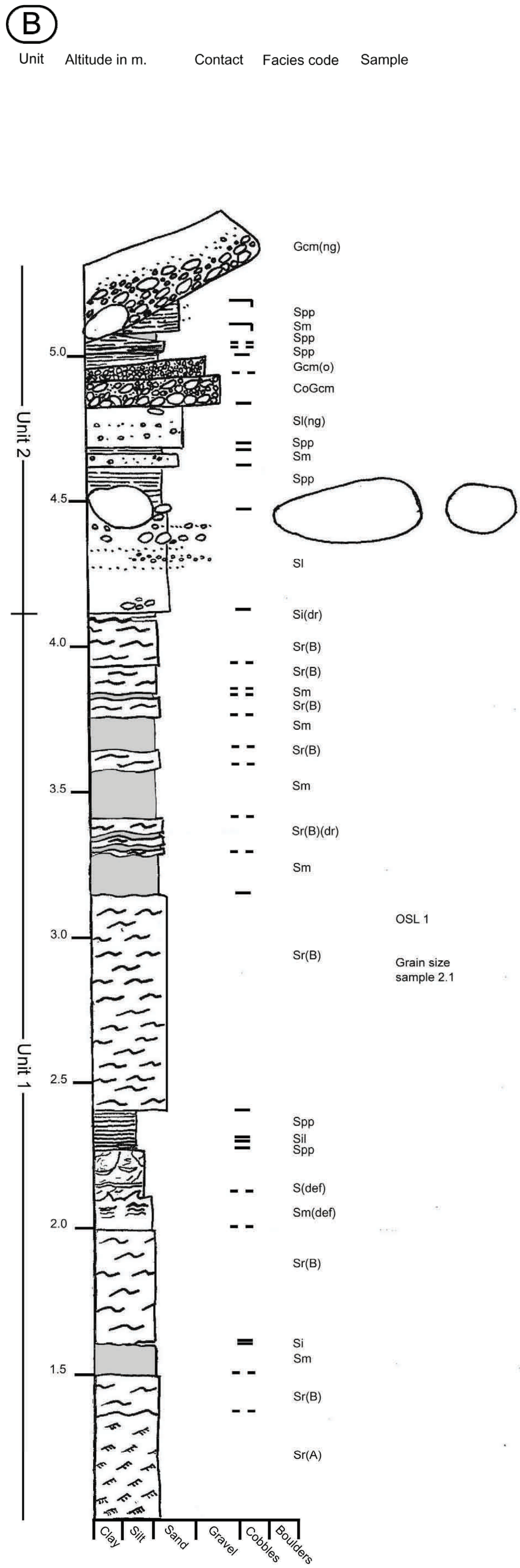


Fig. 5. Legend to figures 6-9 and 11-12.





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Lithofacies code	Lithofacies type desctription
Cl	Clay
Si	Silt
Sil	Silt laminated
Si(dr)	Silt, draped
Si(inj)	Silt, injected
Sm	Sand, massive
Sm(ng)	Sand, massive, laminated, normally graded
Sm(def)	Sand, massive, deformed
S(def)	Sand, deformed
Sr(B)	Sand, type-B ripple-laminated
Sr(B)	Sand, type-B ripple-laminated, draped
Sr(A)	Sand, type-A ripple-laminated
Sl(ng)	Sand, laminated, normally graded
Spp	Sand, planar parallel-laminated
Spc	Sand, planar cross-laminated
Stc	Sand, planar cross-laminated
GS	Gravelly sand
GSl	Gravelly sand, laminated
GSmm(ng)	Gravelly sand, massive, matrix supported, normally graded
SGmm	Sandy gravel, massive, matrix supported
SGpp	Sandy gravel, planar parallel-lamninated
Gmm	Gravel, massive, matrix supported
Gcm(ng)	Gravel, clast supportet, massive,

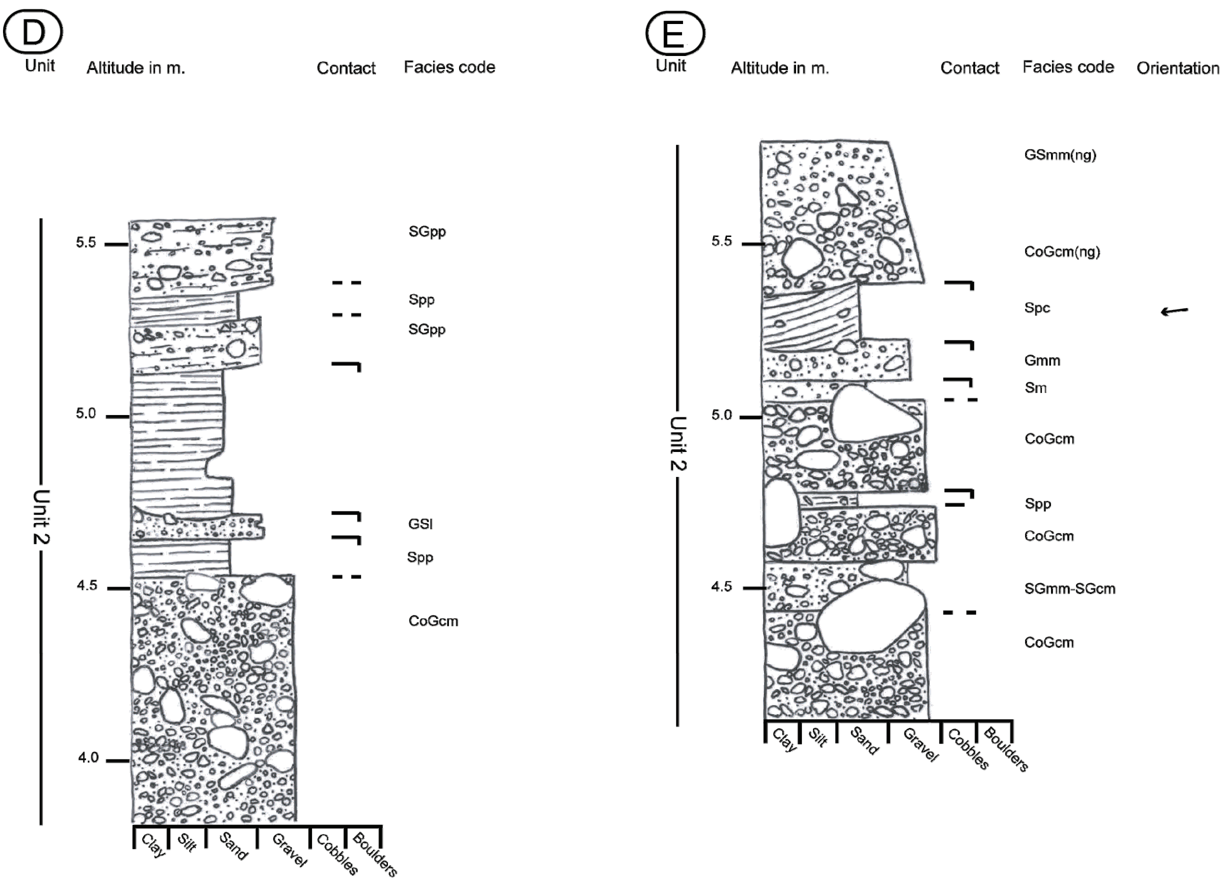


Fig. 6. A) Log 1, marked as L1 in Fig. 3. B) Log 2, made in section 2 (S2 in Fig. 3). C) Explanations for the lithofacies codes used in the figure. D) Log 4, made in section 4 (S4 in Fig. 3), position in section 4 shown in Fig. 9. E) Log 5, made in section 5 (S5 in Fig. 3), position in section 5 shown in Fig. 11. Elevations represent the height over local ground reference point. Lithofacies as described by the legend in Fig. 5.

3 Results

3.1 Area overview

The investigated gravel pit lies in the Sörälven river valley at the south side of the Sörälven river. The valley floor is covered by flat plateaux with steep sides. The plateaux are between a few hundred meters up to almost a kilometer across. The Tvärkroken gravel pit lies in one of the plateaux (Fig. 4, plateau 1 in Fig. 17) of which the southeastern side is constrained by an erosional channel which continues into the Sörälven river, while the western and northern sides are constrained by the Sörälven river. The plateau is a few hundred meters across with *c.* 7 high slopes (in the measured profile) and a mainly flat upper surface with some minor depressions. There are scattered occurences of large boulders (1-1.5 m in diameter) on the plateau surface (Fig. 4E), though the plateau is predominantly made up of sorted sediments. A moraine hummock, *c.* 8 m high is situated on the southern part of the gravel plateau, its southern flank being part of the erosional channel (Fig. 3B). Most of the hummock has been quarried away, its original cross-section hatched in the profile. Section 6 is situated in the quarried part of this hummock. Southeast of the channel on the south and east sides of the plateau another plateau (plateau 2, Fig. 17) is situated. It is a few meters higher than plateau 1 and has a surface at approximately the same height as the top of the hummock on plateau 1. Its southern edge is restrained by the walls of Idreberget (Idre mountain) while the west and north sides are steeply sloping. At the edges of plateau 2 a few channels are eroded. The channels are inclined toward the main channel between plateau 1 and plateau 2 although they are not as deep and their upper part continues into small depressions in the plateau surface.

Rogen moraines were identified both in the Sörälven and Storälven river valleys, between 2.5-5 and 8-11 km northwest and north of the Tvärkroken gravel pit. Rogen moraines also occur on the north side of Burusjön. The Rogen moraines in the Sörälven river valley generally have their horns pointing in a southeasterly direction. The Rogen moraines in the Storån river valley are more abundant and better developed than in the other areas, most of them with horns pointing in a southeastern to southwestern direction, which is approximately the same direction as the trend of the river valley. This fits with the localities described by Borgström (1989).

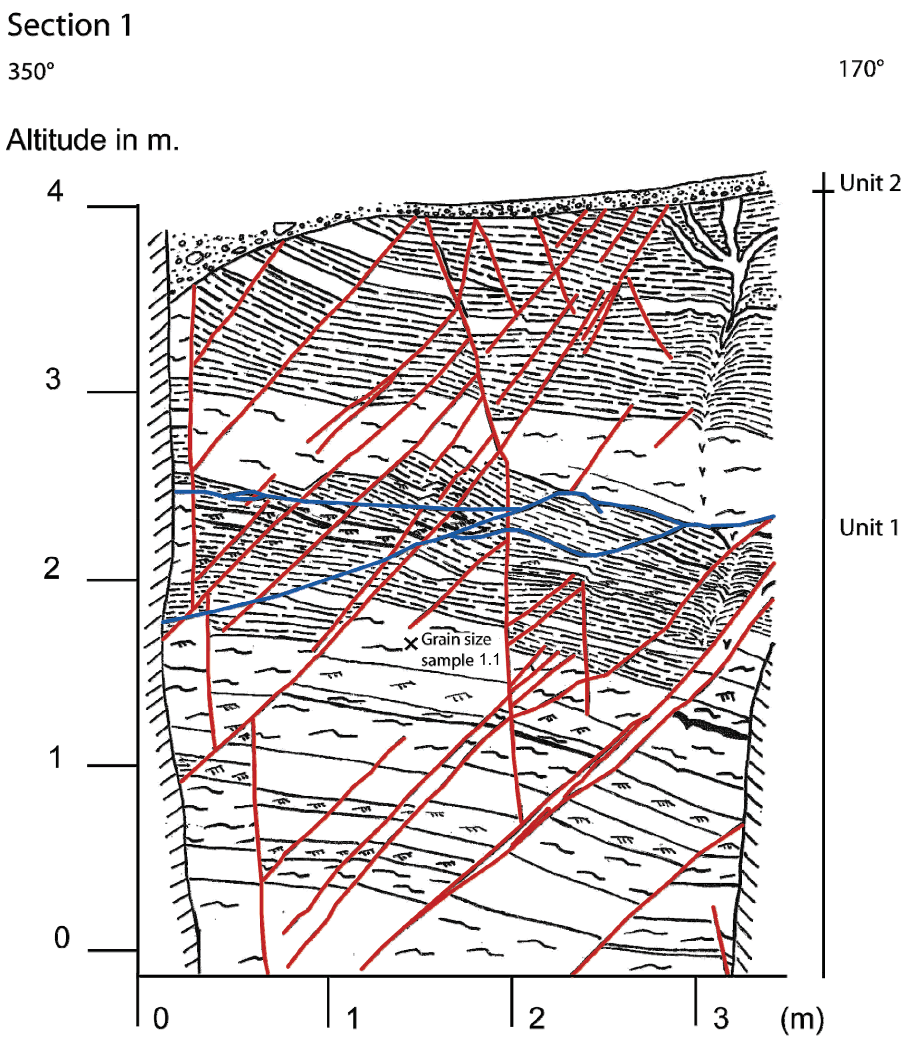


Fig. 7. Section 1. The red lines mark the fault planes while the blue lines show silt injections. Lithofacies as described by the legend in Fig. 5. Elevations represent the height over local ground reference point.

A small drumlin field was identified east of Öresjön, 2.5 km southeast of the Tvärkroken gravel pit with their stoss sides facing northwest. These drumlins have also been described by Borgström (1989).

Channels and plateaux interpreted as the result of fluvial erosion were found on several places in the investigated area. The most prominent forms are found in the Sörälven river valley around the Tvärkroken gravel pit and along the Nysäterån river, 5.5 km south of the Tvärkroken gravel pit. Smaller or fewer forms are found along the Storån river, around Idre and approximately 4 km west of the Tvärkroken gravel pit.

3.2 Sediment descriptions

Based on the sediment studies of the six mapped sections, the sediments were divided into 3 units, namely:

Unit 1: The lowermost unit. It consists of sorted sediments, mainly fine to medium sand. Normal faults are abundant and silt injections occur in some parts.

Unit 2: This unit overlies unit 1 with an erosional contact. It consists of sorted sediments, mainly gravel to cobble gravel but with some sand beds and some larger boulders.

Unit 3: A heterogeneous diamicton which consists of a bimodal, sandy diamicton in most parts while other parts consist of deformed sorted sediments or a silty sandy bimodal diamicton.

3.2.1 Section 1

Section 1, *c.* 4 m high, is cut into unit 1 sediments which, with an erosive contact, are overlain by unit 2 sediments, in the documented part of the section only 0.1 m thick.

Unit 1 consists of a stacked sequence of 1 to 75 cm thick beds of over-consolidated fine sand, interbedded with a few beds of silt and coarser sand, mainly in the top of the section (Fig. 7). The fine sand is predominately type-A to type-B ripple laminated in the lower part of the section, while beds of planar parallel-laminated sand become more abundant in the upper part (Fig. 14F). A few meters south of section 1 unit 1 sediments continue to coarsen up-wards (Log 1, Fig. 6A), here consisting of trough cross-laminated and planar cross-laminated sand. Palaeoflow measurements on ripples suggest a flow from S to SSE, predominately being from azimuths 160°-170° even though the whole range is from 136°-200°. Measurements on cross-laminated beds indicate a flow direction from SSE (azimuth 150°-160°) with azimuth variations between 127° and 177°.

Unit 2 consists of planar parallel-laminated sandy gravel, in the section only 0.1 m thick due to quarrying at an upper level in the gravel pit. The lower contact to unit 1 has a curved configuration, cutting diagonally down into unit 1 sediments from right to left (Fig. 7).

A wedge structure exists in the upper part of section 1 (Fig. 7 and 14A). It is approximately 2.4 m deep and 0.6 m wide in its upper part (Fig. 14A). The upper part of the wedge has a bifurcating appearance while the lower part consists of a single wedge. The primary sediment laminae on both sides of the wedge are bent down-ward close to the wedge contact. The upper part of the wedge is eroded in the contact with unit 2 and in the lower part the wedge has been displaced by fault planes, the wedge thus being older than the faulting.

Unit 1 has experienced extensive normal faulting (Fig. 14D). Mean strike of the fault planes is 111°-291° (Fig. 10A). The fault planes form two sets, one with a steep dip toward NNE (azimuths to planes: V_1 = 20°/50° ; S_1 = 0.969), while the other set has a steep dip towards SSW (azimuths to planes: V_1 = 197°/79° ; S_1 = 0.980). The relative displacement of sediment beds on each side of the fault planes varies between a few centimeters to a couple of tens of centimeters in the projection of the section. No obvious age relation was found between the faults. Some of the faults with dips toward ENE are older than faults dipping toward SSW, while others are younger.

Silt injections, ranging in thickness from a few millimeters to a few centimeters and several meters long, cross both sediment bed boundaries and faults (Fig. 14B and 14E). No grain size variation within the silt injections was detected and only a weak lamination parallel to dyke boundaries was seen. The boundaries are irregular and some silt injections are diverging and/or converging in different parts of the section. Neither the faults nor the injections continue above the erosive contact to unit 2 in section 1, which also is the case at log 1.

3.2.2 Section 2

Most of section 2 reveals unit 1 sediments (Fig. 6B). These consist of a stacked sequence of over-consolidated, moderately sorted (according to Folk and Ward 1957) silt to medium grained sand. The dominating facies is type-A and type-B ripple-laminated sand, interbedded with thinner beds of planar parallel- laminated sand and massive silt. A single clay bed also occurs, approximately one mm thick. The silt below the clay bed shows flame-type water escape structures (Fig. 14C). There is a general slight coarsening up-ward trend in the sediment sequence with the silt and fine-sand facies mainly in the lower part of the section, followed by a 0.8 m thick coset of moderately sorted ripple-laminated fine-sand and above that a zone of alternating beds of ripple-laminated sand and beds of draped massive sand, a few centimeters to almost 20 cm thick.

Normal faults cut sediment beds in unit 1 but do not continue into unit 2 in the upper part of the section. Mean strike of the fault planes is 137°-317°. The fault planes form two sets, one with a dip toward NE (azimuths to planes: V_1 = 43°/62° ; S_1 = 0.987), while the other set dips toward SW (azimuths to planes: V_1 = 231°/56° ; S_1 = 0.991) (Fig. 10B).

The relative displacement of the sediments on each side of the faults varies between 0.20 and 0.68 m in the projection of the section. The faults are less abundant than in section 1. Silt injections with thicknesses of a few millimeters and length up to a few meters occur in the section, following irregular but continuous paths. They cross the fault planes, thus being younger.

Unit 2 has an erosive contact to unit 1 and is composed of alternating beds of sandy and gravelly facies, between 2 and 40 cm thick and up to 5 m long (Fig. 15F). Sediment facies vary between massive sand, planar parallel-laminated sand and clast-supported massive gravel to cobble gravel, with or without an open-work framework. The general trend in the unit is coarsening upward with mainly sandy facies in the lower part and gravelly facies in the top. In the lower part of the unit there is a lag horizon with out-sized boulders with a-axes varying between 0.3 and 0.5 m in lengths. Except for the out-sized boulders the maximum particle size is less than 0.2 m in the lower part of the unit and less than 0.3 m in the upper part.

3.2.3 Section 3

Section 3 reveals unit 1 sediments, erosively cut and overlain by unit 2 sediments (Fig. 8). Unit 1 consists of stacked beds of silt to coarse sand with a weak upwards coarsening trend. The sequence is dominated by planar parallel-laminated sand and type-A and type-B ripple laminated sand, interbedded by massive to weakly laminated sand. Sets of trough cross-laminated sand and a thin but continuous bed of gravelly sand occur in the upper part of the unit. Beds range between 5 and 50 centimeters in thickness and have, except for the trough cross-laminated beds, parallel boundaries.

Unit 1 sediments are cut by three normal faults, ending in the upper parts at the erosive boundary to unit 2. Fault planes in the documented part strike *c.* 110˚-290˚ with a dip of *c.* 60˚ towards the SSW. The relative displacement on each side of the fault planes is 0.3 and 1.1 m, respectively, in the projection of the section.

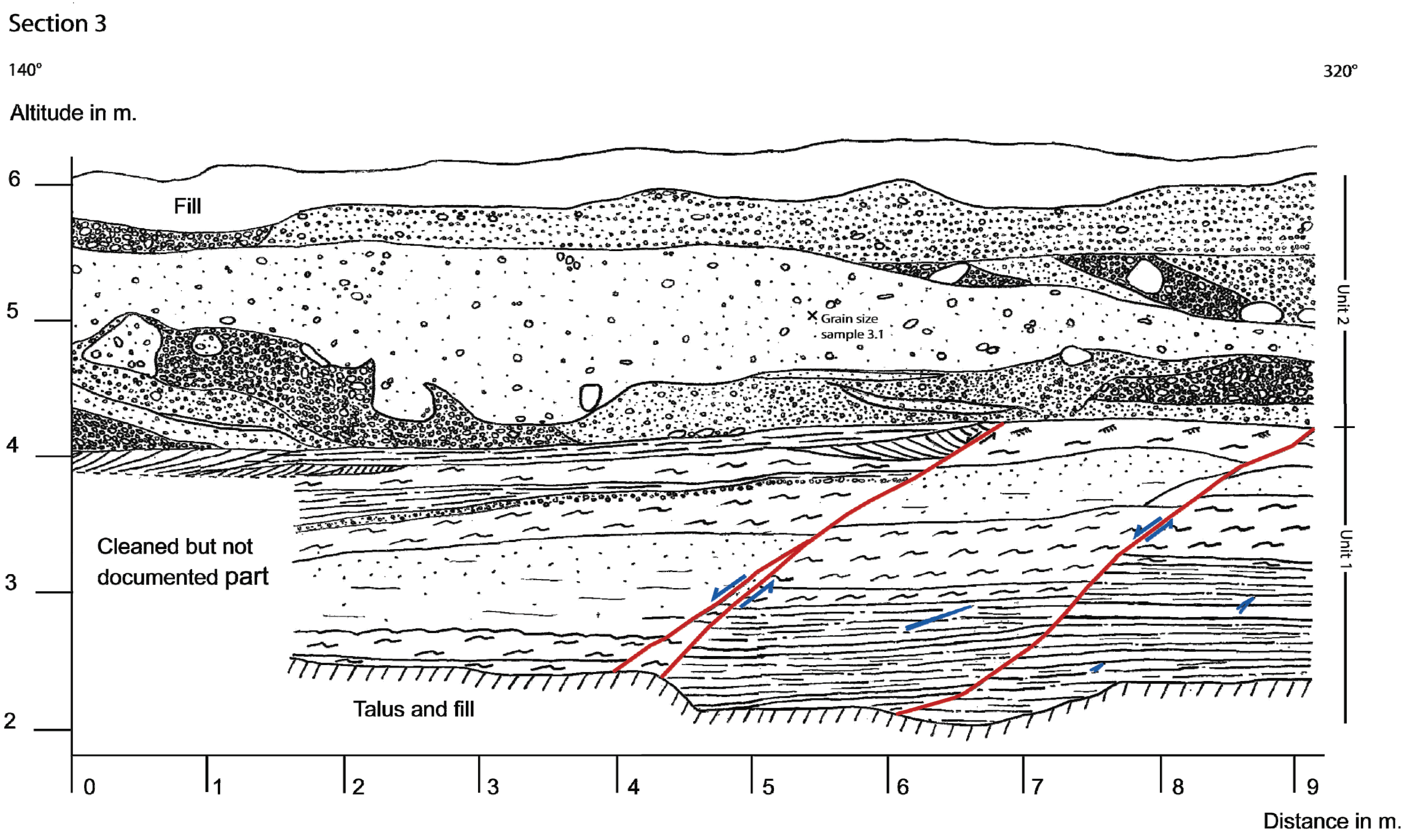


Fig. 8. Section drawing of section 3. The red lines represent fault planes while the blue lines represent silt injections. Blue arrows show relative displacement direction of faulted sediments. Lithofacies as described by the legend in Fig. 5. Elevations represent the height over local ground reference point.

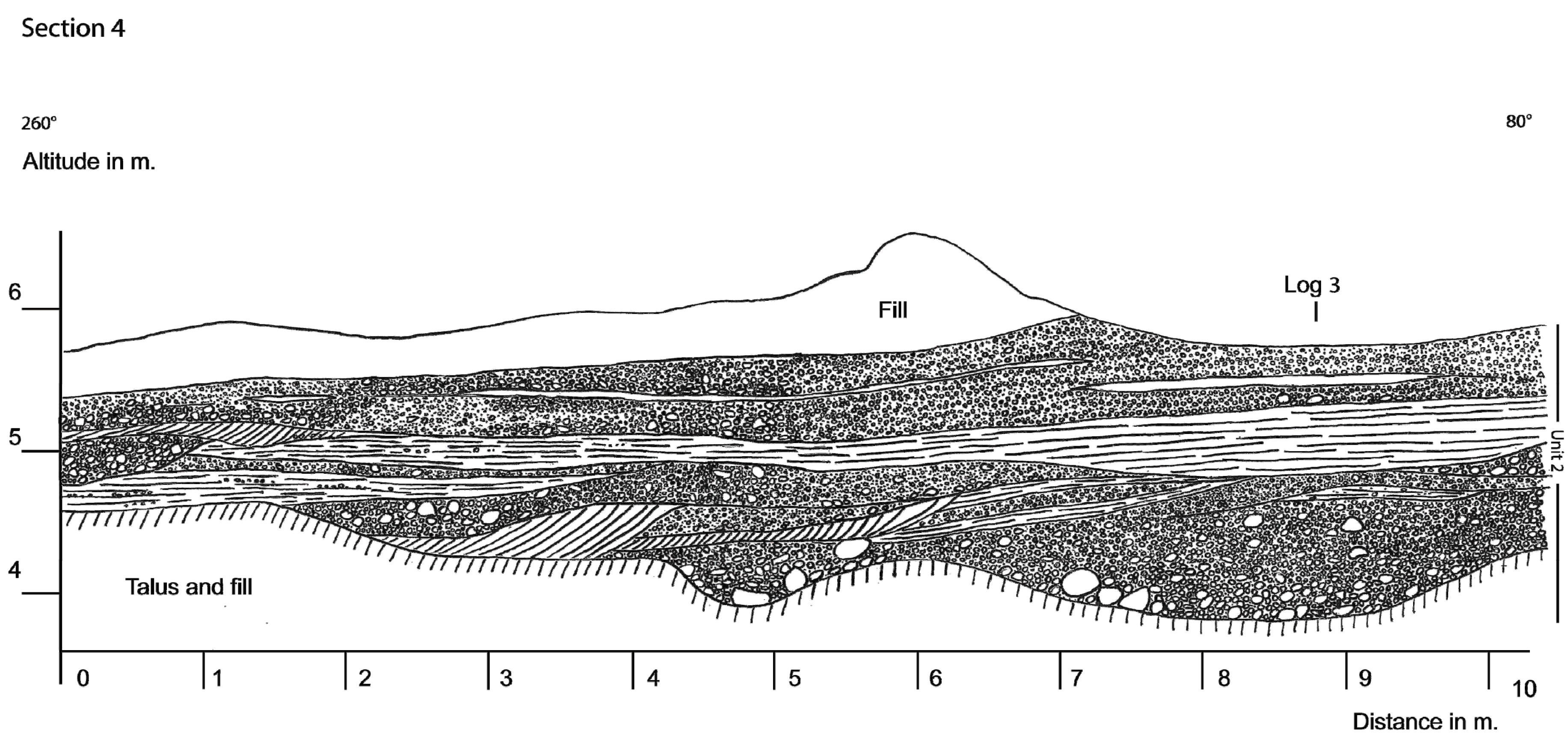


Fig. 9. Section drawing of section 4. Lithofacies as described by the legend in Fig. 5. Elevations represent the height over local ground reference point.

Short silt injections, up to 0.6 m long and a few mm thick occur in the section. The injections are massive and homogeneous. Two of the shorter injections have an abrupt start in their lower, wider parts while the upper parts are thinning out. The silt injections cross unit 1 bed boundaries but are eroded in the contact with unit 2. Contacts between the injections and the fault planes are not visible in the section.

Unit 2, lying with a sharp and erosive contact to unit 1 sediments, consists of coarse, sorted sediments, ranging from gravel to cobble-gravel with occasional boulders (maximum particle size ~0.3m). Sediment facies vary between massive sand, planar parallel-laminated gravelly sand to sandy gravel, massive matrix-supported sandy gravel to gravelly sand and clast-supported cobble gravel. The contacts between the beds are usually erosional but often with irregular boundaries. The predominately well sorted unit 2 sediments are interbedded by a large lens of diamictic sediments in the middle part of the unit, thinning in lateral direction of the section wall and eventually pinching out outside section 3 (Fig. 8 and Fig. 15D). The lens forms a homogeneous, very poorly sorted, moderately clast-rich, matrix-supported diamict. Clasts are of gravel to cobble sizes with the gravel-sized clasts the most abundant and with a few boulder-sized clasts along the basal contact. Clast roundness seems to be fairly similar to that in the sorted sediment beds of unit 2. Maximum particle size in the diamicton is *c.* 14 cm. The uppermost boundary of unit 2 is a quarrying surface covered by filling.

3.2.4 Section 4

Unit 2 sediments are the only sediments visible in section 4 (Fig. 9). However, large angular boulders of sizes not occurring in unit 2 sediments are infrequently draping the plateau surface into which the sediments are cut. Unit 2 is here dominated by 0.05-0.7 m thick, subhorizontal beds of matrix to clast-supported sandy gravel, gravel and cobble-gravel, the latter at places with open-work framework. There is a general fining upward trend with cobble gravel in the lower part and sandier sediments in the upper part of the section. The coarser sediments are interbedded with planar parallel-laminated sand (Fig. 15E), planar cross-laminated sand, trough cross-laminated sand and, occasionally, massive sand. The sand beds are between a few cm and 0.5 m thick and generally a few meters long, although the lengths of the sand beds vary between 0.5 m and 12 m (Fig. 15C). The boundaries between the beds are often clearly erosional and sharp, but gradational boundaries also occur. Maximum particle size ranges from 20-35 cm in the lower part of the section and 9-16 cm in the upper part. Palaeoflow direction as indicated from measurements in planar cross-laminated sediment is from the west (azimuth 270°).

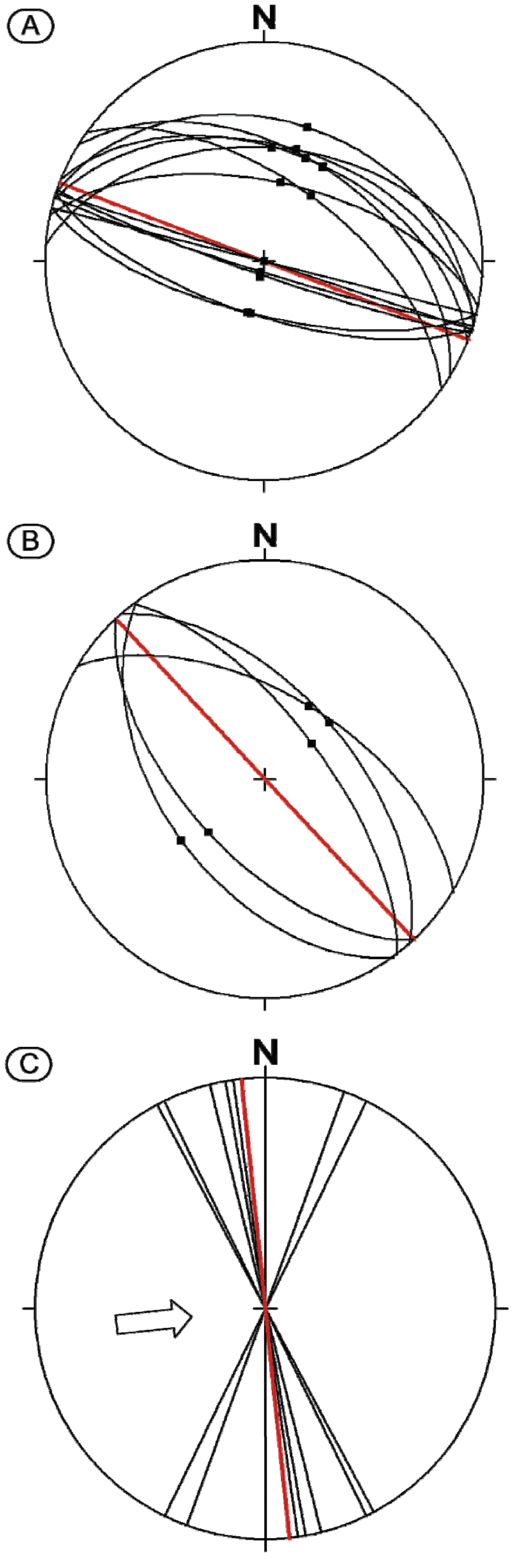


Fig. 10. A) Fault planes in section 1, the red line marks the mean strike direction. B) Fault planes in section 2, the red line marks the mean strike direction. C) Strikes of the fold axis in section 6. The red line represents the mean strike. The arrow marks the pressure direction.

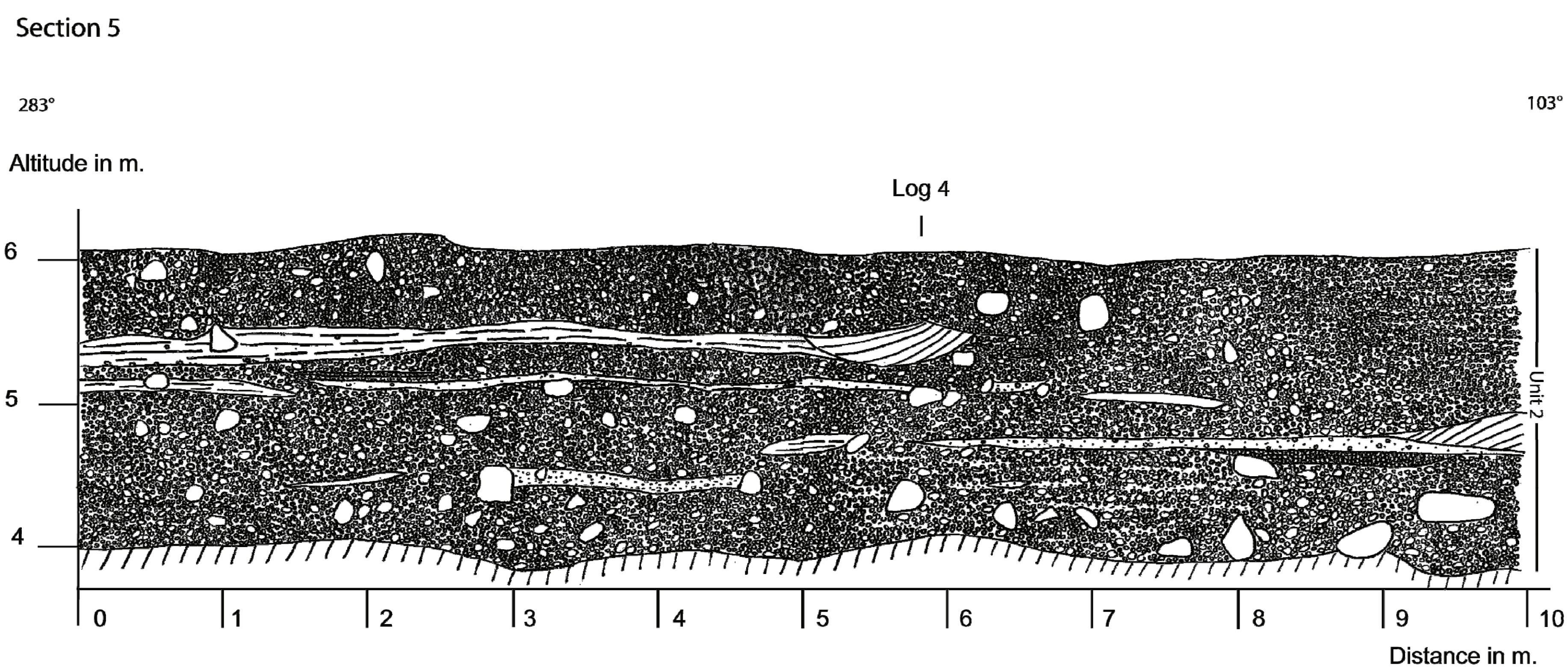


Fig. 11. Section drawing of section 5. Lithofacies as described by the legend in Fig. 5. Elevations represent the height over local ground reference point.

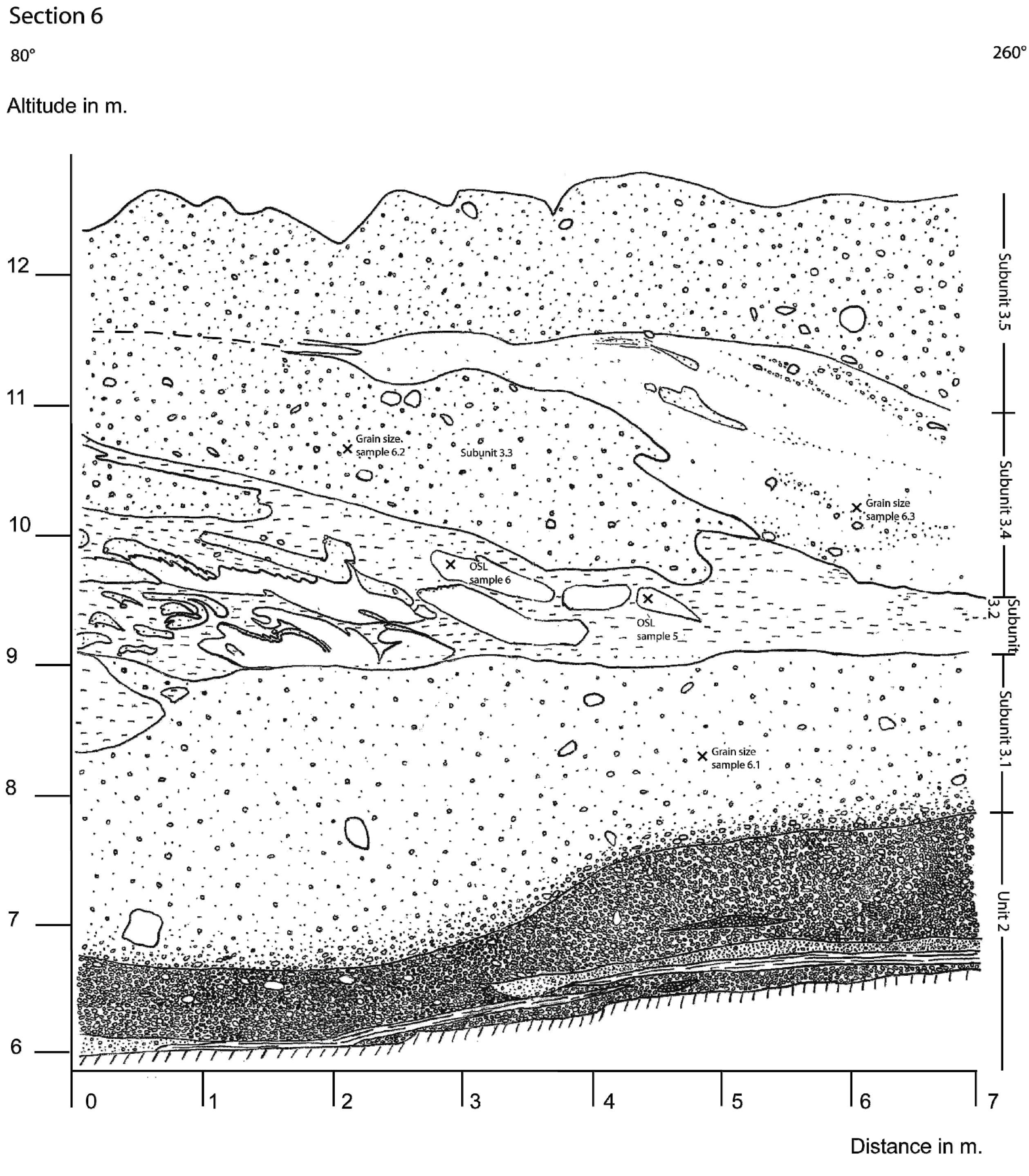


Fig. 12. Section drawing of section 6. Lithofacies as described by the legend in Fig. 5. Elevations represent the height over local ground reference point. The hatched line is the suggested but not identified boundary between subunit 3.3 and 3.5.

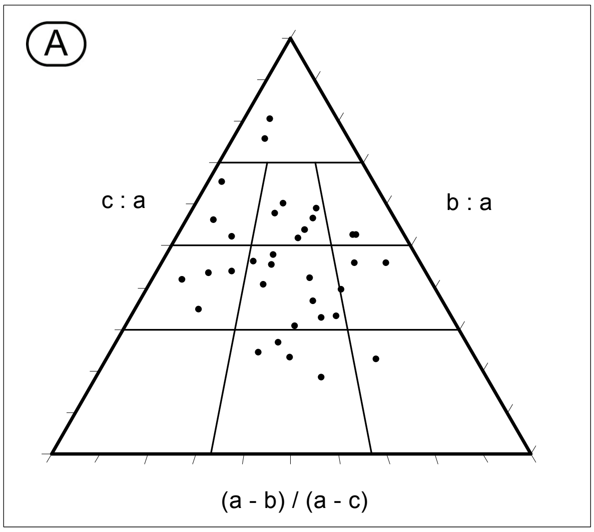
3.2.5 Section 5

Unit 2 is the only unit visible in section 5 (Fig. 11). It is dominated by clast- to matrix-supported gravel to cobble-gravel with a few occurring boulders, up to 0.5 m in diameter. Some clast-supported gravel beds reveal an open-work framework. The coarse sediment beds are interbedded by 4-25 cm thick and 0.5 to *c.* 5 m long beds of sand. The sandy facies vary between planar parallel-laminated sand and planar cross-laminated sand, massive sand to gravelly sand and matrix-supported sandy gravel. The sand beds consist of medium to coarse sand and the same fractions make up the matrix of the gravel beds, except in the small parts with open-work frameworks. Boulders occur in the cobble gravel in all parts of the section but are more abundant in the lower part. The topmost cobble gravel unit is normally graded but no general trend of fining upward was found. The lower boundaries of the cobble-gravel beds are generally erosional. The boundaries beneath the other beds vary between gradational, sharp and erosive. Maximum particle size in the section varies between 0.3 and 0.5 m. Palaeoflow measurements in one of the few occurring cross-laminated beds indicates a flow direction from the west (azimuth 263˚). The upper boundary of unit 2 is missing in the section. On the plateau surface into which the section is cut there is a sparse occurrence of angular boulders, larger than those found in the section sediments.

3.2.6 Section 6

Section 6 reveals the uppermost part of unit 2 sediments and is the only section showing the sediments of unit 3. Unit 2 consists mainly of clast-supported cobble gravel with slightly imbricated clasts. Thin beds of planar parallel-laminated sand, massive gravelly sand and clast-supported, normally graded gravelly sand occur in the lowest part of the unit, while the upper part consists of clast-supported cobble gravel, in some parts with an open framework. The beds of sand or gravelly sand are approximately 0.1 m thick and a few meters long. Maximum particle size is between 12 and 20 cm. Roundness measurements of clasts from the cobble gravel range from angular to well rounded (Powers 1953) with the median clast categorized as rounded (Appendix 2). The shape distribution is shown in Fig. 13A. The imbrication indicates a flow direction from ESE (91˚-130˚).

Above unit 2 is a gradational contact to unit 3. Unit 3 has been divided into five subunits (Fig. 12 and Fig. 16B, E, F), namely: (3.1), the lower part of unit 3 which consists of a bimodal, sandy diamicton, (3.2), the middle part of unit 3 which consists of deformed and faulted sorted silty and sandy sediments, (3.3), a bimodal, sandy diamicton in the left part of the section, (3.4), a silty, sandy, bimodal and deformed subunit in the upper right part of the section and, (3.5), a bimodal, sandy diamicton in uppermost part of the section.



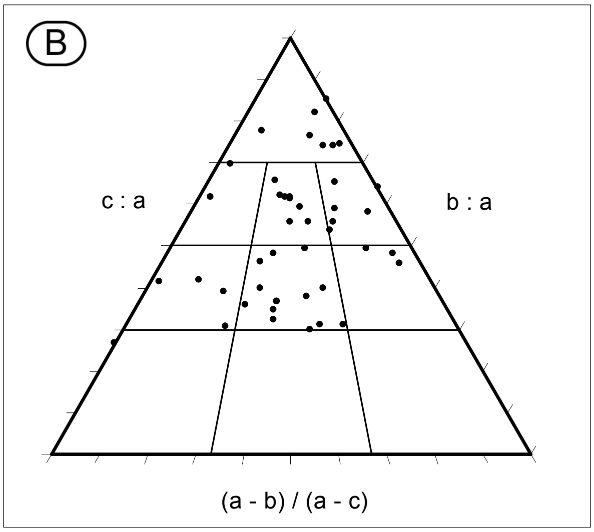


Fig. 13. General shape triangles of two samples from section 6. Sample A) is taken in the cobble gravel bed in unit 2 and sample B) is taken in subunit 3.1 . The a-, b- and c-axis are plotted in general shape triangles using the TRI-PLOT spreadsheet from Graham and Midgley (2000).

The boundary between unit 2 and the sandy diamicton above, subunit 3.1, is gradational. The diamict has a bimodal, very poorly sorted composition with gravel and cobble clasts in a sandy matrix (Appendix 1). The subunit is between 1.2 and 2.4 m thick and has a gradational upper boundary to subunit 3.2. Subunit 3.1 has a high content of clasts in its lower part with appearances similar to the clasts in unit 2. Higher up in the subunit the number of clasts decreases, but they continue to be approximately as rounded as in the lower part. The matrix consists of silty sand with no grading detected. Roundness of subunit 3.1 clasts range from angular to well rounded, with the median clast in the subrounded class (Appendix 2). The shape distribution is shown in Fig. 13B.

The middle part of the section, denoted subunit 3.2 and being 0.5 to 1.4 m thick, consists of deformed sediments ranging from silty sand to coarse sand. Beds of fine sand or of medium to coarse sand form coherent clasts in a massive sediment body of sandy silt. The boundaries to the sediment intraclasts are often sharp, especially between the medium to coarse sand and the surrounding sandy silt, but in the left part of the section the boundaries are more gradational. The intraclasts have experienced some asymmetric folding, both of their external configuration and of their internal primary bedding when seen (Fig. 16A, C, D) with fold axes striking 332˚-26˚ and with a mean direction of about 354˚ (Fig. 10C). The vergences of the folds are toward the west, inferring an applied stress direction from the west (*c.* 264˚). With a gradational boundary, subunit 3.2 is overlain by subunit 3.3 in the left part and subunit 3.4 in the right part of the section.

Subunit 3.3 is a bimodal, sandy diamicton, similar to subunit 3.1. Its lower boundary to subunit 3.2 below is gradational, as is the boundary to subunit 3.4 in the upper left part of the subunit, but the boundary to subunit 3.5 in the upper right part is not visible. It is very poorly sorted (according to Folk and Ward 1957) with a matrix consisting of sandy silt and rounded clasts (Appendix 1).

Subunit 3.4 is a deformed silty sand pinching out toward the left part of the section. It is a very poorly sorted (according to Folk and Ward 1957) bimodal sediment with inclusions of a few gravel and cobble clasts (Appendix 1). The unit is heterogeneous with variations in intraclast abundance, and some primary structures are still visible. The intraclast-rich parts of the subunit occur as elongated and irregular shaped sediment bodies with gradational boundaries to the enclosing silty sand. The boundaries between the medium to coarse sand and the silty sand are sharp and clast-rich horizons occur as a continuation of these beds.

Subunit 3.5 is a bimodal, sandy diamicton, similar to subunit 3.1 and 3.3 but in the uppermost part of the section. Its lower boundary to subunit 3.3 is not visible, while the boundary to subunit 3.4 in the lower right part of the subunit is gradational. The sediment is very poorly sorted with rounded clasts and a matrix consisting of sandy silt.

3.3 Sediment interpretations

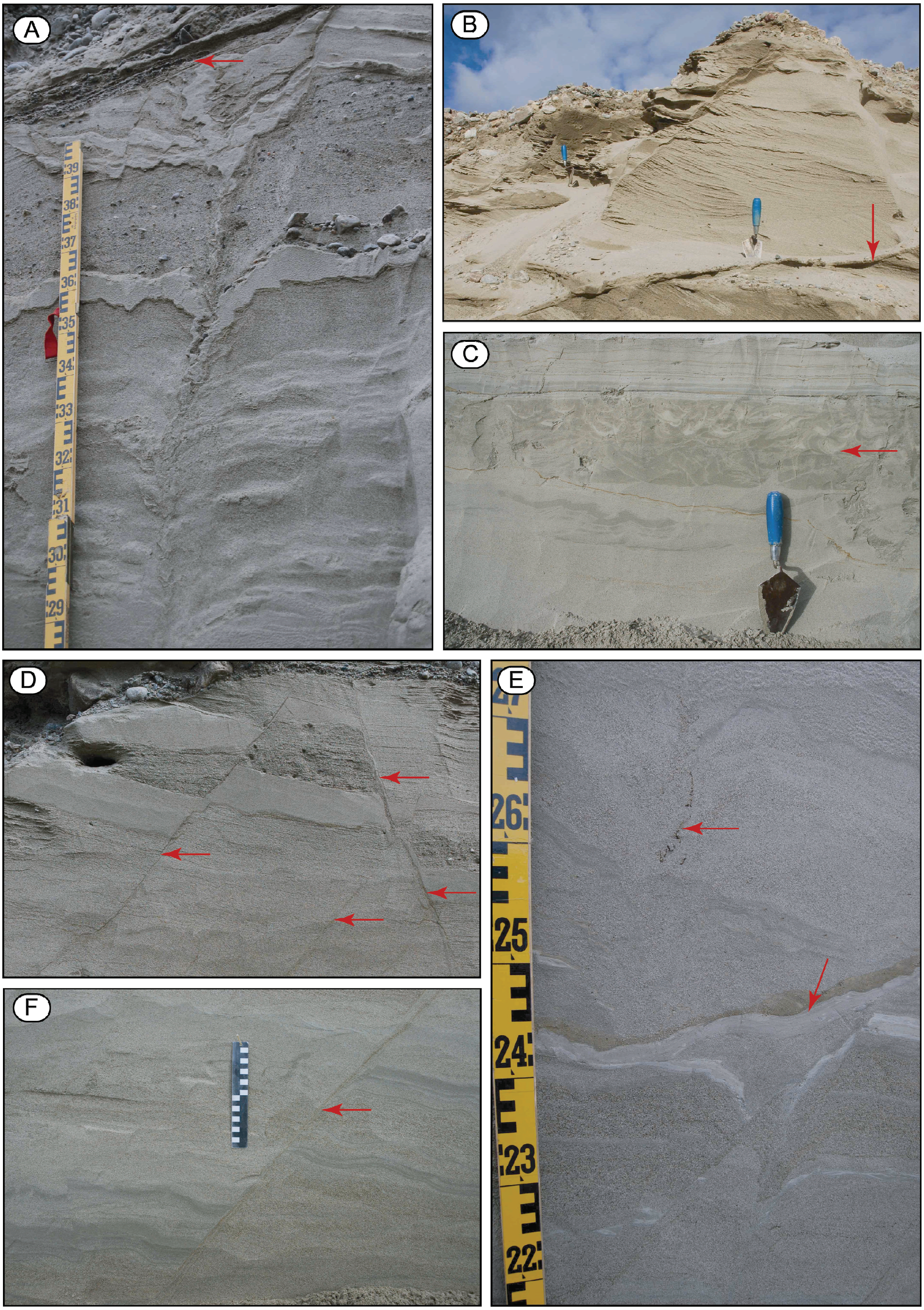
3.3.1 Unit 1

The sediments in the lower part of unit 1 consist of complete or partial successions of type-A ripple-laminated sand followed by type-B ripple-laminated sand, which in turn is draped by massive sand. Type-A ripples are primarily formed by bed-load transported sand at situations when aggradation is low and migration high, followed by type-B ripple-laminated sand when migration decreases and aggradation increases. Draping occurs when deposition of suspended sediments dominates (Ashley el al. 1982). This type of bedform and sediment successions are typical in stagnant water-body environments dominated by underflows (Ashley 1985), but are also conceivable in a fluvial environment. However the widespread occurrence of these facies successions in both vertical and lateral direction makes a stagnant basin such as a glacial lake with repeated influx of turbulent underflows more likely. At occasions deposition was totally from suspension load, forming massive silt to clayey silt beds and even clay. As indicated from section 2, clay bed draping of the ripple laminated sediments led to pore-water trapping, eventually leading to deformation of underlying sediments at water escape. The ripple-laminated sequences are followed by slightly coarser planar parallel-laminated sand, typical for traction transport at a plane bed. The planar parallel-laminated sand is followed by planar and through cross-laminated facies indicative of 2D- and 3D dune migration, respectively. Paleoflow measurements on ripples and cross-laminated beds indicate a flow from S to SSE which is oblique to valley trend, but that is not unexpected at the gradational transition from a lacustrine to a fluvial drainage system. The planar parallel-laminated sand and the cross-laminated sand indicate an increase in stream velocity (Benn and Evans 1998). This increase in stream velocity indicates a shift from a glacio-lacustrine to a glacifluvial environment as a result of a decreasing water depth, either as a result of sediment infill of the basin or by lowering of the water table.

The wedge structure in section 1 is post-depositional with respect to host sediment deposition and is interpreted as a fossil ice-wedge cast. This interpretation is complicated by the lack of other wedges and the atypical appearance of the upper part of the wedge. The interpretation is supported by the down-turned laminae in the sediments at both sides of the wedge, which makes a sand wedge interpretation improbable (Murton et al. 2000). Wedge structures formed by collapse along tension fractures have been reported by Black (1976) but his description is not detailed enough to determine whether that might provide an explanation for the wedge in this section.

The fault planes continue all the way to the erosional contact to unit 2, implying that the faulting must have occurred after the deposition of unit 1 but before the erosional event preceding the deposition of unit 2. The age relations between the faults are complex, the northeast-plunging fault planes being

Fig. 14 (Page 23). Unit 1 sediments. A) Wedge structure in section 1, the arrow marks the erosional contact between unit 1 and unit 2. B) Upper part of unit 1. Cross laminated beds. The arrow points at a silt-injection. C) Flame type water-escape structures in section 2. D) Upper part of section 1. Beds of planar parallel-laminated sand and massive sand. The arrows mark the fault planes. E) Post-depositional features in section 1. The upper arrow marks the lower part of the wedge while the lower arrow points at one of the silt injections. F) Sequences of ripple-laminsted sand. The arrow marks a fault plane. Photographs 14B, C, D and F are taken by Per Möller.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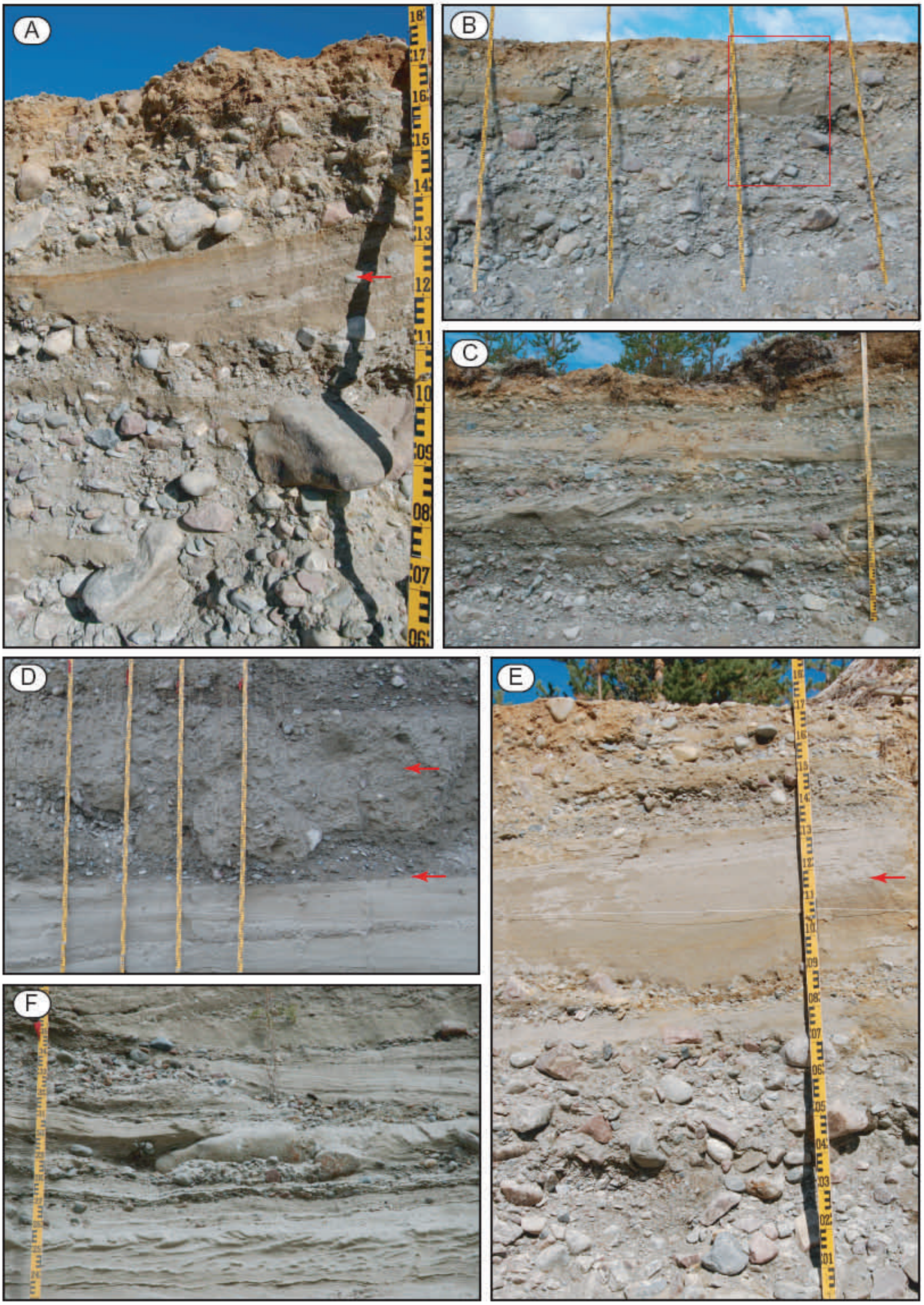
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both the oldest and the youngest whereas the southwest-plunging fault planes are somewhere in between. The normal faulting indicates that the unit 1 sediment beds have experienced extension in NE-SW direction, most likely from loss of ice-support when dead-ice buried in the sediments melted away.

The silt injections cross fault boundaries and continue into the cross-laminated upper part of unit 1, implying that they must be at least somewhat younger than the faulting phase, but as they are eroded at the boundary to the gravelly sediment of unit 2, they are younger than these. The injections are interpreted as water-escape structures and classified as soft-sediment intrusion dykes according to the system of water-escape structures proposed by Lowe (1975). The injections are more or less massive and no directional markers were found. No source bed for the injections was found but since the lower part of the unit is covered by fill and the upper contact to unit 2 above is erosive it might have been eroded away or covered. However, as there is a general coarsening upward trend in unit 1 sediments, this could possibly indicate that a source bed from beneath the visible part of the unit is more likely, thereby supporting an upward directed flow.

3.3.2 Unit 2

An erosional contact is deeply cut into the unit 1 sediments, followed by deposition of the unit 2 high-energy fluvial sediments. From a facies succession view, nothing speaks against this change being a continuation of the sedimentary environment of unit 1. However, the ice-wedge cast in unit 1 infers that time must have been sufficient for ice wedge formation as well as ice wedge disintegration and eventually infill before the erosional event preceding deposition of unit 2. Also time must be allowed for dead ice embedded in unit 1 to melt. This taken together infers that a substantial time period must be allowed before the deposition of unit 2 sediments, making it most improbable that unit 2 is a proximal, coarser part of the low-energy unit 1 sediment sequence. The erosional contact is seen in all sections where the boundary between unit 1 and unit 2 is present (sections 1, 2 and 3).

In section 2 the erosional contact to unit 1 is connected with a boulder horizon with boulders larger than the maximum particle size in the rest of the unit in that section. These boulders might either be erosional remnants of an uppermost coarse ending of unit 1 below, sediments which should now be missing in all sections or, alternatively, they might be residual boulders from the sediment load associated with the major flooding event that cut into the unit 1 sediment.

The massive, clast-supported to vaguely imbricated gravel beds in unit 2 are interpreted as remnants of longitudinal bars and channel lags, predominated by vertical accretion (Miall 1977), whereas interbedded sandy layers were deposited in lower-energy environments as at the lee-sides of bars (Miall 1977). Paleoflow measurements in cross-laminated beds indicate a flow direction from the west. The clast roundness indicates a transport length not long enough for all angular and sub-angular clasts to disappear. This is consistent with deposition in a proximal braided river system. The unit is closest corresponding to the Scott-type braided river according to Miall (1977), although the sediments in the Tvärkroken gravel pit are slightly finer grained.

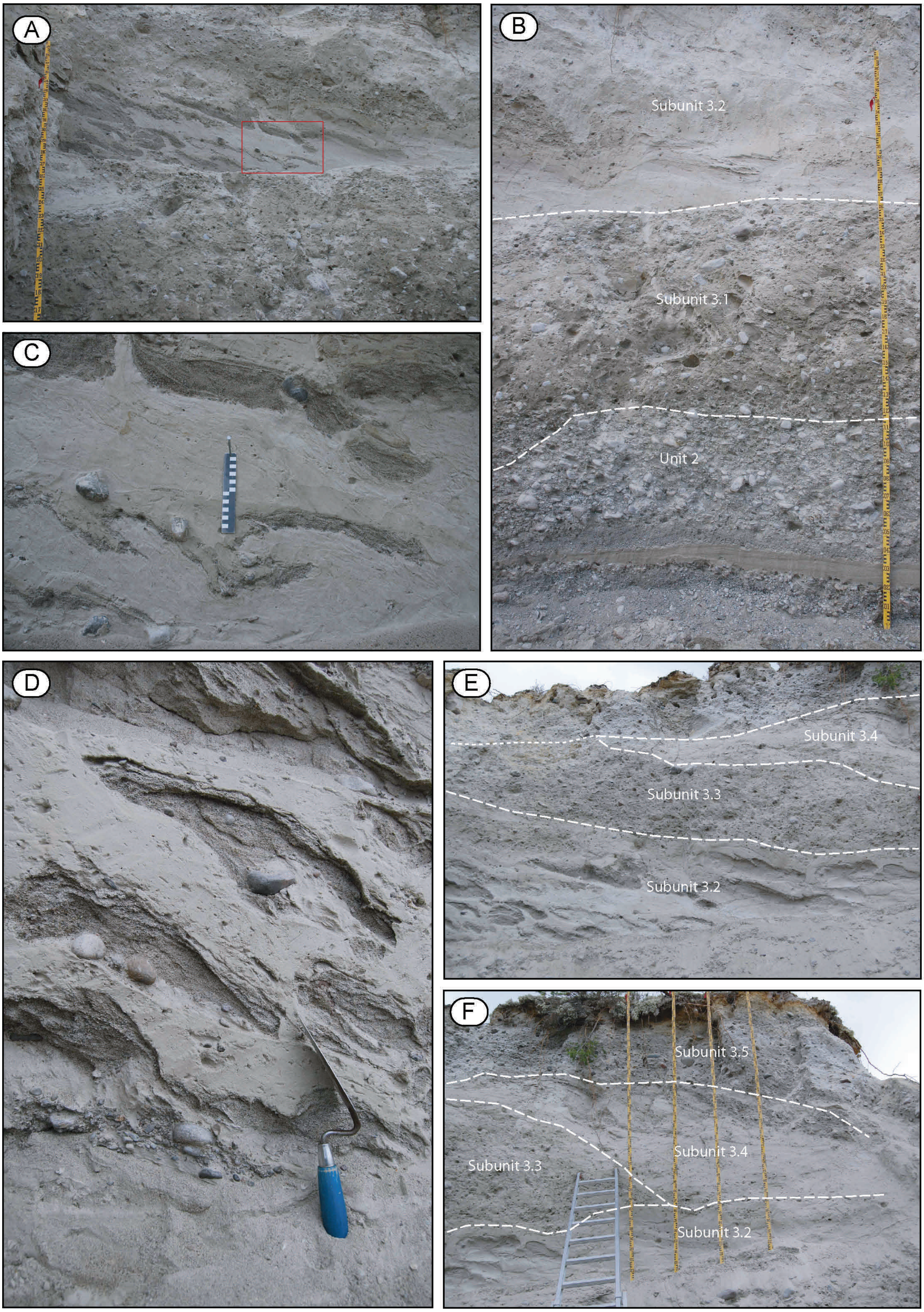
The appearance and grain-size distribution of the sediment forming the diamict lens in section 3 is consistent with what would be expected in a sediment consisting of a mix of sediments from unit 1 and unit 2. Since the sediments seems to be derived from the valley floor where the general gradient is low, the transport must have been short. It is therefore suggested that these sediments represent a slump deposit due to the collapse of a channel wall in the braid-plane system. The local and lens-like appearance within the predominating unit 2 sediments also supports a local provenance.

3.3.3 Unit 3

Unit 3 is interpreted as a stacked sequence of up-thrusted sediments. The boundary between unit 2 and unit 3 is a gradational change from homogenised cobble gravel through a zone with an upward increasing amount of finer sediments and into a homogeneous diamict, subunit 3.1. The homogenisation of the sorted sediments below is interpreted as the result of deformation in a deforming bed beneath the glacier. As more glacially transported sediments were mixed with the gravel, the lithology changed from sorted gravel to a sandy diamicton. The subglacial origin and homogeneous appearance of the diamicton fits the characteristics of a subglacial traction till, defined by Evans et al. (2006) as "sediment deposited by a glacier sole either sliding over and/or deforming its bed, the sediment having been released directly from the ice by pressure melting and/or liberated from the substrate and then disaggregated and completely or largely homogenised by shearing". The clasts are more rounded than what would be expected in a normal till, instead having a fairly similar appearance to the clasts in unit 2, indicating that they might have been derived from this unit.

In subunit 3.2 intraclasts of fine to coarse sand occur in a matrix of silty sand. The matrix has experienced penetrative deformation obliterating any

Fig. 15 (Page 24). Sediments from unit 2. A) Log 5. Planar cross-laminated sand (arrow) surrounded by cobble gravel. B) Section 5, the red square marks the part seen in A). C) Section 4, alternating beds of sand and gravel. D) The diamict lens in section 3. The arrow marks the erosional contact between unit 1 and 2. E) Log 4, section 4, the arrow marks a planar parallel-laminated bed. F) Section 2, unit 2 sediments are interbedded with sand sediments similar to the ones in unit 1. Photographs 15C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Subunit 3.2
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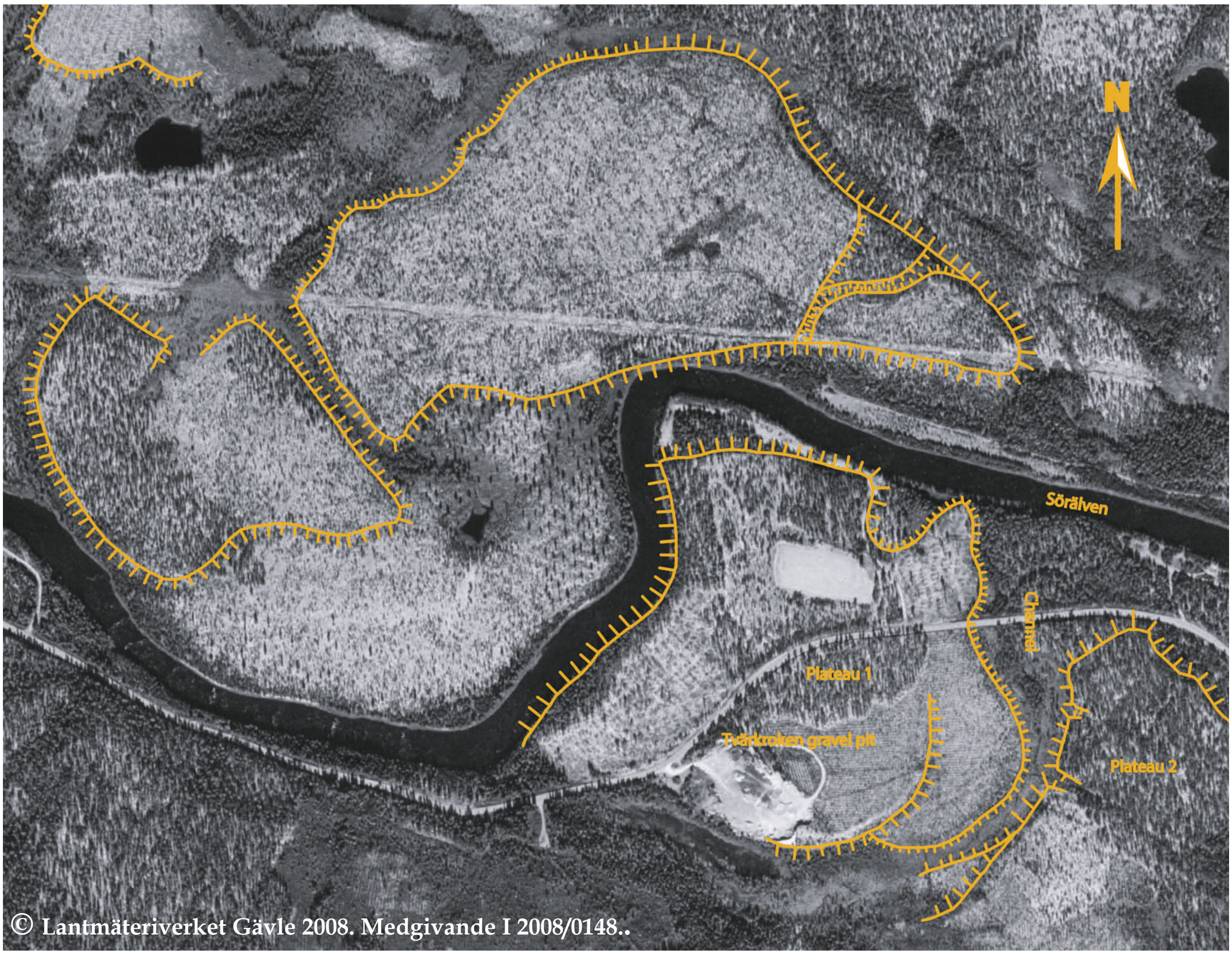

Fig. 17. The morphology of the area around Tvärkroken gravel pit, inferred from air-photo interpretation and drawn on an ortophoto. 1 cm in the figure corresponds to approximately 100 m. The yellow lines mark the plateau slopes, longer lines indicate steeper slopes. Ortophoto from the digital library of maps (Digitala kartbiblioteket).

primary structures, while some primary structures are still visible in the intraclasts, probably as a result of differences in rheological behaviour between the silty matrix and the coarser intraclasts resulting in a slower deformation of the intraclasts. The intraclasts are thus interpreted as boudins and the subunit as a glaciotectonite according to the definition proposed by Benn and Evans (1996) and Evans et al. (2006). The folding of the intraclasts as well as folding of internal bedding within them indicate a stress and ice flow direction from the west.

Subunit 3.3 has an appearance similar to the upper part of subunit 3.1 and is interpreted as a subglacial traction till.

Subunit 3.4 is a silty sandy heterogeneous, deformed unit with a few streamlined intraclasts and some primary structures visible. It is interpreted as a glacitectonite similar to subunit 3.2, which has been thrusted on top of subunit 3.3.

Subunit 3.5 has an appearance similar to subunits 3.1 and 3.3 and is interpreted as a subglacial traction till. As subunit 3.4 pinches out towards the left in Fig. 12, and thus subunit 3.5 being on top of subunit 3.3 sediment, it is suggested that there should be a thrust plane in between. This is however not visible, probably because of the massive appearance of both sedimentary units.

3.3.4 Plateaux and terraces

Flat plateaux surfaces separated from each other by channels with steep sides is the predominating landform relief in the area surrounding the Tvärkroken gravel pit (Fig. 17). On top of the plateaux are occasional boulders, larger and more angular than the

Fig. 16. (Page 26). Unit 3 sediments in section 6. A) Overview over the mid left part of section 6, the red square marks the position of the close-up in C. B) The sequence from unit 2 to subunit 3.2 with subunit 3.1 in between. The sketched lines mark approximate unit and subunit boundaries. C) Close up of folded sediments in subunit 3.2. D) Weathered folds in subunit 3.2 E) Overview of the upper left part of section 6. The sketched lines mark approximate subunit boundaries, the dotted line is the suggested but not identified boundary between subunit 3.3 and 3.5. F) Overview of the upper right part of section 6. The sketched lines mark approximate subunit boundaries. Photographs A, B and C are taken by Per Möller.

ones found in unit 2. Unit 3 sediments form a single moraine hummock on top of plateau 1. It is unlikely that the glacier left a single, well-defined, *c.* 7 m high moraine hummock but didn't affect the surrounding area at all. Instead the moraine hummock, as well as the angular boulders on top of the braidplain sediments of unit 2 are interpreted as erosional remnants from a till which covered the valley. A phase with extensive fluvial erosion, probably in connection with the melting of the Late Weichselian ice-sheet in this area, led to the removal of most of the till. The melt-water eroded deep channels into the underlying sediments and remaining sediments between the channels form the free-standing plateaux and the terraces toward the valley sides. This interpretation is supported by Borgström (1989) who found drainage channels in the area west of Idre, indicating a drainage from the southwest, northwest and north which continued along the south side of the Idresjön valley.

4 Discussion

4.1 A depositional model for the sediments at the Tvärkroken gravel pit

1. A retreating ice sheet left dead-ice in the Sörälven river valley. A stagnant water body, possibly a glacier-dammed lake, was situated at the site where the Tvärkroken gravel-pit is today. Sediment-loaded meltwater was fed into the basin predominately as underflows from which sediment was deposited both from traction and suspension, forming the lower part of unit 1.
2. Water-depth decreased gradually as a result of drainage of the basin or by infill of the basin, or a combination of both. During this stage the shallow-water to fluvial upper part of unit 1 was deposited.
3. An arctic climate with permafrost resulted in ice-wedge formation. Permafrost conditions from interstadials of pre-Late Weichselian age have been suggested for other sites in west-central Sweden too (e.g. Kleman and Borgström 1990). However, as OSL datings are not yet ready, it is to early to make certain correlations.
4. Permafrost and dead-ice melted away and the loss of support led to normal faulting of unit 1 sediments. This deformational event led to release of trapped water and injections of silt into unit 1.
5. A proximal braided-river environment migrated into the area and eroded unit 1 sediments, followed by deposition of unit 2 sandur sediments, dominated by vertical stacking of braid-bar units. A hiatus might thus exist at the erosive contact between unit 1 and unit 2.
6. Sandur sediment deposition was followed by an advancing ice-sheet which at some stage eroded, deformed and re-deposited the underlying sediments. The deforming bed situation also suggests that the ice sheet was warm-based.
7. At ice-retreat the area was subject to extensive meltwater erosion. Channels were cut to varying depths, leaving varying parts of the described sediment succession as flat plateaux with eroded upper surfaces and also at places unit 3 diamicts as residual ridges and hummocks.

4.2 Comparison with other exposures in the area

Catto (1989) investigated two sections in the Idre area, one in the Storån river valley 4 km north of the Tvärkroken gravel pit and the other 1.5 km ESE of the Tvärkroken pit. At the Storån river site Catto (1989) reported seven different units, units 1.1-1.7 and made the following interpretations:

1. The lowermost unit (1.1), consists of interbedded gravel and sand and was interpreted as sediments deposited in a braided river environment.
2. Unit 1.2 consists of irregular lenses of massive gravel and was interpreted as reworked sediments from unit 1.1.
3. Unit 1.3 is a stony sandy diamicton interpreted as a subglacially derived basal till, primarily deposited through melt-out.
4. Unit 1.4 consists of interbedded massive sand. No deformation structures were reported in the unit. It was interpreted as sediment deposited in stream channels in direct contact with glacial ice, probably in subglacial or englacial channels.
5. Unit 1.5 consists of a complex of diamict units interbedded by gravel and sand. The unit was interpreted as debris-flow deposits within a supraglacial environment.
6. Unit 1.6 is a sandy diamicton interpreted as supraglacial deposits disturbed by colluviation.
7. Unit 1.7 consists of parallel-laminated fine to medium sand interpreted as sediment deposited in a shallow pond on top of a stagnant glacier.

At the section 1.5 km ESE of the Tvärkroken pit, Catto (1989) identified and interpreted three different units, units 2.1-2.3:

1. The lowermost part of the section, unit 2.1, consists of a massive sandy diamicton with scattered irregular lenses of massive sand and silt. The unit was interpreted as basal melt-out till.
2. Unit 2.2 is a sandy diamicton with a high abundance of sorted lenses. The unit was interpreted as a melt-out till, most likely subglacially deposited although the upper part might have been deposited in a supraglacial environment. The sorted lenses were interpreted as sediment deposited in seasonal cavities.
3. Unit 2.3 is a massive sandy diamicton interpreted as a supraglacially deposited diamicton.

The lowermost unit at the Tvärkroken site, unit 1, does not correspond to any of the units investigated by Catto (1989). However, these sediments might exist beneath the exposed parts of his sections.

The braided river sediment identified by Catto (1989), units 1.1 and 1.2, might correlate with unit 2 in the Tvärkroken pit. However, as they occur in two different valleys with different drainage areas they can not be part of the same braided river. But of course the same type of depositional environment could have developed simultaneously in these close by-lying valleys. From the available information it is impossible to make a more certain correlation.

Unit 3 in the Tvärkroken pit could correlate to units 1.3, 1.4, 2.1 and 2.2 of Catto (1989). Their interpretation is quite complex, but primarily suggested to be subglacial in origin, preferently a complex of basal melt-out till(s). Opposed to this, the unit 3 sediments from the Tvärkroken site are interpreted to be formed by subglacial deformation, first as ductile deformation reaching down into pre-existing unit 2 gravels and at a later stage a more brittle/ductile deformation, resulting in more deep-reaching quarrying into both unit 1 and 2 sediments, followed by thrust stacking. These differences could be due to true differences in the depositional environment between the localities or, more probable, due to the change in how we interpret diamicts during the last 20 years.

The supraglacial sediments in units 1.4, 1.5, 1.6, 1.7 and 2.3 of Catto (1989) have no corresponding sediment in the Tvärkroken pit. This might be explained by the extensive fluvial erosion at the Tvärkroken site which eroded most of the upper part of the sediment sequence.

According to Catto (1989) the glacial flow direction indicated from what was interpreted as melt-out till was toward the south-east. This differs from the easterly direction found in the Tvärkroken gravel pit, as indicated from the glaciotectonic structures. However it is quite possible that these sediments represent the same event. The southerly trend of the Storån river valley and the easterly trend of the Sörälven river valley might have had a strong topographic effect on the ice flow.

4.3 Correlations

In lack of the pending OSL datings on unit 1 and 2 sediments it is only possible to speculate about the timing of deposition and environmental change. The relative chronology of the sediments suggests that the sorted sediments in the gravel-pit were deposited during an ice-free period between two glacial advances. The earliest of these is only indirectly visible in the sections, as inferred from the normal faults in unit 1 sediments, interpreted as the result of melting ice support and the presence of glaciolacustrine sediments, followed by a terrestrial environment with periglacial conditions. These circumstances preclude that the depositional environment, as marked by the unit 1 sediments, was just a distal one to the more proximal fluvial environment of unit 2. The second, and later ice advance is represented by unit 3 sediments. As the deglaciation east of the Scandinavian mountains after Younger Dryas is assumed to be without re-advances (e.g. Lundqvist 1986b), a Late Weichselian to Holocene origin of the sediments beneath the till (unit 3) seems highly unlikely. However, for an older origin to be possible, the conditions beneath the Late Weichselian ice sheet must have allowed sedimentary units below it to be preserved. It is evident that such conditions might occur beneath an ice sheet (e.g. Kleman 1994; Lagerbäck 1988a,b) and the existence of landforms and sediments interpreted as pre-Late Weichselian in west central Sweden (Borgström 1989; Kleman et al. 1992; Möller 2006) indicate that the Late Weichselian ice sheet was cold based at least in parts of this area, thereby creating a favourable environment for preservation of older sediments. Nothing indicates that the sorted sediments in unit 1 and 2 have been overriden by more than one ice sheet. The most likely conclusion is therefore that unit 1 and 2 were deposited during a Weichselian interstadial. This interpretation is consistent with a cold enough climate for ice wedge formation. However, as earlier discussed, the timing and number of Weichselian interstadials in west central Sweden are still under discussion although it seems to be clear that at least one interstadial, presumably during the Early Weichselian, led to ice-free conditions in the Idre area (e.g. Boulton et al. 2001). The ice sheet must have been warm-based during a period in order to deform the sediments in unit 3, most likely when the ice first advanced over the area or, alternatively, during the last deglaciation. Kleman et al. (1997) suggested that parts of the previously cold-based core area of the Late Weichselian ice sheet became wet-based due to inward transgression of the wet-based zone during a late stage of the deglaciation, as also suggested by Möller (2006) at the deforming phase of Rogen moraine formation. Such change from cold-based to wet-based conditions could provide the necessary conditions for the subglacial deformation indicated in unit 3.

5 Conclusions

1. Based on their characteristics, the sediments in the Tvärkroken gravel pit can be divided into three different sedimentary units.
2. The oldest unit, unit 1, was deposited from underflows into a stagnant water basin, probably a glacier-dammed lake. A coarsening upward trend in the unit indicates a change from a glacio-lacustrine to a glacifluvial environment in this part.
3. The next unit, unit 2, is interpreted as deposits in a proximal braided river environment.
4. Between unit 1 and unit 2 there is a time-gap sufficient for formation of ice wedges and their consecutive melting and for melt-out of buried dead-ice in unit 1 sediments, resulting in faulting.
5. The uppermost unit, unit 3, consists of stacked subunits of more or less deformed pre-existing sediments (units 1 and 2) due to an overriding ice-sheet with local ice flow directions from west.
6. Extensive fluvial erosion, probably by melt water

from the latest deglaciation of the area, eroded into the sediments and created flat plateaux separated by channels and also residual ridges and hummocks, the latter primarily composed of unit 3 diamicts.

7. The unit 1 and 2 sediments are most likely of a pre-Late Weichselian age, most likely deposited during the beginning and end of an Early Weichselian interstadial.

6 Acknowledgements

I want to thank my supervisor Per Möller for making this study possible and for his help with fieldwork and in improving this report in every way. I want to thank Ulf Häggberg for allowing me to work in the Tvärkroken gravel pit, Lena Adrielsson for answering all my questions and Emilie Stroh for her help with GIS and the digital library of maps (Digitala kartbiblioteket). I also want to thank all my fellow students and all the teachers at the geology department for making these years so fun.

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Appendix 1 Grain size distribution

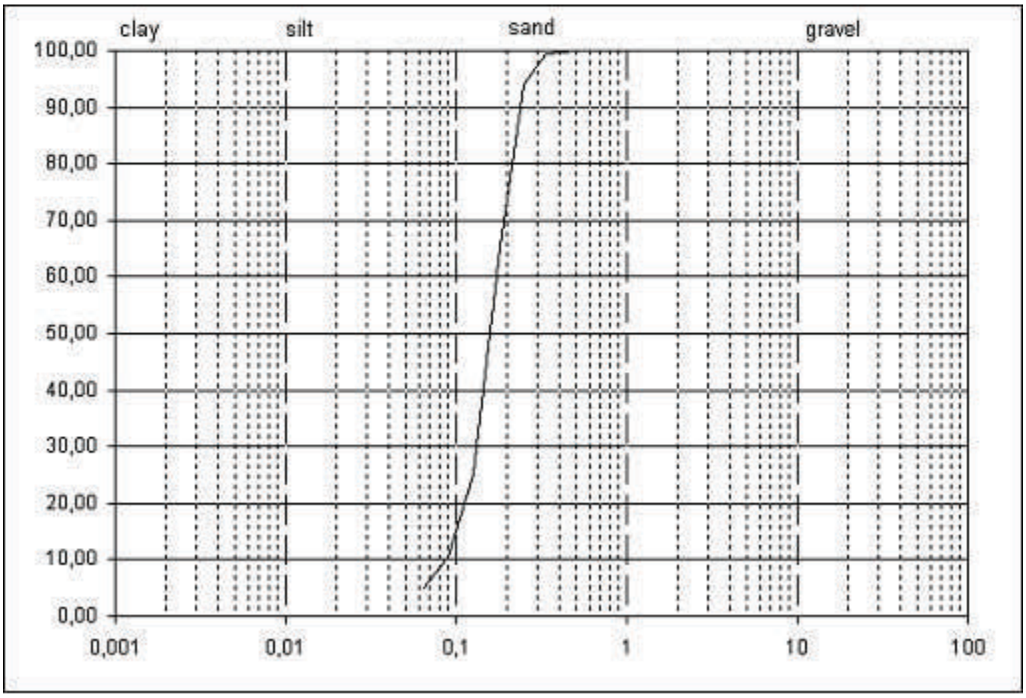


Fig. A1.1. Grain size distribution for grain size sample 1.1, type-B ripple-laminated sand in unit 1, section 1.

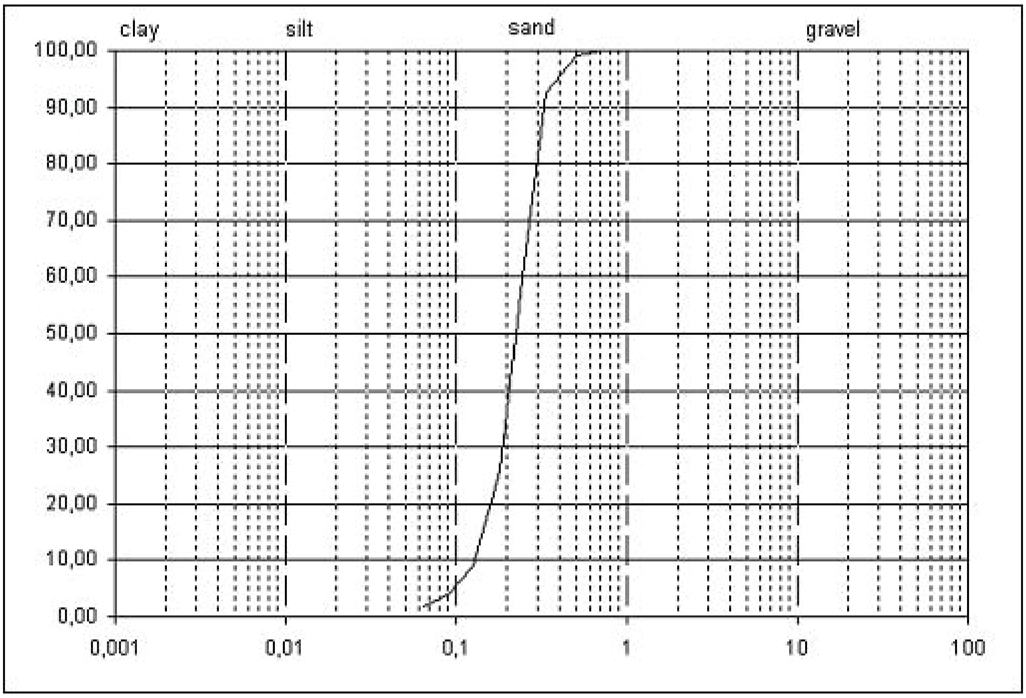


Fig. A1.2. Grain size distribution for grain size sample 2.1, type-B ripple-laminated sand in unit 1, section 2.

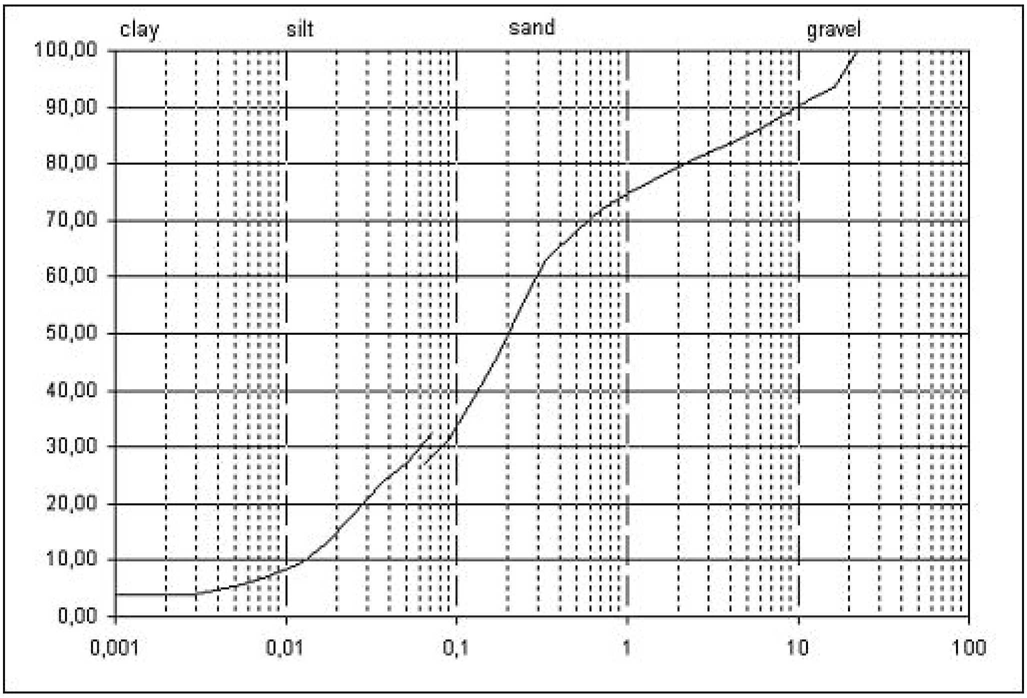


Fig. A1.3. Grain size distribution for grain size sample 3.1, diamict lens in unit 2, section 3.

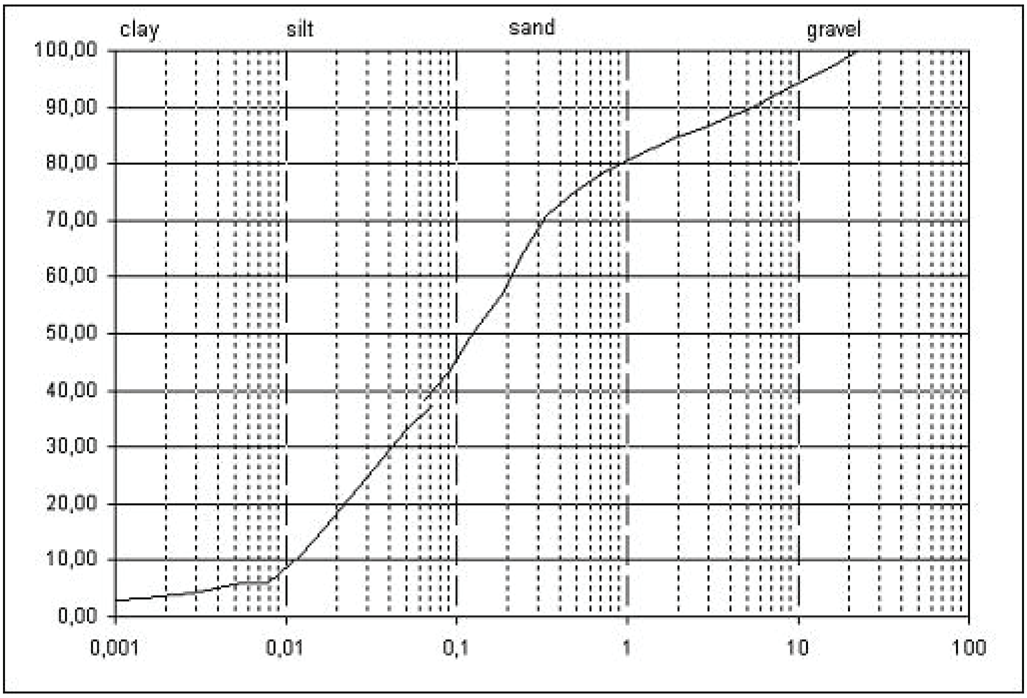


Fig. A1.4. Grain size distribution for grain size sample 6.1, sandy diamict subunit 3.1, section 6.

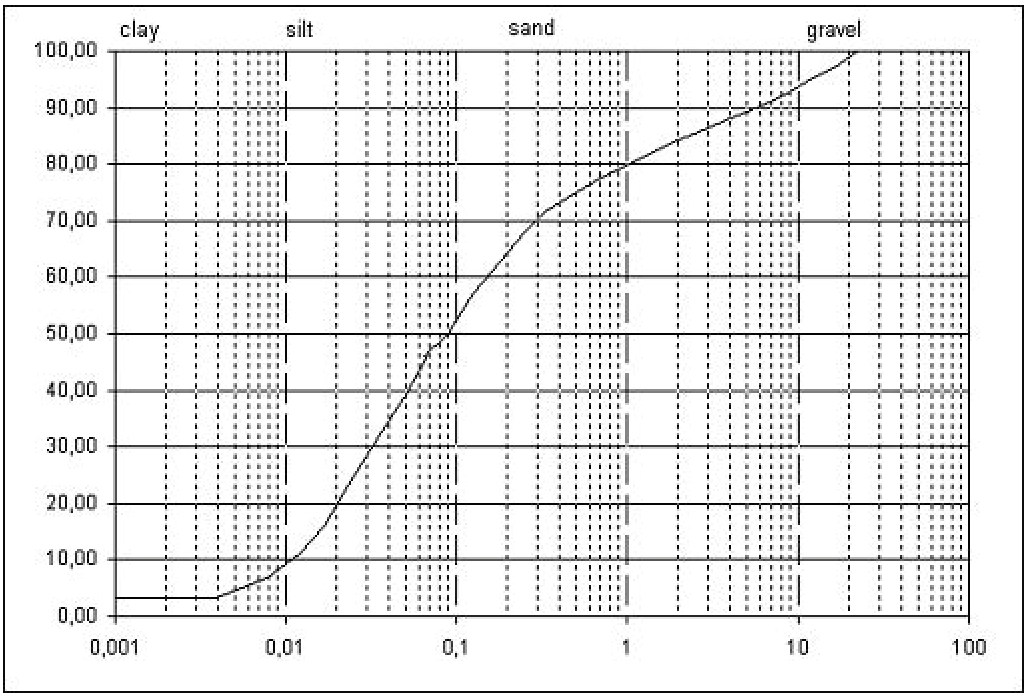


Fig. A1.5. Grain size distribution for grain size sample 6.2, sandy diamict subunit 3.3, section 6.

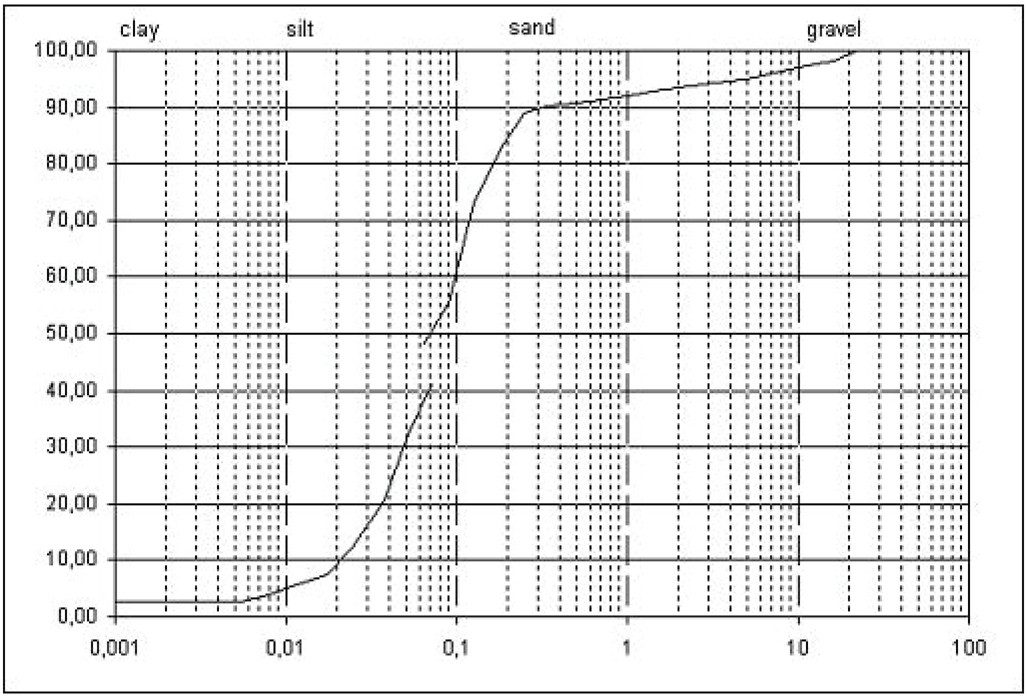
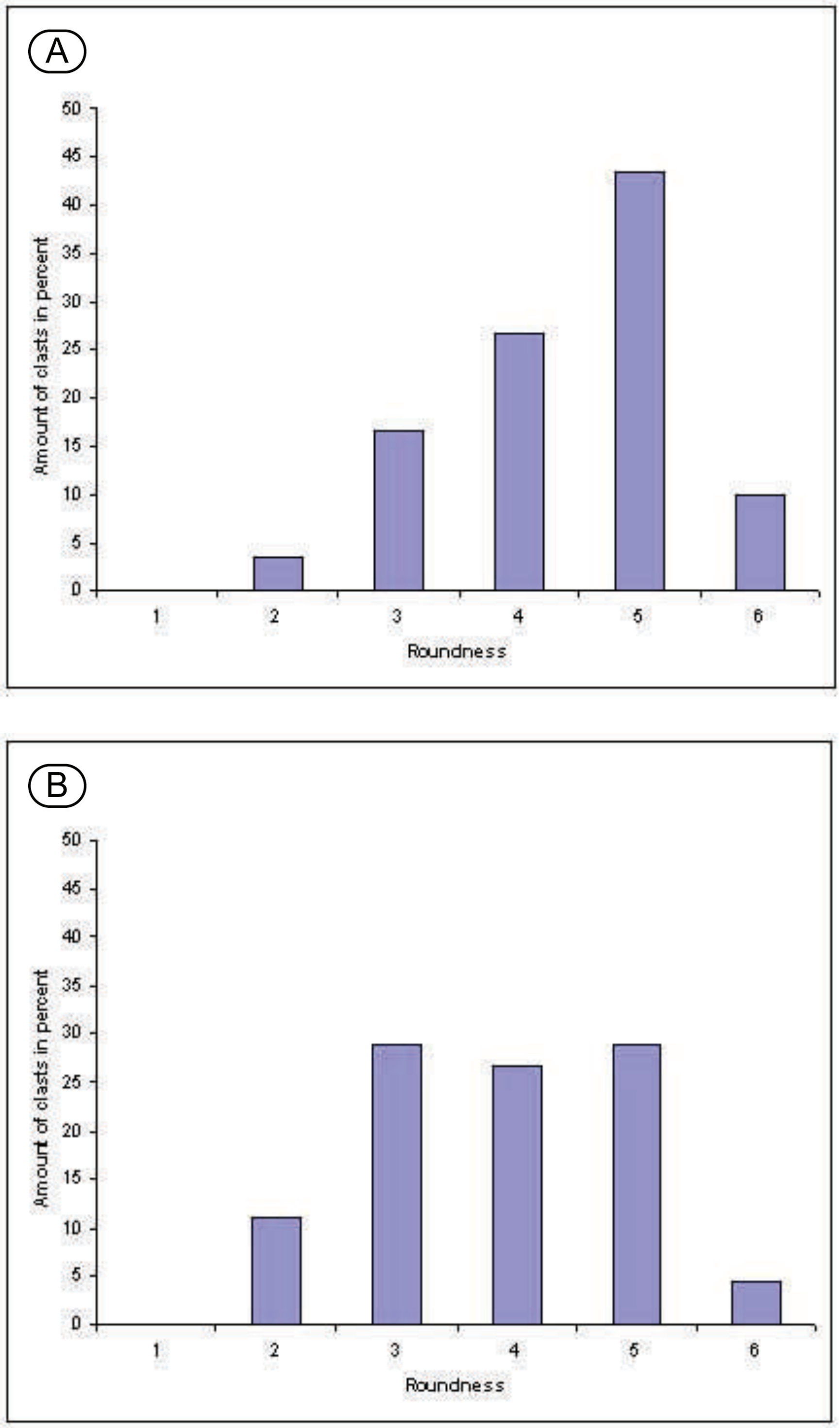


Fig. A1.6. Grain size distribution for grain size sample 6.3, glaciotectonite, subunit 3.4, section 6.

Appendix 2 Clast roundness



Clast roundness measured according to the classes very angular (1), angular (2), subangular (3), subrounded (4), rounded (5) and well rounded (6) suggested by Powers (1953). A) Clast roundness measured on 34 clasts from unit 2, section 6. B) clast roundness measured on 45 clasts from subunit 3.1, section 6.

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