A sedimentological study on the formation of a hummocky moraine at Törnåkra in Småland, southern Sweden

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Thorbergsson, G. B., 2011: A sedimentological study on the formation of a hummocky moraine at Törnåkra in Småland, southern Sweden. *Examensarbeten i geologi vid Lunds universitet*, Nr. 286, 29 pp., 45 ECTS credits.

Abstract: A detailed sedimentological study was made on a section along the side of a moraine hummock at Törnåkra in Småland, south Sweden. Two sedimentary units, A and B, were identified, based on their sediment characteristics. Unit A, the lower one, was formed due to vertical stacking of sediment gravity flow deposits (diamict beds) in combination with melt water disaggregation of such beds, leaving residual lags and redeposited sorted sediment beds. This stacked sequence was laid down into a depression or a low in stagnant/dead ice. Syn- and post-depositional deformation as indicated from folds, faults and injection structures were also identified in unit A. Unit B overlies unit A and was formed due to continued deposition of debris flows. However, this unit is distinct from unit A by its lack of sorted sediments, suggesting that the melt water activity had ceased in the late stage of depression infilling. The overall bed configuration in the investigated section suggests that this was in an ice-proximal location; the sediment beds were both syn- and post-depositionally tilted towards the direction of the lost ice support. The section thus shows the sediment composition at the edge of a moraine hummock, and the sediment composition and architecture here might thus differ from that of the interior part.

Keywords: Dead ice, diamict, glacier, hummocky moraine, melt water, Törnåkra.

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En sedimentologisk studie av bildningen av kulliga moränformer vid Törnåkra i Småland, södra Sverige.

GUNNLAUGUR BRJÁNN THORBERGSSON

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Sammanfattning: En detaljerad sedimentologisk studie har gjorts på en sektion längs med en moränkulle vid Törnåkra i Småland, södra Sverige. Två sedimentära enheter, enheterna A och B, identifierades baserat på deras sedimentologiska särdrag. Den understa enheten (A) bildades genom vertikal pålagring av gravitationsdrivna sedimentflöden (diamiktona lager), kombinerat med att smältvatten dissaggregerade en stor del av dessa gravitations-sediment. Detta resulterade dels i bildandet av residualavlagringar, dels att de diamikta sedimenten omformades till sorterade sedimentära lager av växlande kornstorlek. Denna pålagringssekvens byggdes upp i en sänka i omgivande dödis. Veck- och förkastningsstrukturer samt brant stående sedimentinjektioner av finkorniga sediment i de primärt avsatta sedimenten indikerar att avsättningen av dessa skedde under successiv ned- och tillbakasmältning av den omkringliggande dödisen. Enhet B ligger ovanpå enhet A och bildades under mer enhetliga förhållanden med ihållande deponering av massrörelse-avsatta sediment. Enhet B skiljer sig således från enhet A genom frånvaron av sorterat sediment. Detta tyder på att smältvattenaktiviteten börjat avta för att helt sluta under den senare delen af sekvensens bildning. Som helhet visar den undersökta sektionen att sedimenten avsattes i nära kontakt med is; de sedimentära lagern har fått en lutning mot den riktning där isen gradvis smälte ner och sedimenten tappade därmed successivt sitt isstöd. Sektionen representerar den sedimentologiska sammansättning av en yttre del av en moränkulle bildad i en dödismiljö; sedimentsammansättningen och sedimentarkitekturen här kan därför förväntas avvika från densamma i en mer central position inom moränkullen, där kanske med ännu högre frekvens av sorterade sedimentbäddar och mindre frekvens av diamikta bäddar.

Keywords: Dödis, diamikton, glaciär, kullformad moränterräng, smältvatten, Törnåkra.

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1 Introduction

The genesis of glacially formed landscapes can often be derived from the sediments left behind. Determining the processes involved with glacially formed landforms helps with the reconstruction of the glaciation history; the number, age, beginnings and ends of glaciations. This can help our understanding of how climate changes and how glaciations have interacted with each other and thus may help to model future changes, the past being the key to the future.

Hummocky moraine is a common landform in formerly glaciated regions. The term has been used in the literature to describe hills and ridges that can have anything from very irregular to circular form, often with depressions on top of and around them. The hummocks are most often part of groups that can cover large areas. The proposed formational processes behind hummocky moraine vary a lot, as the term hummocky moraine can describe landforms that look similar, but may have different origin (*e.g.* Aario 1977; Benn 1992). If all the models describing the formation of hummocky moraine are correct, then different processes can produce the same morphological result as an end product, i.e. different processes lead to form equifinality.

One of the first geologists describing hummocky moraine more systematically was Tanner (1915). He suggested that supraglacial debris, dumped into crevasses, was the source for their formation. Later Hoppe (1952) explained the same landform as the result of squeezing of subglacial sediments into crevasses in the overlying ice. Gravenor and Kupsch (1959) proposed a depositional model that was a combination of these two processes, and that they formed within stagnant ice.

The many different theories on the conditions and processes that lead to the formation of hummocky moraine can be categorized as (1) deposition/formation from and within an area of stagnated ice or, (2) direct deposition and moraine hummock formation from active ice. The first case (1) invokes active ice, leaving behind stagnant ice (dead ice formation) within which hummocky moraine forms due to various combinations of sediment redistribution processes, *e.g.* as mentioned above (Tanner 1915; Hoppe 1952; Gravenour and Kupsch 1959) or englacial sediments melting out in supraglacial position and then being redistributed in more or less complex ways into the final hummocks (Boulton 1967, 1968, 1986; Marcussen 1973; Eyles 1983; Paul 1983; Benn 1992; Kjær and Krüger 2001). It is also suggested that remoulding of existing sediments in subglacial position can form hummocky moraine due to stagnant ice sinking or pressing down into these (Stalker 1960; Eyles *et al.* 1999). The latter process could be seen as the reverse of Minell´s (1979) rising diapirs of ice through overlying sediments. Finally, hummocky moraine can form as a result of melt out of unevenly distributed, debris-rich stagnant ice (Möller 1987, 2010; Johnson *et al.* 1995). The second case (2) of above thus means formation of hummocky moraine by direct glacial action at the ice margin or at the ice/bed interface of active ice. This could then include submarginal to proglacial thrusting of basal sediment (*e.g.* irregular deposition of lodgement till (Menzies 1982) or englacial sediments stacked at the margin of active ice (Hambrey *et al.* 1997; Bennett 2001)). Outside these two formational scenarios is that of partially eroded sediment plateaus during subglacial megafloods, as described by Shaw (1983) and Rains *et al.* (1993).

In this thesis a site in Törnåkra, Småland, situated, above the highest coastline, has been studied (Fig. 1). The site is located within a patch of hummocky terrain that is physically detached from, yet genetically a part of, a larger area of hummocky moraine that has been identified as the terrestrial continuation of the subaqueously formed Göteborg moraine (Möller 2010). Different settings above and below the highest coastline should, according to Möller (2010), explain the vast differences between the formational environments at and near the glacier margin as the ice-sheet retreated over these parts of southern Sweden.

The aim of this thesis is to determine the formational processes of this particular hummock by applying sedimentological analysis in order to determine whether it was formed by an active glacier or by passive melt out and/or gravity-induced sediment redistribution. The results may then possibly be applied to the larger hummocky area. The scope of the investigation is rather small: A small section was cleared along the side of one hummock and the features observed were documented and analysed. The local morphology was derived from geological maps and air photographs.

2 Study area

At the Last Glacial Maximum (25-20 kyr BP) the Scandinavian Ice Sheet covered most of Fenno-

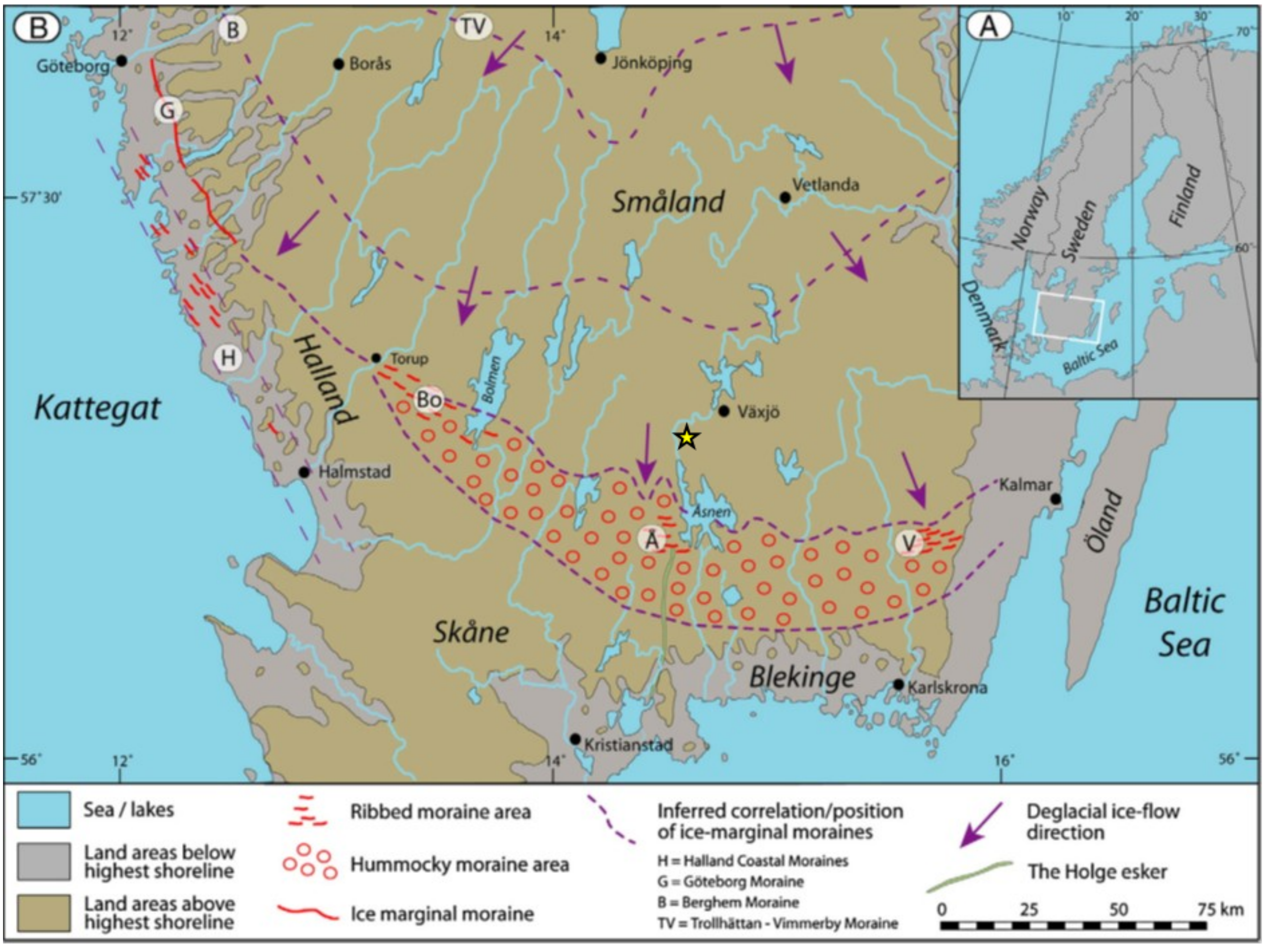


Fig. 1. Map of southern Sweden, showing areas above and below the highest shoreline (maritime limit in the west) at deglaciation, and inferred ice-marginal positions according to Lundqvist (2002). The continuation of the Göteborg moraine (G) into a regional coverage of hummocky moraine and ribbed moraine is indicated. Larger ribbed moraine areas are: Bo = the Bolmen area (cf. Johnsson, 1956), Å = the Åsnen area (Möller, 1987), V = the Vissefjärda–Karlslunda area (cf. Bergdahl, 1953). Ribbed moraine areas occur at a number of other sites within the demarcated zone, but on smaller scales, intercalated with hummocky moraine. Study site marked with yellow star (see Fig. 2). –Taken and adapted from Möller 2010, with permission.

scandia (excluding parts of Jutland) (Houmark-Nielsen and Kjær 2003). At the subsequent late Weichselian deglaciation the retreating ice had at first a freshwater terminating ice margin into the Baltic Basin (the Baltic Ice Lake) in the south-east. However, when the ice retreated above what became the highest shoreline (today at ~65 m a.s.l. in Blekinge; Fig. 1), the deglaciation was subaerial. Deglaciation of this part of Sweden had no known standstills or ice margin oscillations (Möller 2010).

The deglaciation of Halland (western part, Fig. 1) was in a marine environment. There the deglaciation had several stand stills and oscillations, remnants of which are marked in Fig. 1. Relevant here are (1) the Halland Coastal Moraines (Fig. 1, zone H), radiocarbon dated from molluscs to 14000 ^{14}C yr BP (Påsse 1992 as cited in Möller 2010) (~18–16 cal kyr BP; Lundqvist and Wohlfarth (2001) as cited in Möller (2010)) and (2) the Göteborg Moraine (Fig. 1, line G). The Göteborg moraine forms thick deposits in lower areas from east of Göteborg and southeast-wards, linked with thinner ridges at higher elevations in between (Wenner 1951; Wedel 1971; Hillefors 1975, 1979, as cited in Möller (2010)). Dating of molluscs from some of these ice-marginal deltas and subaqueous fans give radiocarbon ages of 12800–12600 ^{14}C yr BP (Hillefors 1975, 1979 (from Möller 2010)) and despite difficulties in calibrating radiocarbon ages from that period since the ages are within a ^{14}C plateau, it is suggested by Lundqvist and Wohlfarth (2001) that they are formed any time between 15400 and 14500 cal yr BP.

The Göteborg Moraine can easily be followed along its subaqueous parts, but becomes fainter and uneven closer to the marine limit (~70 m a.s.l.). It is generally accepted though, that it continues to the ice contact delta at Torup (Fig. 1) from where it continues in a south-eastward direction into an area of transverse moraines around Lake Bolmen (Johnsson 1956; Andersson 1997, 1998; (from Möller 2010)). Further east, this area forms a 20–40 km wide zone of hummocky moraine, interfingering with a zone of transverse moraine that continues across southern Småland (Fig. 1) (Möller 2010).

According to Möller (1987, 2010), this hummocky/transverse moraine area is a continuation of the Göteborg moraine as it climbs above the highest shoreline. Here glacial retreat was characterised by gradual stagnation of ice distal to the boundary between melted bed and frozen bed conditions, leaving a wide zone of stagnant, debris-loaded ice. During final melt out a landscape of hummocky moraine or transverse (ribbed) moraine was formed, depending on depositional processes and patterns (Möller 1987, 2010). The hummocky terrain shows clear indications of the thermal regime of the glacier changing from warm-based, to cold-based. Those signs are not found in the streamlined terrain further north (Möller 2010).

The study site of this thesis, Törnåkra (yellow star in Fig. 1), is situated north of the regional boundary between hummocky moraine and streamlined terrain. The hummocky moraine area around Törnåkra represents a smaller such in a landscape dominated by streamlined landforms.

3 Methods

3.1 Studies of existing data

3.1.1 Morphological map

A morphological interpretation of the immediate area around the study site was carried out by air photo interpretation (air photo colour images at a 1:20 000 scale (Lantmäteriet 2009) and the resulting landforms were combined with a 1:50 000 scale topographic map (Lantmäteriet 2003).

3.2 Field investigations

3.2.1 Data collecting

To investigate the structures of the hummock, a partially open section was further opened up and made near vertical, ~20 m long and up to ~8 m high. The bottom of the section was set at a level about 0.5 m below the ground surface of the section. No attempt was made to reach the bedrock. The section was roughly cleaned by an excavator and then cleaned further by hand. A drawing in the scale of 1:20 was made of the whole section and another in the scale of 1:10, for part of the section, where more detail was needed. Sedimentary structures were drawn in detail and every clast larger than 5 cm was marked. Lithological units were classified according to Möller´s (2010) adaptation of Eyles *et al.* (1983) lithofacies classification. Measurements were made of strike and dip on inclined bedding planes and cross-cutting sediment veins, as well as on occurring folds. Six clast-fabric measurements were made in the diamicts, excavated from ~50 by 40 cm horizontal shelves into the section, the clasts sample area thickness was less than 20 cm. A minimum of 25 clasts were taken from each measurement; with the a/b-axis ratio set at a minimum of 1.5:1 and the particle sizes between 20 and 60 mm. Pebbles close to cobbles and boulders were discarded, for the risk of interference. Bulk samples were taken from the section for laboratory analysis. Photographs of the section and its finer features were taken with a Canon EOS 450D.

3.2.2 Surveying

Topographic measurements were made with a Kernlevel levelling instrument and a tape. A baseline was set out west of the section, striking NW–SE (315° - 135°). Measurements of height relief were made perpendicular to this baseline at 30 m interval for every 1 m elevation change as well as break points. Each starting point of a perpendicular line, as well as the starting point of the base line, was marked in a GPS receiver. Points were also taken in an adjacent field for comparison with topographic maps of the area. Since the purpose was to map this particular hummock, the lengths of the profiles vary. But in most cases the length was actually determined by ease of access since the edges of the map were heavily forested.

3.3 Laboratory investigations

All samples taken in the field were later analysed in the laboratory. This includes grain size analysis, hydrometer analysis (when needed), measurements of clast shape and sizes and finegrain lithology analysis.

3.3.1 Grain size analysis

Grain size analyses were performed on 10 bulk samples taken from the section. The wet sieving was performed using >200 g of fine sorted sediments, 300-500 g of coarser sorted sediments and 500-800 g of unsorted sediments.

3.3.1.1 Sieving

All samples were weighed after being dried over night at 105°C. Clasts larger than 22.4 mm were removed from the samples and the samples then weighed. All samples were then bathed in 0.05 M sodium pyrophosphate ($Na_4P_2O_7$) to dissolve all aggregates. The finest grains were then washed out through a 0.063 mm mesh. The samples were then dried again at 105°C over night. The washed samples were then weighed again. The washed and dried samples were then sieved through a sieve staple with mesh sizes from 22.4 to 0.063 mm, in a shaker for 15 min. All fractions were then weighed and quantified, all as described by Ambrosiani (1995).

3.3.1.2 Hydrometer analysis

Hydrometer analysis was used for determining the amount of the smaller fractions (smaller than 0.063 mm) when their weight exceeded 10% of the sample. When possible about 100 g of unwashed remains of the samples were sieved, removing particles larger than 2 mm. All samples were weighed and then put into a 1000 ml cylinder along with 100 ml of 0.05 M sodium pyrophosphate ($Na_4P_2O_7$) and 300 ml of distilled water. The cylinder was then sealed with a parafilm and rolled in a cradle for 15 min. Distilled water was then added up to the 990 ml mark and then the sample was stirred with an agitator for 1 min and any grains cleaned off it and the cylinder walls by ~10 ml of distilled water, bringing the total volume to 1000 ml. As the agitator was taken out of the sample, a timer was started and a hydrometer put into the cylinder. Readings on the hydrometer where then done at 0.5, 1, 2, 5, 10, 20, 50, 100, 200, 400 min and 24 hours according to the timer. The process was started over again for the first six readings (0.5-20 min) to determine standard deviation, all as described by Ambrosiani (1995).

The decreasing density of the fluid, as the fines sink to the bottom, was determined at those

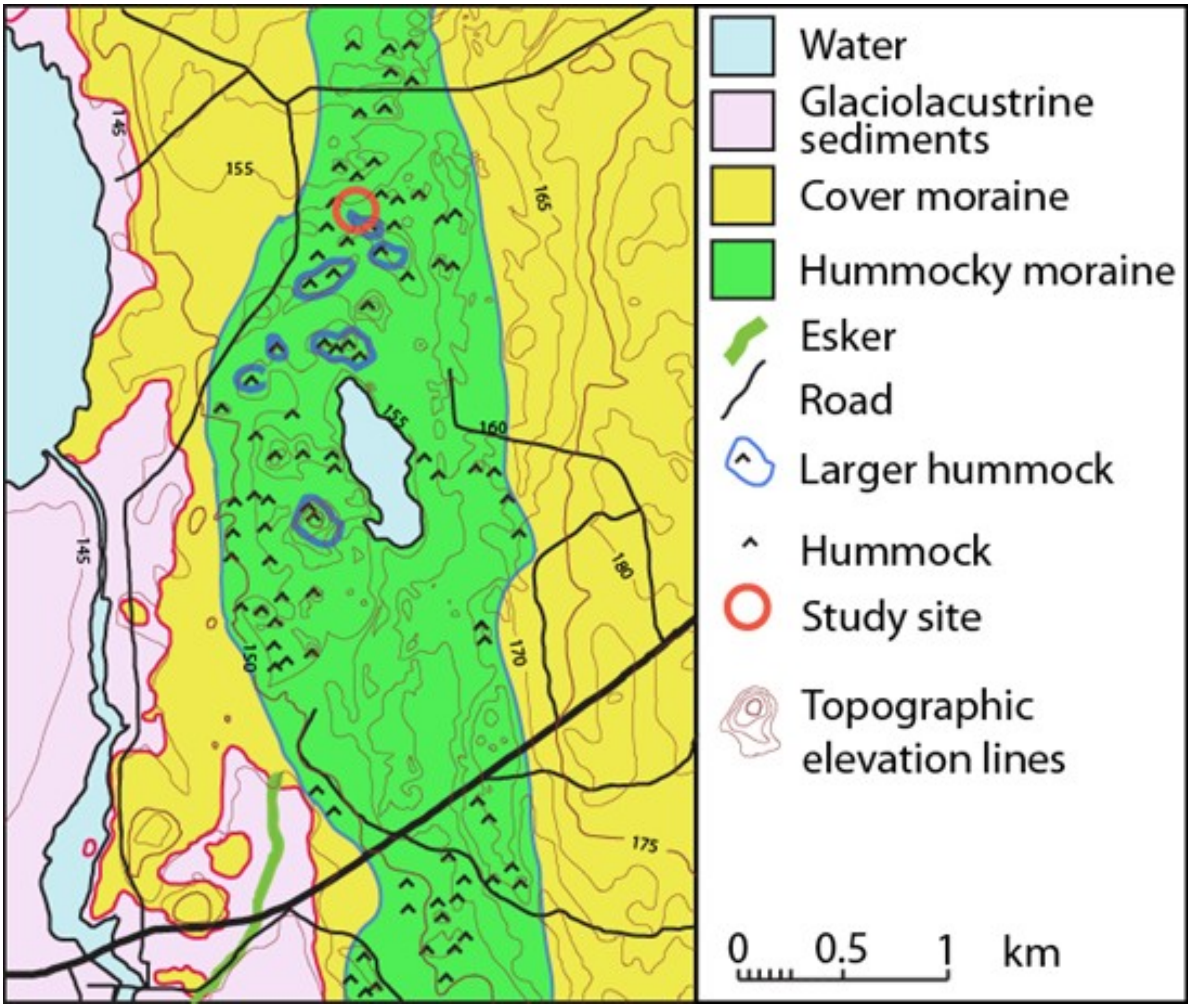


Fig. 2. Morphological map of the area with elevation lines. The study site (marked with a red circle) is situated in a narrow hummocky moraine area (green), flanked by cover moraine (yellow).

time intervals by how much the hydrometer had sunk. From that the clay and silt content was calculated and then plotted on a grain size distribution diagram (Appendix I).

3.3.2 RA values

Roundness/angularity can be an indicator of transport path and length, as the wearing of clasts is different from one environment to another. The wear of clasts was determined visually as described by Matthews (1987) and Benn and Balantyne (1994) (Appendix II).

3.3.3 Fine grain analysis

With the aim of determining the provenance of different units, fine grain analysis of the samples was performed. The lithological composition of the sediments can possibly be traced back to the original bedrock and thus indicate the flow direction of the ice (Evans and Benn 2004). After sieving at grain-size analyses, the fractions between 2 -2.8, 2.8-4, and 4-5.6 mm were separated for lithological analyses. In this study the fine grain analysis was less than conclusive since the finer grain sizes were of similar size as individual crystals and it was very hard to decide the original bedrock type even when comparing larger grain fractions.

3.4 Data processing

The morphological map was drawn with the Adobe CS Illustrator computer program, using Lantmäteriet´s (2003) terrain map, over which the morphological features observed from the aerial photographic interpretation were introduced. The topographic map of the investigated moraine hummock was also drawn with the Adobe CS Illustrator. Measurements of structural data (till fabric measurements, bedding planes, cross-cutting sediment veins, folds, etc.) were evaluated by the eigenvalue method as described by Mark (1973) and Benn (1994) and graphically manipulated in Schmidt equal-area lower-hemisphere net projections with the StereoNet© 3.03 for Windows computer program. The grain-size data were analysed in Microsoft Excel 2003, producing grain-size distribution diagrams (primary results in Appendix I).

4 Geomorphology of the area

The studied hummock is one of many in a north to south elongated pocket of hummocky moraine, being 1-1.3 km wide and >10 km long (~6 km seen in Fig. 2). The pocket is flanked by cover moraine and glaciolacustrine sediment (Fig. 2). Further away - and dominating the area outside the morphological map - are streamlined landforms (Möller 1987, 2010) (Fig. 1). The overall trend is that isolated areas of hummocky moraine occur in the lowest terrain positions in troughs paralleling the N to S trending drumlin ridges.

Within the area shown in Fig. 2, the hummocks rise 5-10 m above the open and/or closed depressions in between (Fig. 3 A and B). They vary significantly in size, ranging from a few tens of m^2 to thousands of m^2 and are subcircular to elongate in varying directions, forming a chaotic topography. Large boulders (1-2.5 m in diameter) are frequent at hummock surfaces, as well as in the depressions in between. Outside the hummocky moraine area and sometimes also in between hummocks within the hummocky moraine area, the ground surface is often relatively flat and smooth (Fig. 3 C), but farming may have contributed to that, levelling out smaller rises and removing boulders.

5 Sediment descriptions and interpretations

The Törnåkra section was cut into the north western flank of a NNW-SSE oriented moraine hummock/ridge, being at most ~13 m high (Fig. 4). The dug section more or less parallels the orientation of the hummock/ridge and is 20.5 m long and ~8 m at its highest (Fig. 5). The bedrock was not found in the section. Sedimentologically, the sediments are divided into two main units, Unit A (lower unit) and Unit B (upper unit), described below. Unit A is characterized by its chaotic appearance and frequent interbedding of diamict and sorted sediment beds, whereas Unit B is a more uniform, massive diamict.

5.1 Unit A

Unit A constitutes the lower part of the revealed sediments, the upper boundary conforming to the ground surface of the morphological expression of the hummock; the thickness of the unit thus increases to the south (to the right in the section drawing, Fig. 5), being here ~5.3 m. However, as the basal contact in not visible, the total thickness is not known. Unit A is characterized by an interbedding of diamict and sorted sediment beds, all being more or less syn/post-depositionally rearranged/disturbed and also syn/post-depositionally cut by high-angle veins of sorted sediment (Fig. 5).

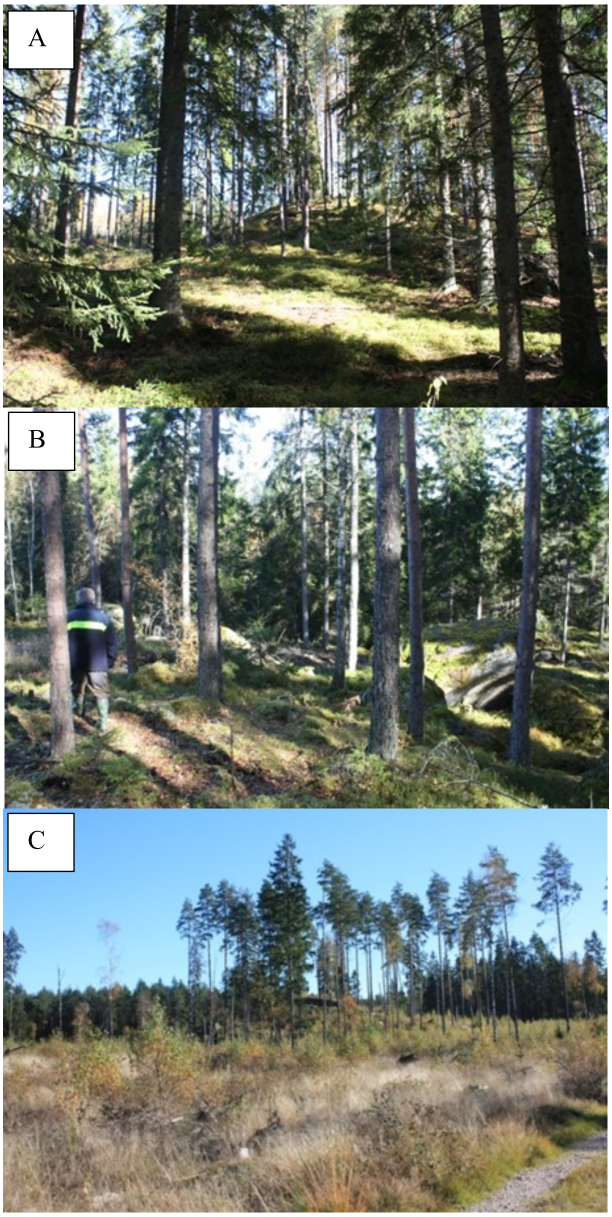


Fig. 3. A) Hummocky moraine close to the investigated site. B) Closely spaced moraine hummocks with large boulders on their surfaces. C) Flat areas between less densely distributed moraine hummocks.

5.1.1 The diamicts of Unit A

Most diamict beds in Unit A are sandy gravely to gravely sandy such, being matrix-supported and massive and carry cobbles and boulders up to 40 cm in diameter. The matrix colour is light brown to light grey/brown. The granulometric matrix composition (<20 mm), as shown in three grain size analyses (analysis 1, 9 and 10, see Appendix I) confirm the field classification as diamict, i.e. unsorted sediment. Roundness (RA) was calculated from measurements on the samples subjected to grain size analysis. The RA values range from 48%-56%, indicating a predominance of angular to subangular clast shape (Appendix II, samples 1, 9 and 10). There are five clast fabric measurements (I, II, IV, V and VI) from this unit (Fig. 6). All but one show scattered fabric shapes and a weak and dispersed clast axis orientation (S_1 = 0.513-0.576) (measurements I and IV-VI) and a wide range of V_1 axis orientations. The exception is clast fabric measurement II with a clustered fabric shape and a relatively strong clast axis orientation (S_1 = 0.684) with a V_1-axis orientation of 26°/8° (Fig. 6).

Within Unit A is also a diamict that differs from the normal such; with start at 16.3 m and continuing to the southern end of the section (Fig. 5) is an up to 115 cm thick bed of sandy gravely diamict, being more cobble-rich and close to clast-supported. The colour of this D(S/G)cm is slightly lighter than the surrounding sediments and it has cobbles up to 15 cm within. There is no granulometric data from this sequence and fabric measurement was deemed impossible due to the

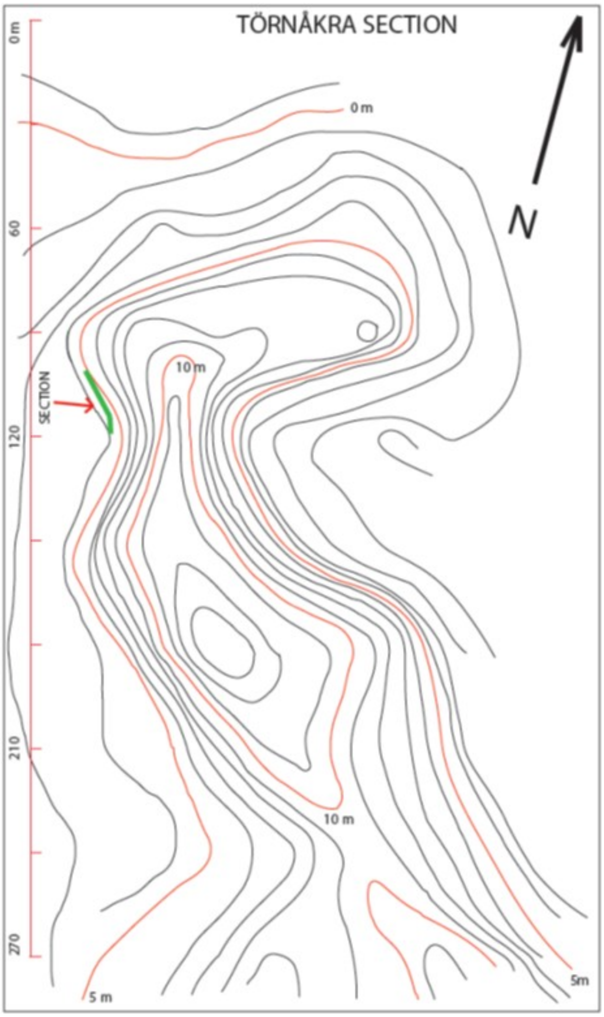


Fig. 4. Topography of the northern part of the studied hummock. Height measurements are relative for the area. Limits of the map are defined by vegetation, which made further measurements of the hummock impossible.

clast-supported nature.

5.1.2 The sorted sediments of Unit A

Sorted sediment beds in multitude facies are interbedded with the diamict beds of Unit A. Occurring facies are laminated silty sand (SiSl), massive silty sand (SiSm), coarse laminated and massive sand (cSl, cSm) and fine to medium massive gravel (fGm, mGm). Often the sorted sediment beds show both an increasing bed thickness and increasing grain size from the north (left) to the south (right) in the section, with bed thicknesses ranging between 10 cm and 80 cm. Larger clasts, from pebbles to boulders up to 50 cm in diameter, occur in the sorted sediments. The colour of the sediments ranges between variations of reddish/yellowish brown, light grey/brown to light grey, though the difference in colour is indistinct. The granulometric matrix composition (<20 mm), as shown in six grain size analyses (analysis 2, 3, 4, 5, 6 and 7, Appendix II) confirms the field classification of different sorted sediments beds. It was only possible to determine the RA value for clasts in the most coarse-grained sorted sediment bed (one mGm bed); the RA value was calculated to 44%, showing that clasts are predominantly angular to subangular, and do not differ from the diamict beds (Appendix II, sample 6). Excluding the high-angle veins, (see below) there is a general trend for the sorted sediment beds (and their interbedded diamict beds) to plunge towards the north (left) in their projection along the section wall (Fig. 5). However, fourteen readings on strike and dip of bedding contacts (Table 1) reveal a very scattered plunge distribution (Fig. 7A). The S_1 value is only 0.53 for the principal eigenvector = 12°/6°, i.e. towards NNE. Most bedding contacts have a predominant true plunge direction towards a NW-NE sector, but some beds also plunge towards SW, S and SE.

The uppermost part of Unit A – and partly demarcating it from the overlying Unit B – constitutes a quite continuous horizon of interbedded laminated to massive silty sand (SiSl, SiSm). It has a maximum thickness of 70 cm, but is also split up in thin beds only a few mm thick, interfingering with diamict beds. The laminated parts show an intrabedding between thin sand and silt lamina (Fig. 8A). A number of the steeply inclined (from left to right, Fig. 5) sorted sediment veins that can be seen penetrate lower beds – both diamicts and sorted sediment – seem to emanate from this horizon (see below).

5.1.3 Deformational and syn- and post-depositional structures within Unit A

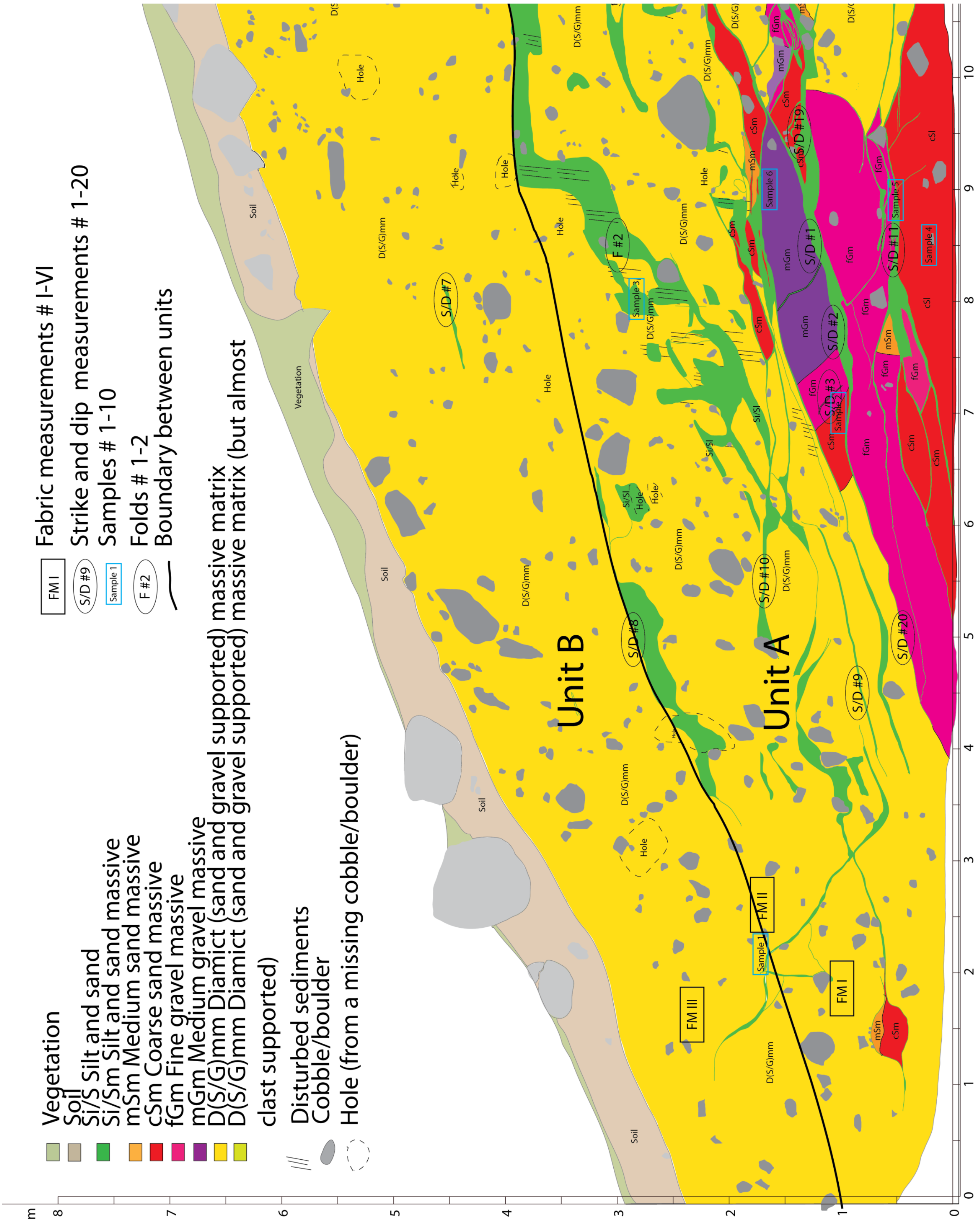
Steeply inclined veins of sorted sediment (SiSl and SiSm), some of which seem to stem from the topmost silt-sand bed, pass through the unit. They range in thickness from a few mm to a couple of cm and slope from the north to the south (right) in the projection of the section (Fig. 5). However, five readings on strike and dip (Table 1) reveal a scattered plunge distribution (Fig. 7B). The S_1 value is only 0.543 for the principal eigenvector V_1 = 245°/28°, i.e. towards SW, suggesting no preferred plunge direction of these structures. Three veins have a true plunge towards W and SW, whereas two veins plunge towards SE.

Two folds were observed in the unit. Fold #1 in the diamict, the folding visible from the thin, interbedded sorted sediment beds and fold #2 developed a laminated silty sand bed (Fig. 8D). The axial planes through these folds plunge 290°/30° and 300°/31°, respectively. Some SiSl and SiSm beds sometimes also enclose coarser sorted sediment beds (Fig. 8B), the enclosed sediments projecting in the section wall as “eye” structures.

At a few places the more continuous sorted sediment beds are cut off, standing at angle with above-lying beds, suggesting syn-sedimentary erosional or slumping events (Fig. 8C).

5.1.4 Sedimentological interpretations – Unit A

Unit A shows a stacked sequence of interbedded diamict and sorted sediment beds, the former being glacial till derived more or less directly from glacier ice and the latter deposited from glacial melt water at different energy levels, as indicated by the range of grain sizes from silt to medium gravel. Sorted sediment interbedding with till beds is not diagnostic for many glacial setting, *e.g.* traction till can be deposited from the base of active ice at the same time as sorted sediments are deposited in melt water channels at the ice/bed interface (*e.g.* Clark and Walder 1994; Walder and Fowler 1994; Boulton and Hindmarsh 1987; Lindén and Möller 2005). Also till beds can be intercalated with sorted sediments during infill of supraglacial or ice-marginal troughs due to sediment gravity flow processes and melt water activity (*e.g.*, Paul 1983; Benn and Evans 1996; Krüger and Kjær 2000; Kjær and Krüger 2001). From this can be concluded that diagnostic criteria for the depositional environment in which unit A was deposited must come from criteria of the diamict beds, combined with the syn- and post-



FM I
Fabric measurements # I-VI
S/D #9
Strike and dip measurements # 1-20
Sample 1
Samples # 1-10
F #2
Folds # 1-2
Boundary between units
Vegetation
Soil
Si/S Silt and sand
Si/Sm Silt and sand massive
mSm Medium sand massive
cSm Coarse sand massive
fGm Fine gravel massive
mGm Medium gravel massive
D(S/G)mm Diamict (sand and gravel supported) massive matrix
D(S/G)mm Diamict (sand and gravel supported) massive matrix (but almost clast supported)
Disturbed sediments
Cobble/boulder
Hole (from a missing cobble/boulder)
Unit B
Unit A
m
8
7
6
5
4
3
2
1
0
1
2
3
4
5
6
7
8
9
10
Soil
Vegetation
Hole
D(S/G)mm
S/D #7
S/D #8
S/D #10
S/D #9
S/D #20
S/D #1
S/D #2
S/D #3
S/D #11
S/D #19
F #2
FM I
FM II
FM III
Sample 1
Sample 2
Sample 3
Sample 4
Sample 5
Sample 6
Si/Sl
cSm
mSm
fGm
mGm
cSl

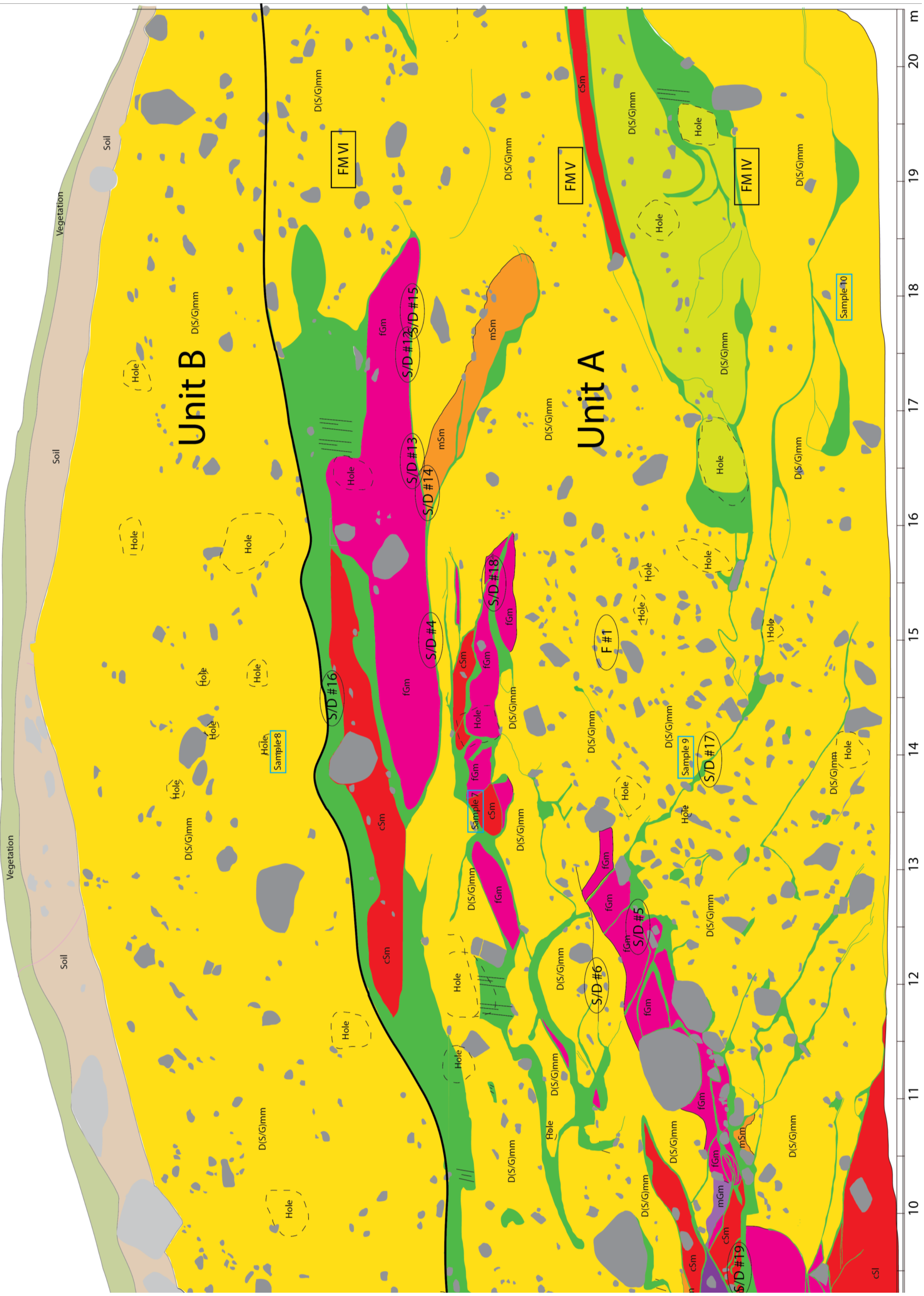


Fig. 5. The study site. Originally drawn in the field in the scales 1:20 and partly 1:10, here downsized to fit the page.

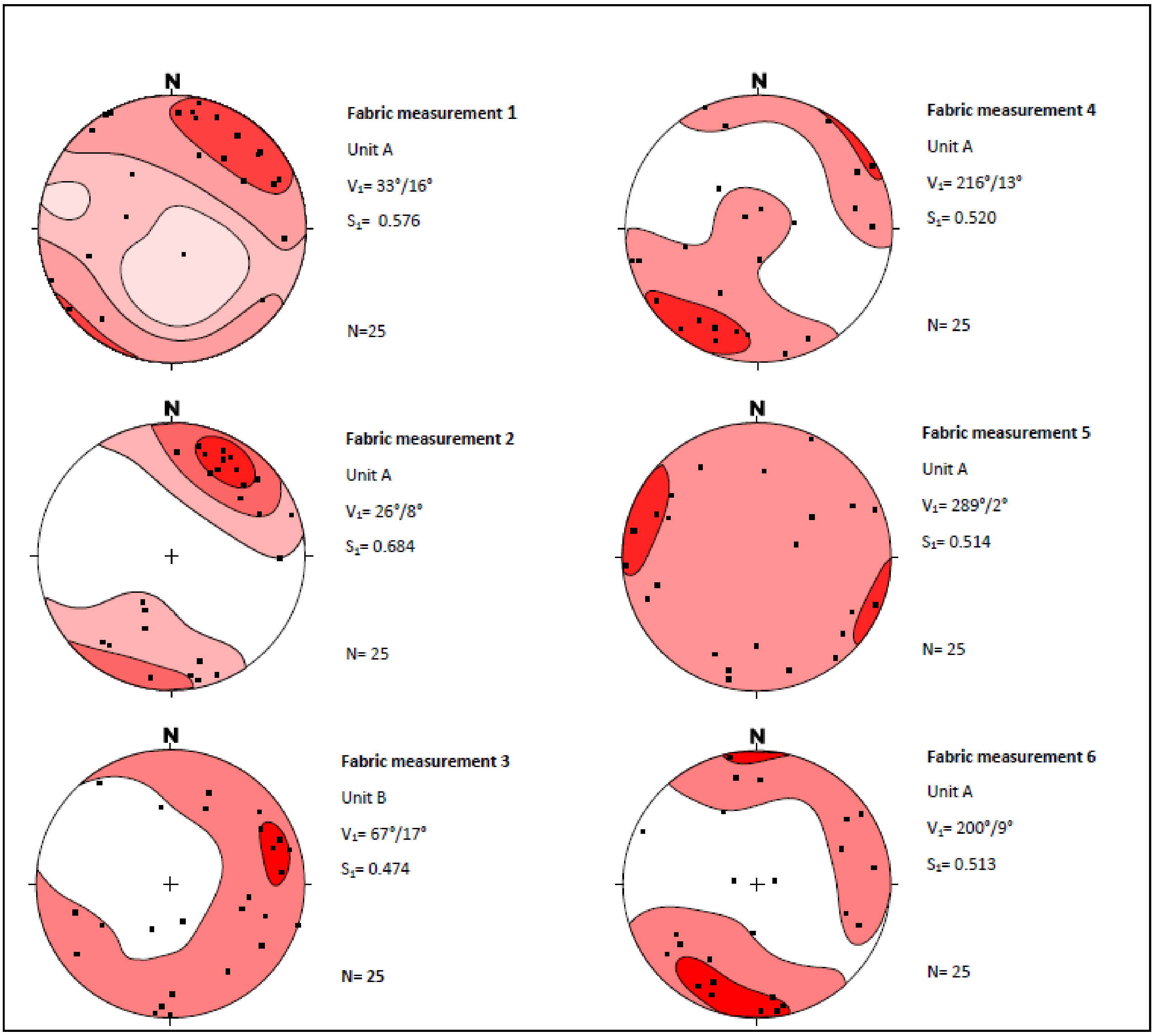


Fig. 6. Results of fabric measurements as plotted in StereoNet©, showing the usually weak (scattered) directional elements. Schmidt equal area, lower hemisphere projections of clast long axis orientation of the 6 clast fabric analyses. Scatter plots are combined with contoured diagrams (conventional step calculation, 2σ contouring interval) for each data set. Calculated major eigenvector azimuth (V_1 axis), as well as normalized eigenvalues (S_1, S_2 and S_3), are according to Mark (1973).

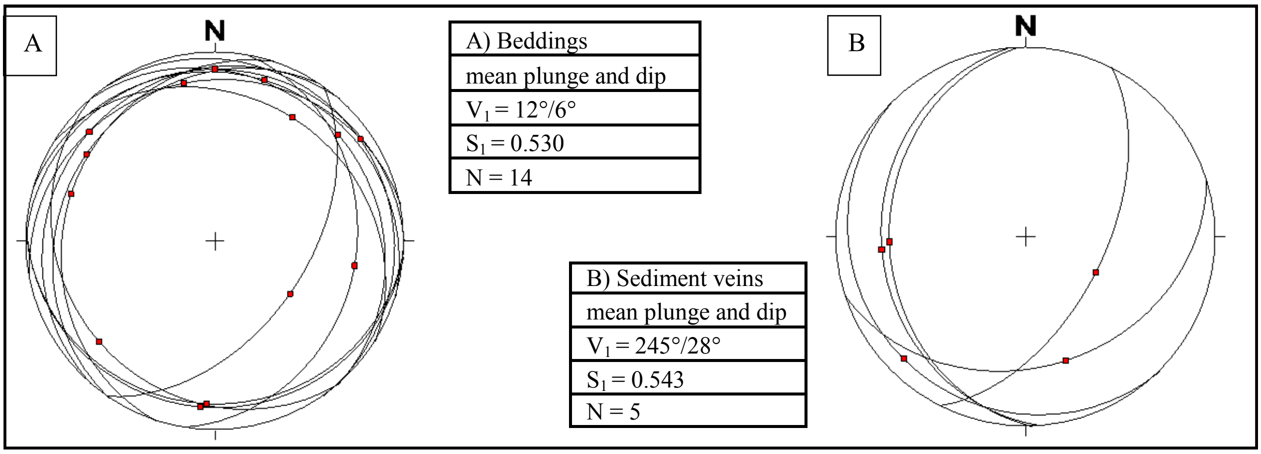


Fig. 7. Schmidt equal area, lower hemisphere projections of plunge directions and dip of 19 plunge and dip measurements. Plotted in Stereo-Net©, showing the weak (scattered) directional elements. Scatter plots are combined with planes diagrams for each data set. Calculated mean plunge direction (V_1 axis), as well as normalized eigenvalue (S_1) - according to Mark (1973). A) Plunge directions and dip measured on beddings. The results show very varied results, with weak signal strength (S_1). B) Plunge directions and dip measured on injections. The results show varied results, with weak signal strength (S_1). S/D number nine is omitted from mean plunge and dip calculations since the measurements is taken where the underlying beds may affect the directions observed.

depositional deformation structures, as revealed in the section.

The fabric analyses and RA-values from the diamict beds suggest that these were deposited by gravity flow processes, as suggested by, *e.g.*, Boulton (1972) and Paul (1983). The fabric analyses generally show scattered, non-modal clast orientation with eigenvectors of weak strength, with one exception. The RA values from the diamicts show little abrasion and suggest that the clasts were not transported subglacially but englacially and/or supraglacialy (Benn and Ballantyne 1994). For traction till, clasts could be expected to show more signs of abrasion than is shown here (Benn 1995) while the clast fabric should yield more unimodal, clustered clast orientation with stronger eigenvectors in thin tills (vs. more scattered polymodal fabric shapes for thicker tills) (*e.g.*, Hart 1994; Benn 1995; Benn and

Fig. 8. A) Example of intrabedding of laminated silt and fine sand, here with coarser sediments around and in between. Thickness can vary between a few mm and 70 cm. B) An extreme example of SiSm enclosing fGm, projecting in the section wall an "eye" structure, at 12 m and 2.1 m height. C) Cross cutting of veins of silty sand at 9 m and 1.3 m height, suggesting syn-sedimentary erosion or slumping events. D) Fold #2 at 8.5 m and 3 m height, with axial plane plunging towards left, as seen in figure.

Table 1. Strike, plunge direction and dip measurements, made on bedding planes and crosscutting sediment veins. Some measurements are taken where two different beds lie together or on contact between units. One measurement may therefor show results for two beds and appear in different descriptions. Injection number nine is omitted from mean plunge and dip calculations since the measurements is taken where the underlying beds may affect the directions observed.

Strike an dip of bedding planes

Number	Strike in °	Plunge dir. and dip in °
1	221	311/13
2	214	304/19
4	325	55/7
7	302	32/24
8	259	349/16
11	139	229/20
12	35	125/50
13	10	100/26
14	95	185/13
15	319	49/15
16	93	183/15
18	270	360/10
19	287	17/12
20	198	288/21

Strike and dip of sediment veins

Number	Strike in °	Plunge dir. and dip in °
3	27	117/56
5	178	268/29
6	175	265/25
9	285	15/12
10	135	225/10
17	72	162/32

Evans 1996). The fabric data do, however, correspond nicely to Lawson´s (1979) and Benn´s (1994) descriptions of the properties of flow till, which can show scattered clasts with poly- or non-modal orientation with very low S_1 values for thicker till flows, as well as low RA-values, since the clasts will change very little from their englacially or supraglacially formed shape (Benn and Balantyne 1994) during a final gravity-flow redistribution process.

The exception of fabric measurement II, which has a unimodal shape with a S_1 value of 0.684 (and possibly fabric I which has close to unimodal shape, but a weak S_1 value) is not contradictory to a sediment gravity-flow interpretation. Lawson (1979) describes how thin flow till beds with high water content can acquire high S_1 values, this is because of shearing though-out the bed during the gravity-induced movement, decreasing the scatter of clast orientation as the clasts align themselves with the flow direction. However, thicker sediment flows are characterized by lower water content, and thus shearing only occurs within a thin layer at the bottom of the flow, whereas the upper part rides on the basal deformation zone as a "plug" with no internal deformation and thus no alignment of long-axis clasts (Lawson 1979).

The RA values for the sorted sediments show slightly more abrasion than from diamicts, but suggest that the clasts have not been transported very far during their fluvial transport (Benn and Ballantyne, 1994). This suggests that the sorted sediments derive from the diamict sediment gravity flows, reworked by melt water over short distances.

The coarser sorted sediment beds indicate the occurrence of stream channels with, at least periodically, relatively high energy and thus larger volumes of water. The laterally increasing grain sizes observed in some beds indicate an increase in energy. This means that some of the smaller grain sizes have been partially or totally winnowed-out from the parent material. Beds with silt, sandy silt and silty sand represent deposits within standing water basins along the fluvial drainage paths when the energy lessened (Paul 1983; Krüger and Kjær 2000; Kjær and Krüger 2001). The boulders and cobbles found in these beds of sorted sediments may have rolled into a stream bed from the sides, possibly as the water eroded the sediments around them, or lags from small slides into streams where all finer material was washed away, leaving only the larger grain sizes.

Originally, all sediment beds were probably more or less horizontal or even dipping away from the primary source of sediment, that should have been debris-rich ice that once surrounded the present moraine hummock which at deposition was a sediment-receiving trough. As supporting ice gradually melted due to down- and backwasting, ice-support was lost and sediment beds were syn-depositionally tilted, as indicated from bed plunges preferentially towards a broad NW-NE sector, i.e. tilted into the direction of the waning support.

The one case of cross-cutting relation between Si/Sl beds (Fig. 8C) is most likely because of syn-sedimentary sliding/rotation of deposited sediments, a process also suggested as responsible for the few fold structures that were encountered in the section (*e.g.*, Fig. 8D). None of these suggest any active-ice stress transfer for their formation.

The combined results thus suggest that an infra-marginal or marginal depression in relation to presumably stagnant ice was infilled with sediment gravity-flow deposits. These were predominantly preserved as diamicts closer to supporting ice and higher up in the sediment succession. More distal to the supporting ice and in the lower part of the sediment succession the sorted sediment bed frequency and distribution suggest frequent erosion and reorganization of debris flows into fluvial sediments, a depositional model that follows those suggested by, *e.g.*, Paul (1983) and Kjær and Krüger (2001) (see interpretation chapter below).

The steeply inclined veins of SiSl and SiSm are most likely syn- and/or post-depositional sediment injections into fractures through the primary infill sediments, fractures that formed at even steeper angle when ice support was removed and trough infill sediments started collapsing. Most fractures were then infilled with the finest available sediments, preferentially emanating from the uppermost SiS bed of unit A. As the support was totally removed, their steep angle was somewhat lessened.

5.2 Unit B

5.2.1 Unit B - sediment description

Unit B is a sandy gravelly, matrix-supported and massive diamict (D(S/G)mm), more or less the same as Unit A but lacking the sorted sediment interbedding. Boulders are evenly distributed and sized up to 50 cm, except for some larger boulders (up to 80 cm) at the ground surface. Unit B forms an uppermost drape of the whole section, increasing in thickness from N to S (left to right), with a thickness of up to ~3 m (Fig. 5). The colour of the D(S/G)mm is light grey/brown. The granulometric matrix composition (<20 mm), as shown in one grain size analysis (analysis 8, Appendix I) confirms the field classification as diamict, i.e. unsorted sediment. The RA value is 44%, indicating a predominance of angular to subangular clast shape (Appendix II, sample 8). Only one fabric measurement (III) is from this unit (Fig. 6). It shows a very scattered fabric shape with a weak dispersed clast axis orientation ($S_1 = 0.474$) with V_1-axis orientation of 67°/17° (Fig. 6).

5.2.2 Sedimentological interpretations – Unit B

Unit B is almost solely massive diamict with very few diagnostic criteria usable for a genetic interpretation. However, as it is a continuation from the Unit A succession it is genetically interpreted to have been formed in the same way as the diamicts of that unit, i.e. by infill of a supraglacial or ice-marginal trough from adjacent debris-loaded stagnant ice. This infill stage should then be the final stage of trough infill on top of the sediments already deposited (unit A) in that depression (Paul 1983; Krüger and Kjær 2000; Kjær and Krüger 2001) due to sediment gravity flow processes (Lawson 1979; Paul 1983; Benn and Evans 1996). The non-modal clast fabric orientation with the extremely low S_1 value (0.474) (FM III, Fig. 6), and RA values (sample 8, Appendix II) that show little abrasion, indicate that the final sediment gravity-flow units were thick and with low water content (Lawson 1979; Benn 1994; Benn and Ballantyne 1994).

As Unit B occurs in the upper part of the section and without interfingering/interbedded sorted sediment beds, this suggests that, at the time of deposition, most of the fluvial activity had moved to other areas within the down-wasting ice.

The larger boulders on the surface of the hummocks (Fig. 3B) suggest that they are the result of late stage infilling. They were probably kept in suspension in the ice as it moved in its active phase before stagnation (Fig. 9). At the later gradual melt-out of englacial debris they would be supposed to be situated on top of a melt-out sequence. However as they probably were too large to be carried by debris flows during the redistribution process, as suggested above, the boulders on top of the hummocks possibly rolled down the slope in a late stage. The boulders found in present-day depressions and flat areas simply settled on the ground as the ice finally melted.

6 A model of sediment build-up for moraine hummock formation, discussion

The moraine hummock in focus of this study is thought to have been formed from sediments accumulating in a depression within stagnated (dead) ice (*e.g.* such as described by Lawson (1979) and Paul (1983)). A retreating ice sheet left dead ice behind that was loaded with sediments, both within it and gradually released at its upper surface during gradual melting. At differential melt-down and back-wasting of dead ice, sedi -ments released on top and in front of the ice were transported into depressions due to gravity flow processes, and were to varying extent reworked by melt-water. A process model for such a development is presented in Fig. 10 for a number of time steps.

The investigated section is suggested to show the sedimentary composition of the outer edge of such a sediment-infilled depression. The outermost (i.e. most ice-proximal) edges are mostly made up of debris-flow diamict beds, deposited straight from the stagnant ice surrounding and supporting. In distal direction from the supporting ice, i.e. towards the centre of the sediment- receiving depression, the investigated succession suggests that reworking of such sediment gravity flows by melt-water was an important process, resulting in disaggregation of these, and leaving both residual larger clasts and lag deposits, as well as depositing sorted sediments of various facies states depending on the energy level of the melt-water stream, inter-bedding with non-reworked debris flows (unit A). The disappearance upwards of interbedded sorted sediments (unit B) suggests that the melt-water, and the resulting reworking of debris-flow sediments, moved elsewhere, most probably due to the gradually elevated position of the sediment infill. The late-stage infill of the trough was thus totally dominated by sediment gravity flow processes.

During the sediment infilling process of the trough and build-up of the hummock-to-be, the ice around and below it was constantly melting, but at different rates depending on thickness of sediments insulating it, access and work of melt-water, etc. Thus most melting occurred where the ice was bare or had a thin debris cover (Lawson 1979). At down-wasting the depression infill sediments gradually lost ice support and were tilted away from the centre and in the direction of the lost support. In connection to this some sediment slumping occurred, as suggested from the few occurring folds and also from normal faulting of sediment, resulting in angular bed contacts. The tilting of the original bedding along the perimeter of the infilled trough also resulted in stretching, followed by the formation of more or less high-angle fractures into the sediments, simultaneously infilled by fine sediments, resulting in the Si/S veins.

Boulders that had been kept high in the ice during its active phase (Fig. 10) either rolled off the ice surface at a late stage of depression infill in the stagnant ice, and thus occur over high-relief areas after the sediment inversion process, or were simply draped over what was to-be low-lying areas, after the same inversion process as the ice finally melted away. When all stagnant ice had melted away the final result thus was an inverted landscape with moraine hummocks in the former infilling troughs, and vice versa (Fig. 10).

The aim of this thesis has been to determine the formational processes of the Törnåkra moraine hummock. The result is that it is formed primarily due to gravity-induced sediment redistribution within an area with stagnated ice in front of the actively receding ice margin during the last deglaciation of the area. This result may be applicable to the larger hummocky moraine area, suggesting that hummocky terrain represents a debris rich dead-ice environment where supraglacially melted-out debris was redeposited and reworked into terrain low points. This in turn suggests that the local deglaciation was rapid, leaving patches of dead ice behind. The patch of hummocky terrain that includes the Törnåkra moraine hummock

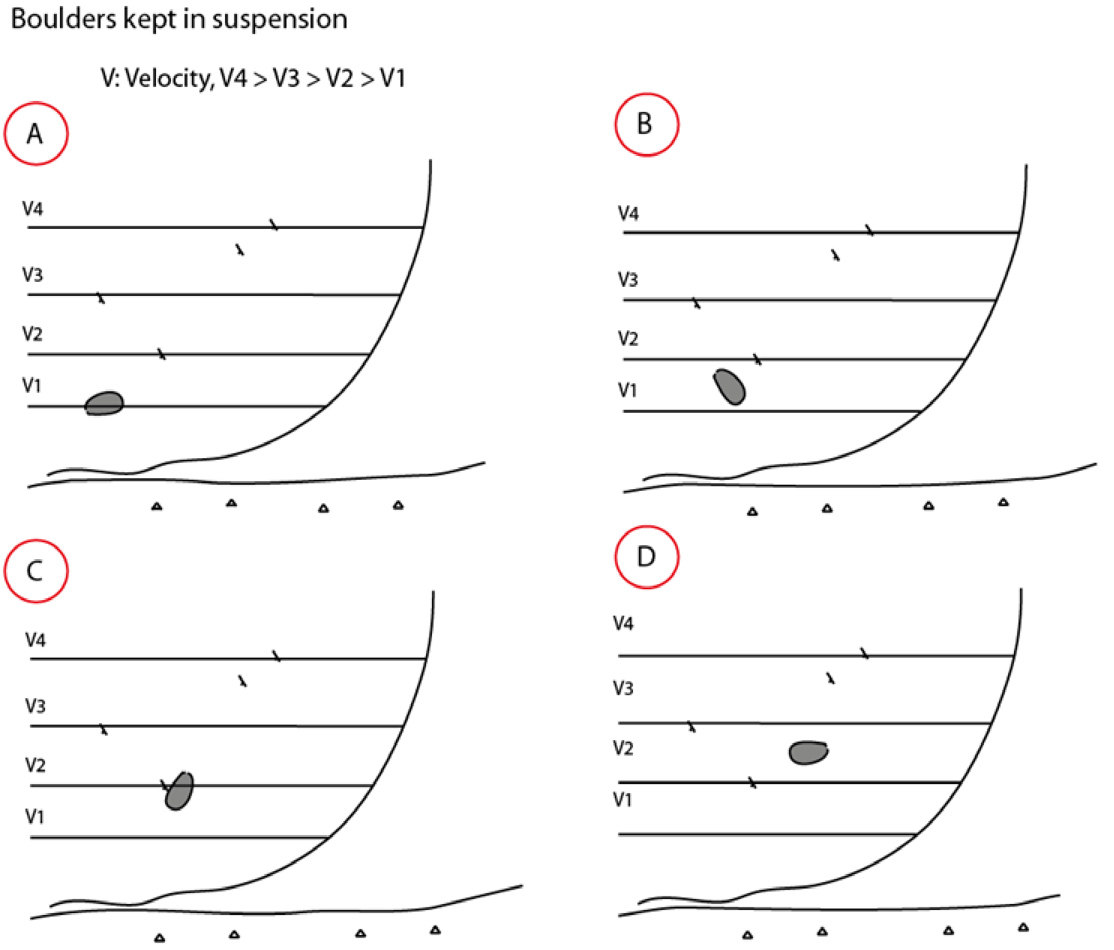


Fig. 9. Ice/glacier moves at different velocities through its column. Slowest at its base and then gradually faster until uniform velocity may be reached from a point in the column and up to the surface. This can affect the larger particles that occupy parts of the column that have different velocities. With a higher velocity affecting the upper part of the boulder, than its lower part, the boulder will start to screw upwards until the boulder reaches an altitude where the difference in velocity no longer manages to lift it further. Then the boulder is kept in suspension until either similar conditions are reproduced or it is transported to the top or front of the glacier, or melted out from beneath.

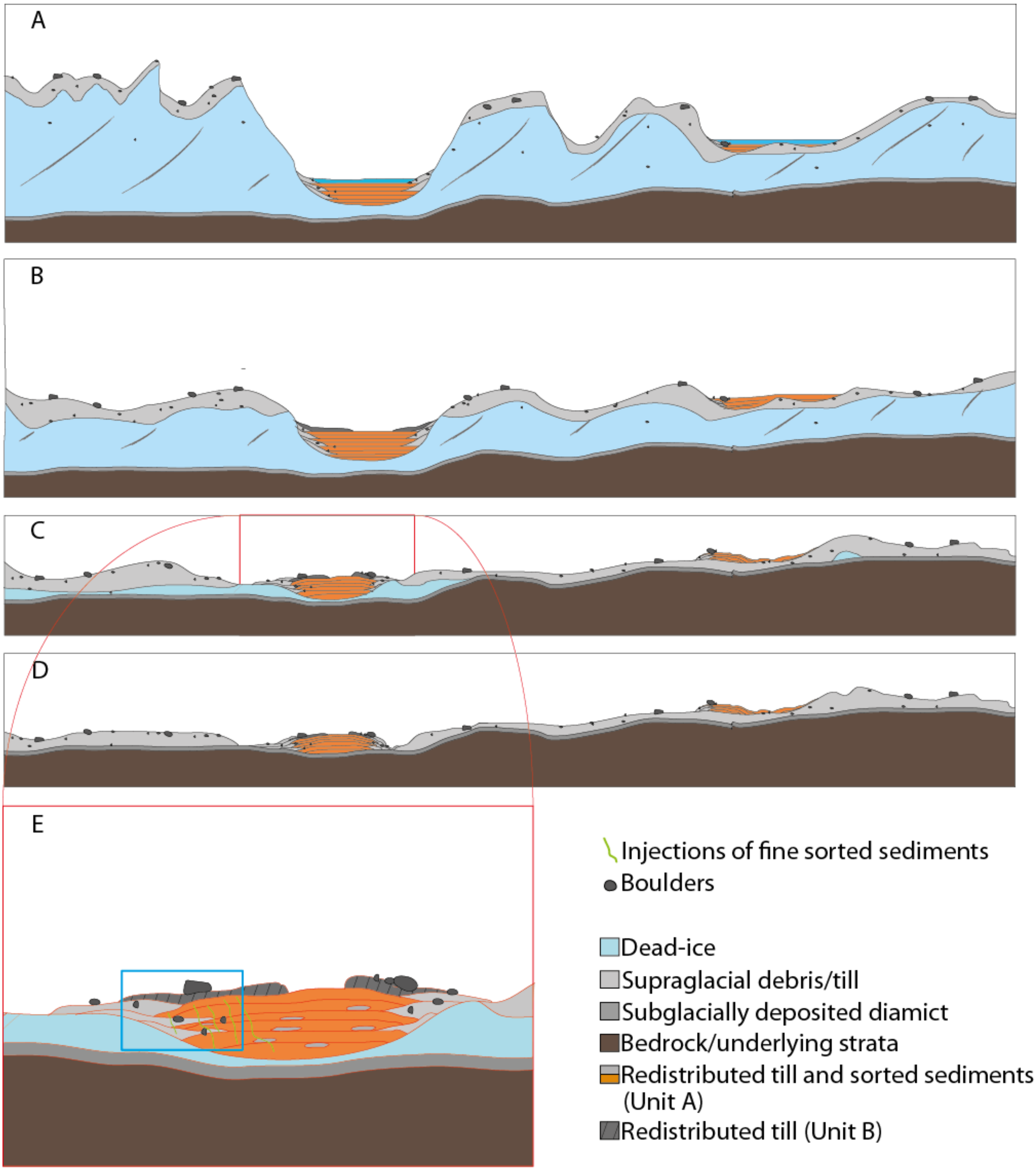


Fig. 10. A model explaining the formation of a hummock in a decaying glacial landscape. A) Moderately advanced dead-ice environment with sediments infilling troughs in the ice -shows formation of unit A . B) More advanced dead ice environment as the ice melts away –shows formation of unit B, with little or no water involved. C) Mature/late dead ice environment with ice free zones –Enlargement: As support wanes, fractures form in the strata and are subsequently infilled with fine sediments. D) Post dead ice environment, all ice is gone and the sediments have tilted or collapsed. E) Enlargement from stage C, -the blue box indicates the location of the formational environment for that part of the moraine hummock, seen in the investigated section. -Redrawn and adapted from Paul (1983).

is one of many that occupy elongated low lying areas (valleys) in N-S directions, within a generally streamlined terrain. This patch is situated only ~20 km north of the 20-40 km wide hummocky (and ribbed) moraine area, stretching in an east to west direction as shown in Fig. 1 (Möller 2010). This belt with incrementally formed stagnant ice was separated from active ice receding northwards at c. 14000 – 14300 cal yr BP (Möller 2010, as recalculated from Björck and Möller

1987) and it is suggested that it took some further hundreds of years until all ice was gone, probably in the early part of the Allerød interstadial (Möller, 1987; Björck and Möller, 1987). The many patches of hummocky moraine north of this zone, intercalated into the preferentially streamlined terrain, are probably connected both genetically and chronologically to the belt of hummocky moraine in the south. The final meltout of those pockets of stagnated ice, forming hummocky terrains would thus have more or less the same age, i.e. the final melting would have occurred in the early part of the Allerød.

7 Conclusions

- The Törnåkra moraine hummock was formed due to sediment infill in a depression in stagnating/stagnant ice.
- The sediments in the section are divided into two separate sedimentary units, based on the occurrence of sorted sediment being interbedded with diamicts, or not.
- The lowermost unit (A) was gradually built up as a stacked sequence of sediment gravity flow diamic beds, intercalated with erosional remnants of such beds due to fluvial activity and deposition of fluvial sediments.
- The uppermost unit (B) without interbedded sorted sediment was built up solely from sediment gravity flows at a late stage of depression infilling.
- The diamict sediments were originally melted out in a supraglacial position and transported into the depression due to gravitational process initiated by down- and back-wasting of the ice surrounding the infill depression.
- The diamict debris flows into the sediment-receiving depression were partially or totally reworked by melt water – especially in the early phase of sediment infill –and sorted sediments make up a substantial part of the sediments in the moraine hummock.
- The edges of the hummock are dominated by diamict beds, representing debris flows unaltered by melt water.
- All sediment beds are tilted into the direction of lost ice support.
- The high angle sediment veins crossing the primary bedding are syn- to post-depositionally filled fractures, formed as the sediment beds experienced stretching and warping due to waning lateral support.
- Cut-off sediment beds, with overlying beds at an angle, along with folding, suggest synsedimentary sliding and slumping of sediments as they settled with the melting of the ice.

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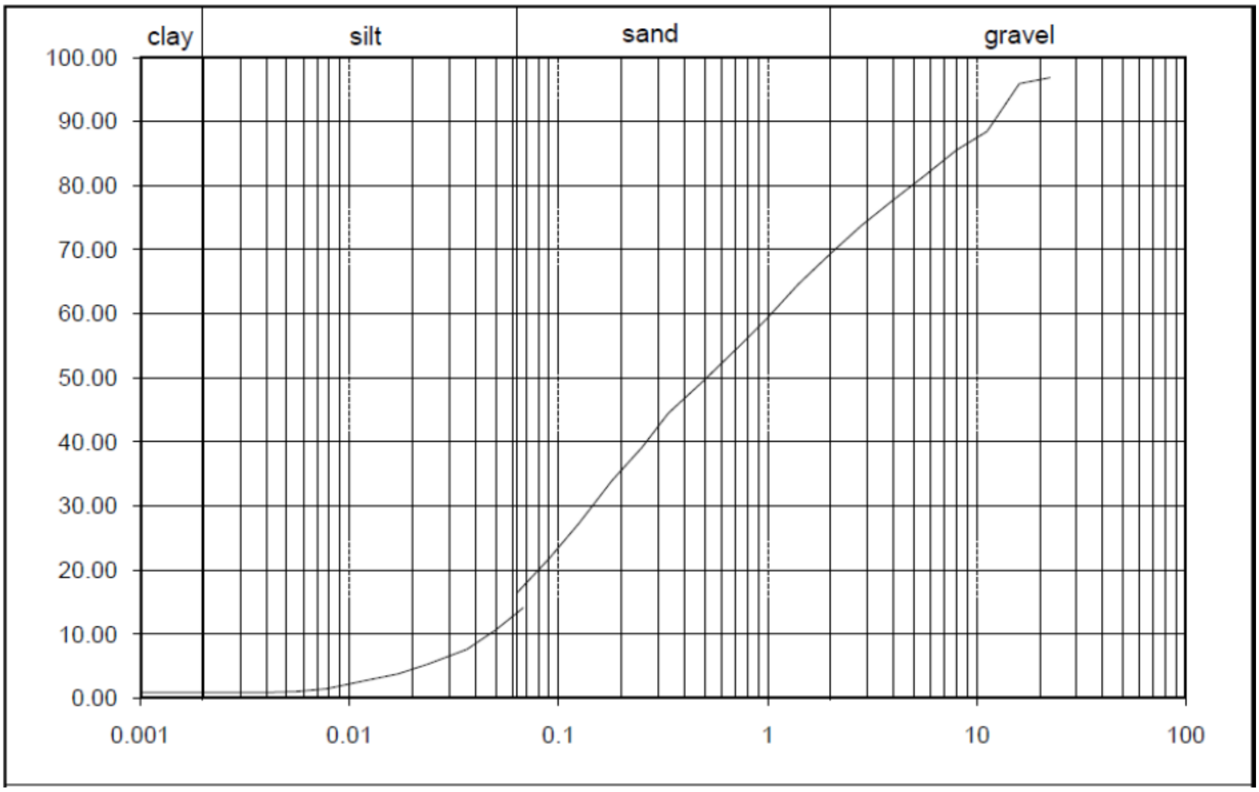
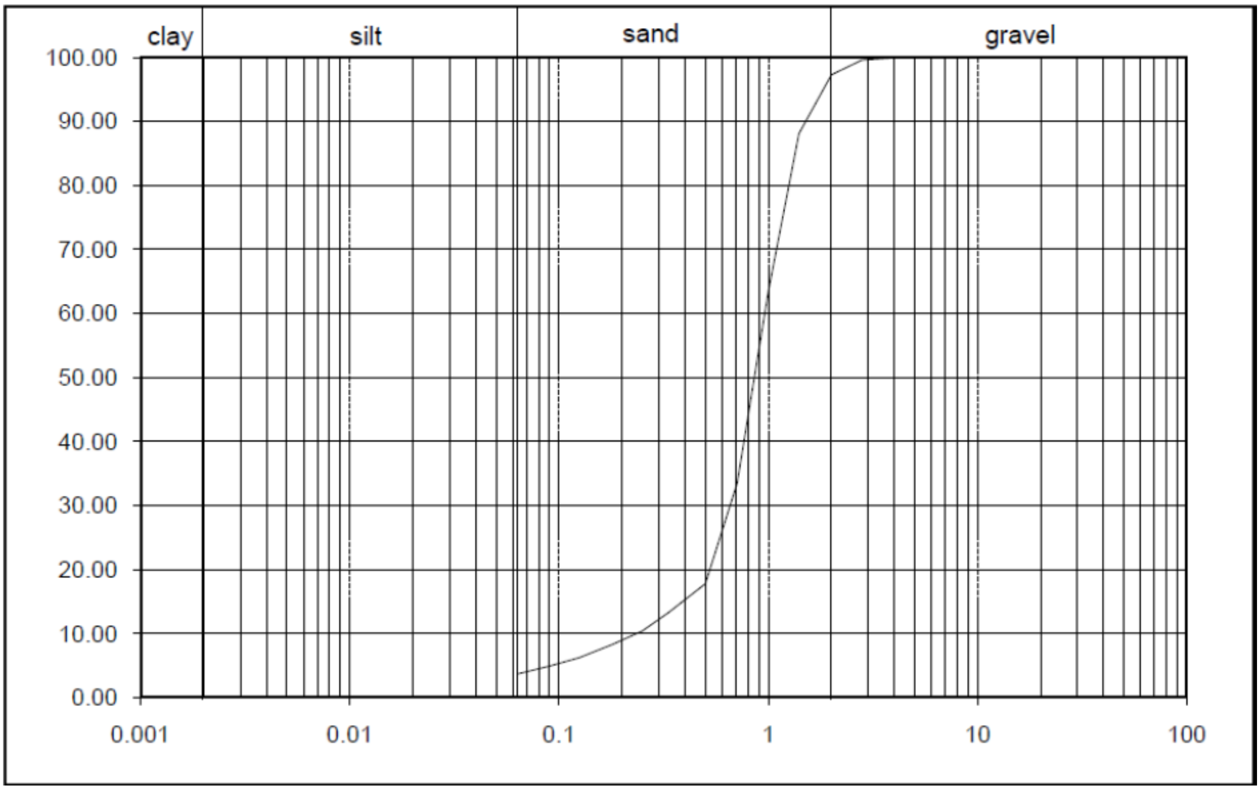
Appendices

Appendix I

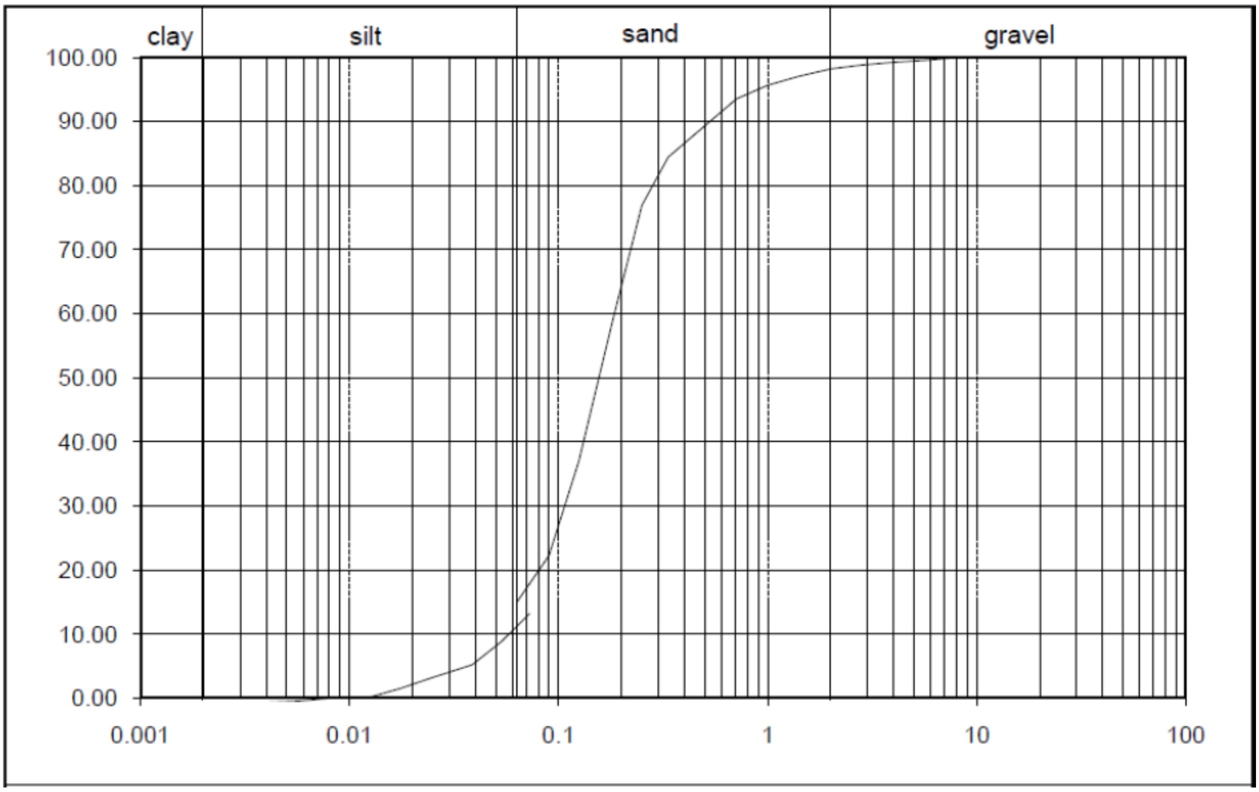
Diagrams from grain size analyses with percentage of total weight on y-axis and sizes in mm, exponentially increasing on x-axis. Calculated and drawn in Excel.



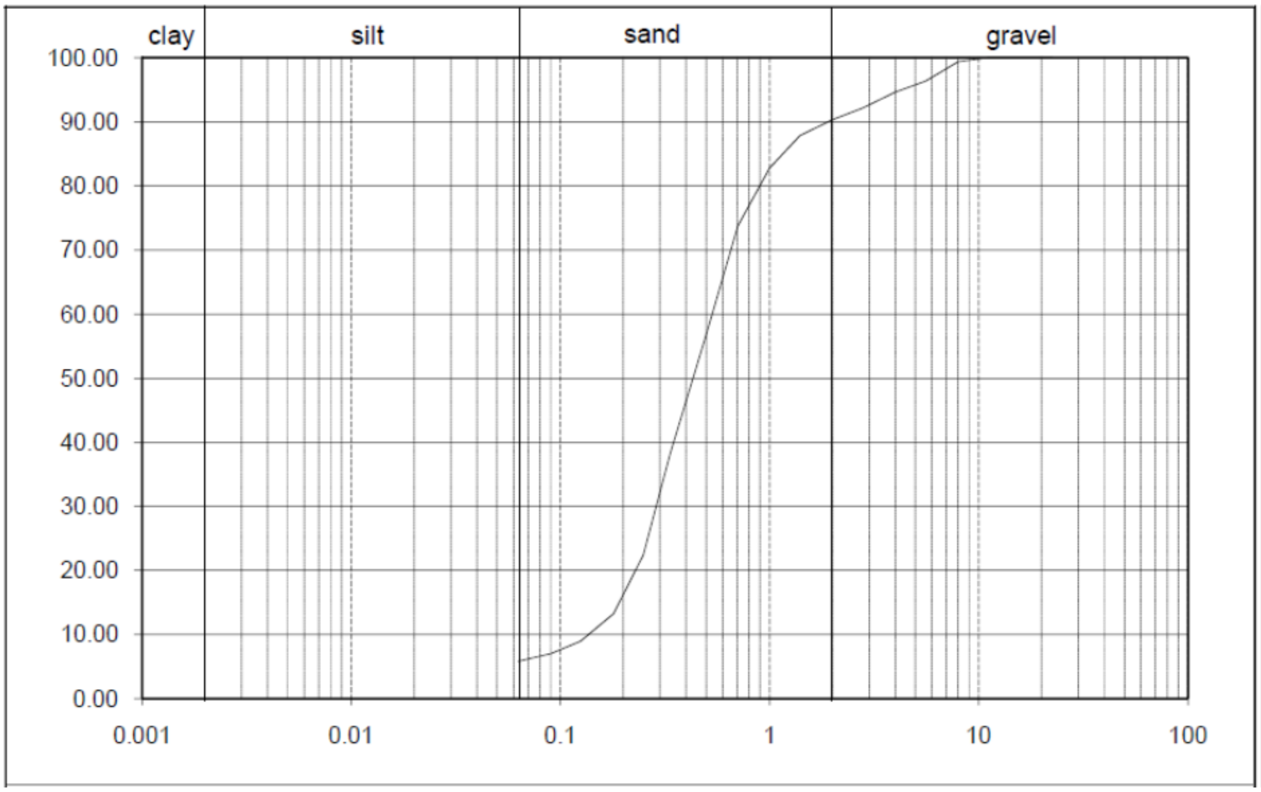
Grain size analysis # 1 -unsorted sediments from Unit A.



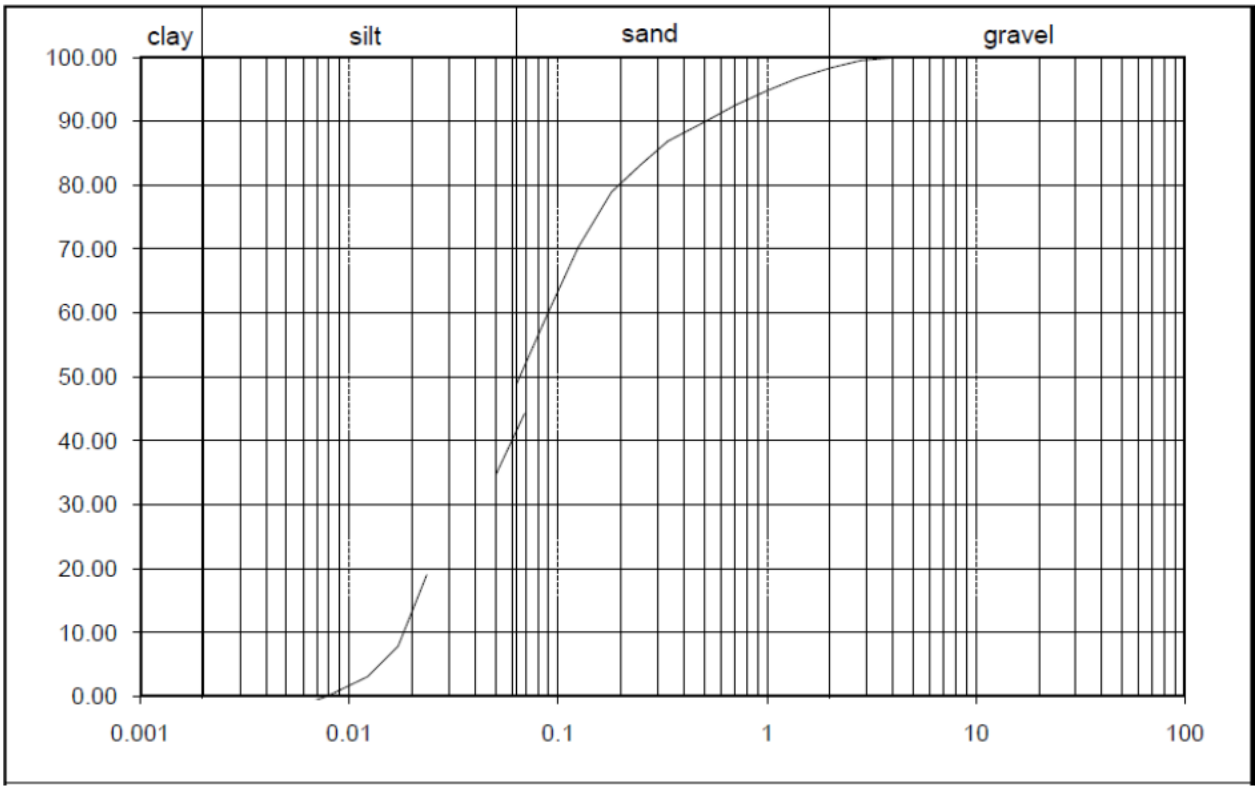
Grain size analysis # 2 –coarse sand from Unit A.



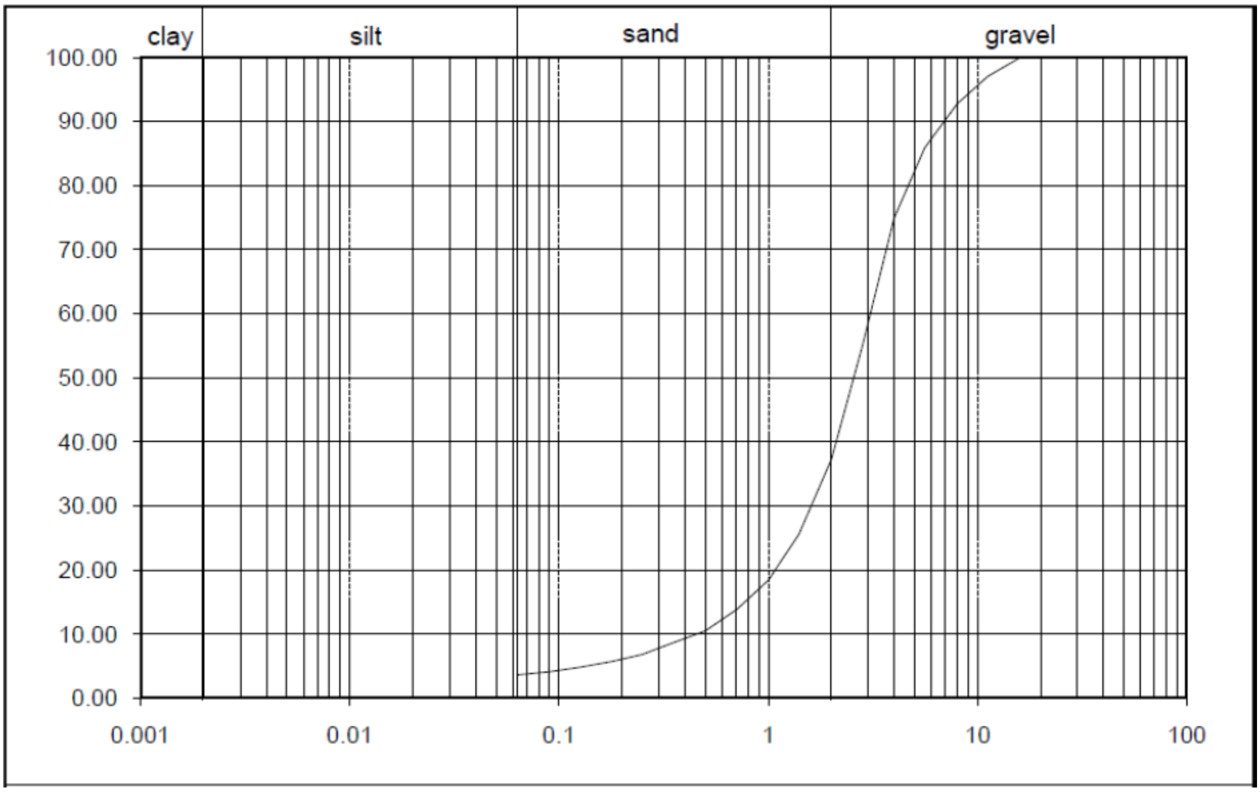
Grain size analysis # 3 –fine sand from Unit A.



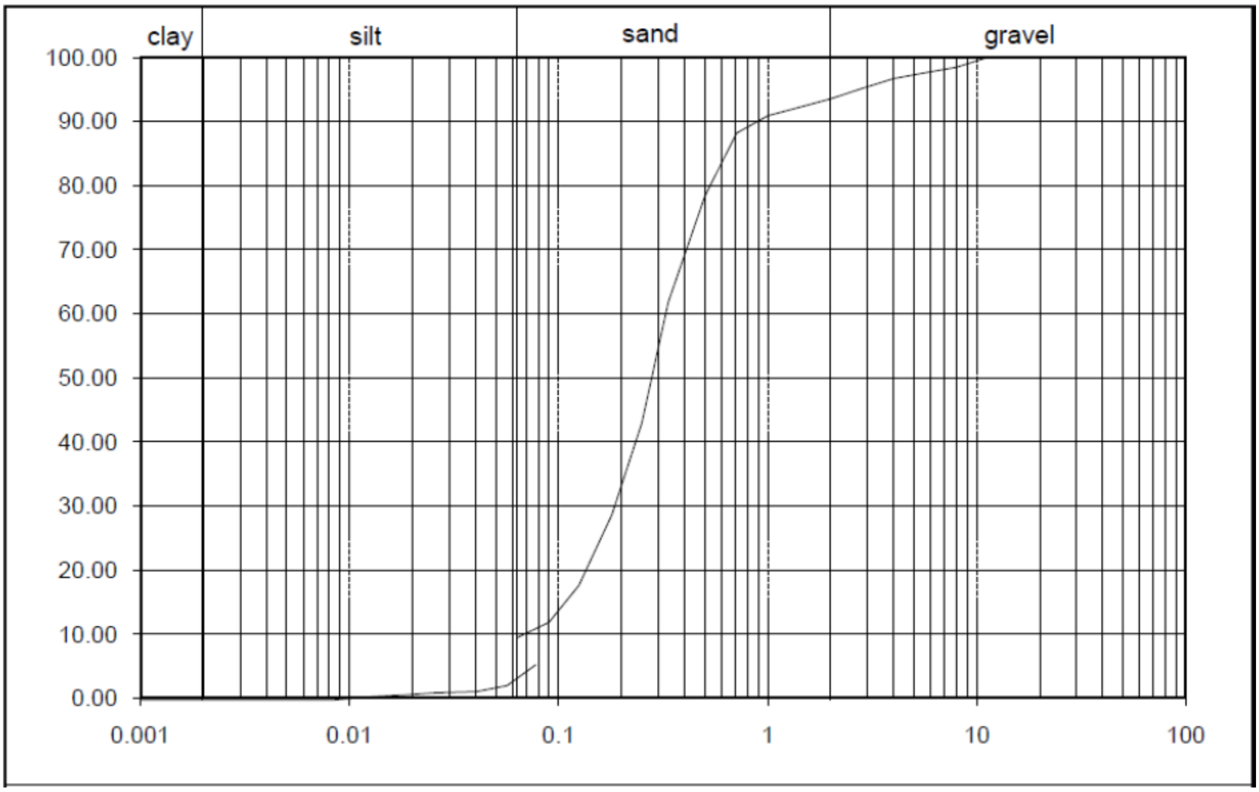
Grain size analysis # 4 –coarse sand from Unit A.



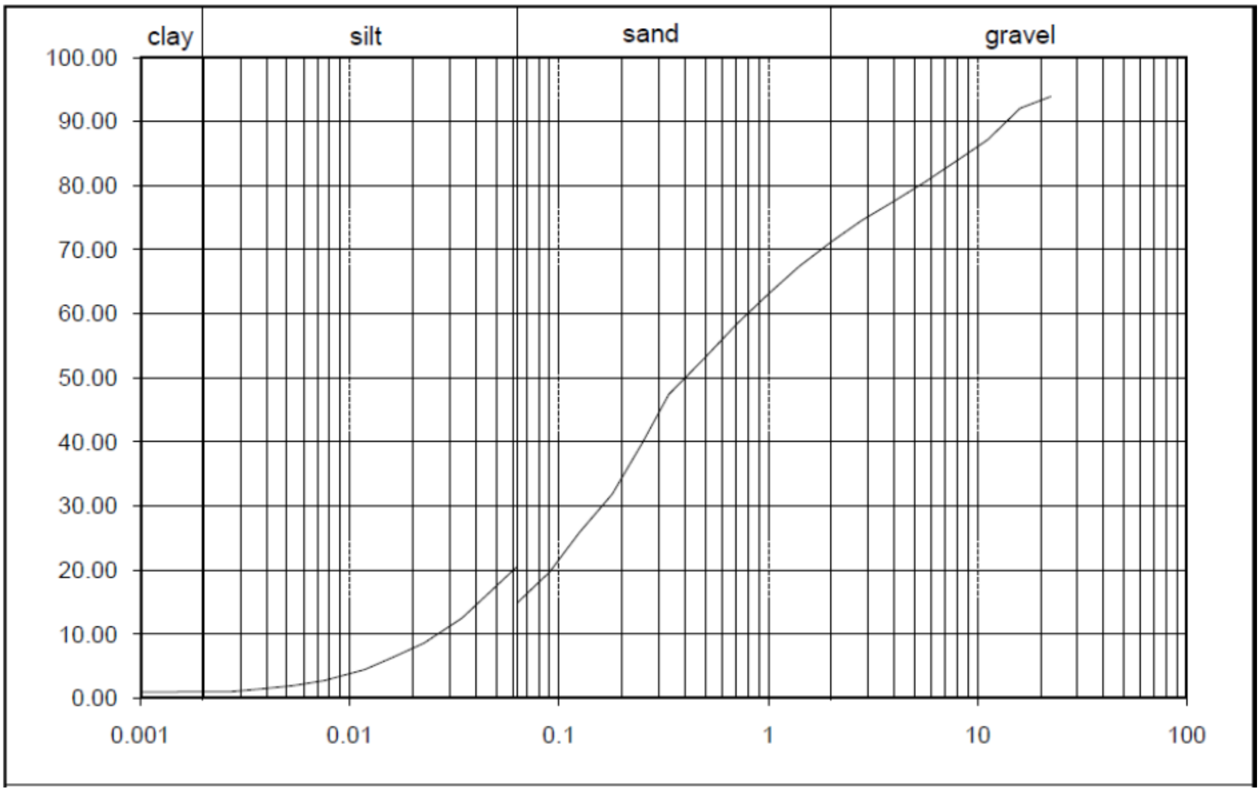
Grain size analysis # 5 –silty sand from Unit A.



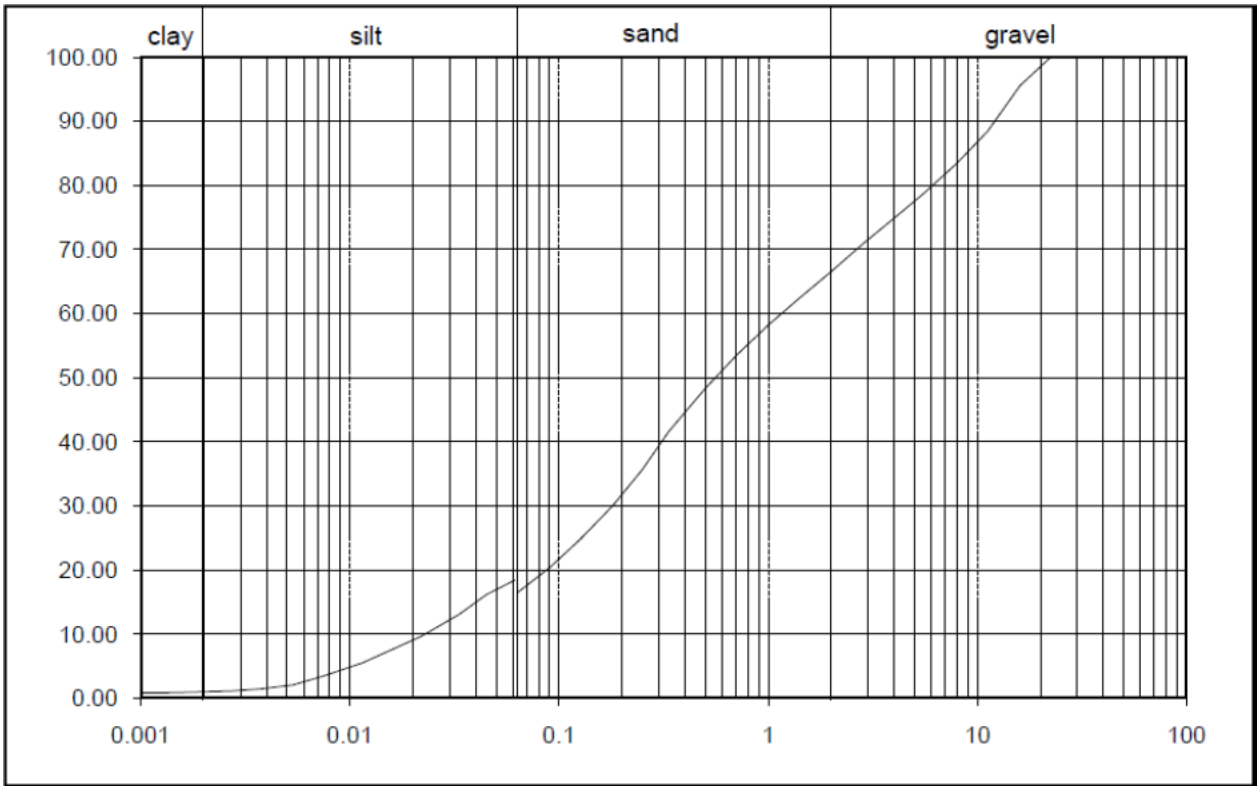
Grain size analysis # 6 –medium gravel from Unit A.



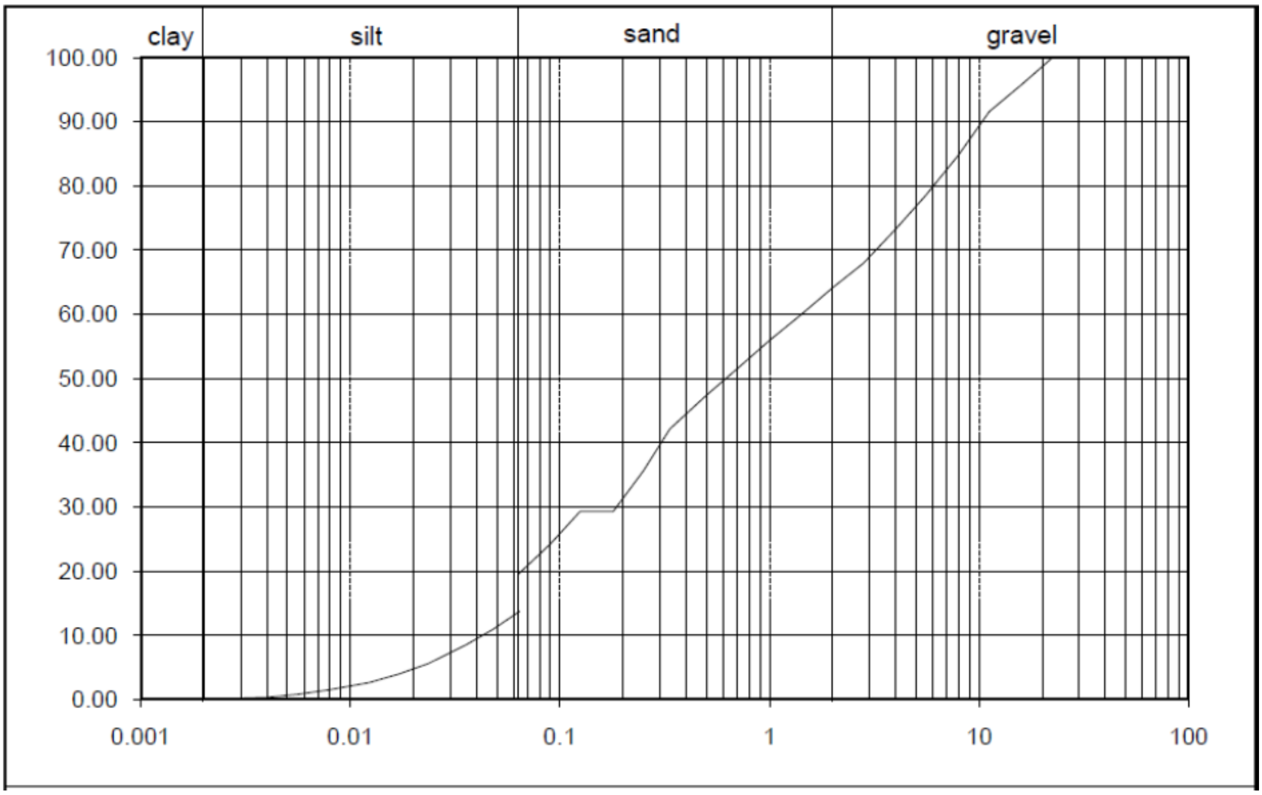
Grain size analysis # 7 –coarse sand from Unit A.



Grain size analysis # 8 -unsorted sediments from Unit B.



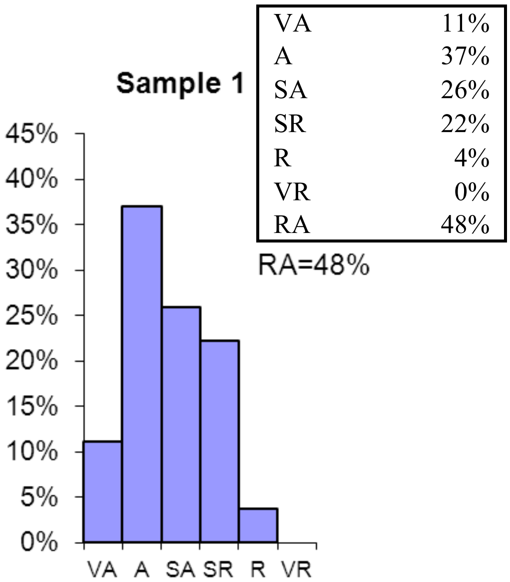
Grain size analysis # 9 -unsorted sediments from Unit A.



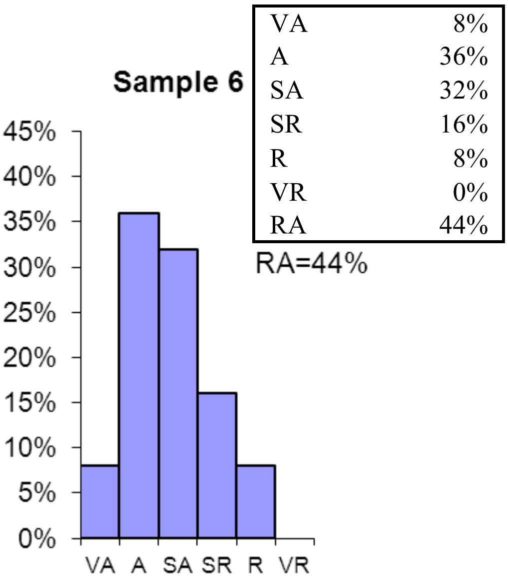
Grain size analysis # 10 -unsorted sediments from Unit A.

Appendix II

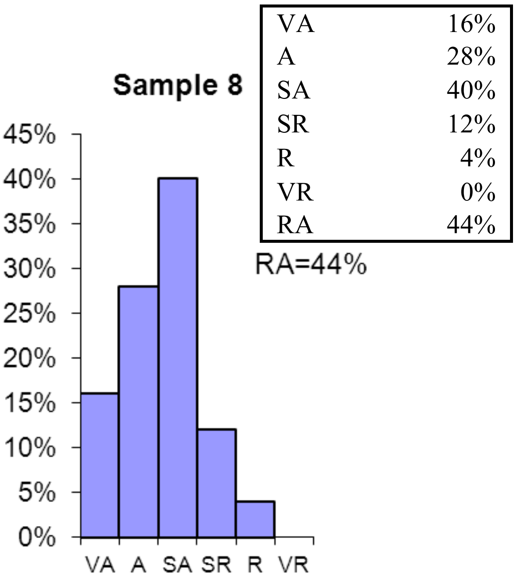
Column charts showing the percentage of particles from that were classified into each of the categories. VA: Very angular, A: Angular, SA: Sub -angular, SR: Sub-rounded, R: Rounded, VR: Very rounded. RA value is calculated by adding the VA and A values; VA + A = RA.



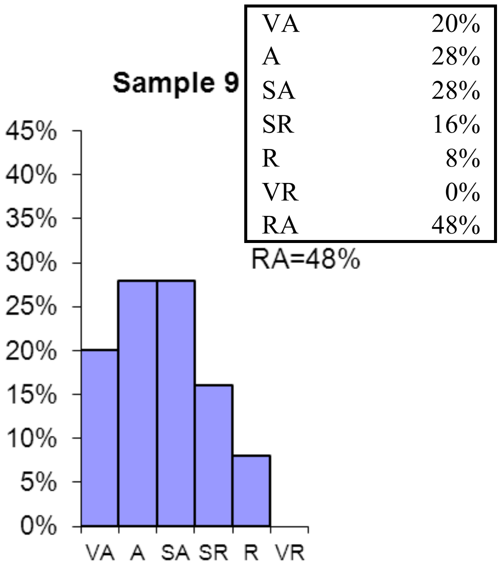
VA	11%
A	37%
SA	26%
SR	22%
R	4%
VR	0%
RA	48%



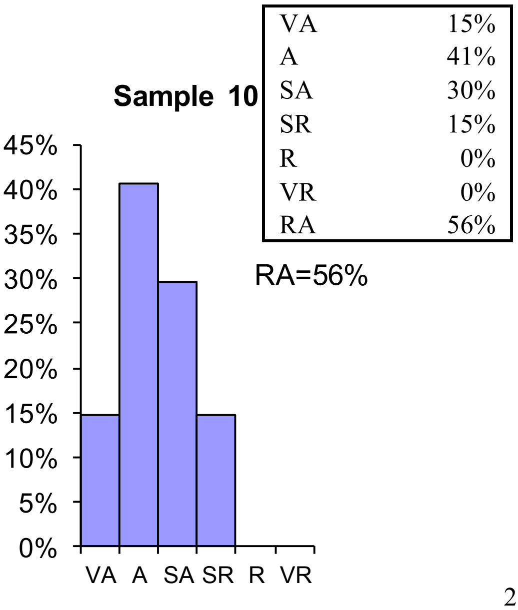
VA	8%
A	36%
SA	32%
SR	16%
R	8%
VR	0%
RA	44%



VA	16%
A	28%
SA	40%
SR	12%
R	4%
VR	0%
RA	44%



VA	20%
A	28%
SA	28%
SR	16%
R	8%
VR	0%
RA	48%



VA	15%
A	41%
SA	30%
SR	15%
R	0%
VR	0%
RA	56%

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