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Authors: Sven A Tirén
Stefan Wänstedt
Thomas Sträng

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The understanding of the formation of valleys and its implication on site characterization

Moredalen and Pukedalen, south-eastern Sweden

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This report concerns a study which has been conducted for the Swedish Radiation Safety Authority, SSM. The conclusions and viewpoints presented in the report are those of the author/authors and do not necessarily coincide with those of the SSM.

SSM Perspective

This report concerns a study which was initially conducted for the Swedish Nuclear Power Inspectorate (SKI), which is now merged into the Swedish Radiation Safety Authority (SSM). The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the SSM.

Background

In south-eastern Sweden, there are a number of over-deepened narrow valleys, more than 20 m deep, formed in Precambrian bedrock located above the highest post-glacial shoreline. Canyon-like valleys, called "kursu" or kursu-valleys, are generally interpreted to be formed by glaciofluvial erosion.

An example of such a valley is Moredalen, which is a marked, approximately 7 km long, E-W striking valley that cuts through a plateau (c.140 m a.s.l.), an elevated block of the sub-Cambrian peneplain. There are also more open over-deepened valleys along which sub-glacial flow has occurred, e.g. Pukedalen which is a northwest-southeast trending valley incised in massive granite. Geomorphological features of this kind indicate certain characteristics of the bedrock that need to be considered in a performance assessment for a future nuclear waste repository.

Purpose

The purpose of the current project is to discuss and describe a combined geological and geophysical investigation of Moredalen, with the aim to investigate possible reasons for the formation of such an unusual feature formed in the Precambrian bedrocks. The outcome of the investigation will be discussed and compared to the similar more open valley, Pukedalen.

Results

Palaeozoic to Mesozoic differential block faulting on both sides of the Moredalen valley and indication of neotectonic movements along the valley is observed. Pukedalen on the other hand, having the same basal erosion level as Moredalen, indicates that the glacial erosion of intact sound rock may be very limited. The shape of the valleys presumably predates the last glaciation and they are formed by deep weathering and fluviatile erosion, mainly of lose material, e.g. weathering products and lose fragments in fracture zones. The study of Moredalen and Pukedalen emphasises that a general knowledge about the formation of the present landforms will improve structural mapping performed by remote sensing. Furthermore, similar valleys may exist below the highest post-glacial shoreline, but then they may be filled with glacial sediments.

Effects on SSM supervisory and regulatory task

The formation of geomorphological features of this kind is important to understand because the distinct weakness zones along which the kursu-valleys are formed may create prominent transport paths for groundwater flows and affect the rock mechanical properties of the bedrock in repositories for nuclear waste.

Project information

SKI reference: 14.9-001331/00212 and 14.9-011176/01254
Responsible at SKI has been Fritz Kautsky and at SSM Lena Sonnerfelt

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Abstrakt

I sydöstra Sverige finns ett antal fördjupade (nederoderade) trånga dalgångar, mer än 20 m djupa, bildade i prekambrisk berggrund ovanför högsta kustlinjen. Canyon-liknande dalar, kallade "kursu" eller kursu-dalar, brukar tolkas som bildade genom glaciofluvial erosion. Ett exempel på en sådan dal är Moredalen. Det finns också mer öppna nederoderade dalar längs vilka subglaciala flöden har skett, t.ex. Pukedalen.

I huvuddelen av den här rapporten diskuteras en kombinerad geologisk och geofysisk undersökning av Moredalen, i syfte att undersöka möjliga orsaker till bildandet av en så ovanlig företeelse, bildad i sura vulkaniter och folierade tonalitiska till granodioritiska bergarter. Moredalen är en markerad, cirka 7 km lång, EW strykande dalgång som skär igenom en platå (ca 140 m ö h) utgörande ett upplyft block av det sub-kambriska peneplanet. Glaciofluviala sediment förekommer uppströms där kanjonen vidgas mot väster. Strax öster om dalen är ett större delta utbildat i nivå med högsta kustlinjen (ca 105 m ö h). Ytterligare öster om, i samma riktning som Moredalen finns en rullstensås. Lossryckta sönderfallna klippstycken i dalen är kantigt.

Pukedalen är en nordväst-sydostlig utbredd dal nedskuren i massiv granit. Dalen är i dess norra delar relativt öppen och blir smalare i dess sydöstra del som har en delvis vertikal sydvästlig vägg. Bergytorna är släta längs dalen och lossryckt berg i dalen består i allmänhet av rundade block. I samma riktning som Pukedalen, på dess båda sidor dock på stora avstånd, förekommer rullstensåsar.

Geomorfologiska drag av detta slag tyder på vissa egenskaper i berggrunden som måste beaktas vid säkerhetsanalys av slutförvar för kärnavfall. De distinkta svaghetszoner längs vilka kursu-dalarna bildas skapar markanta transportvägar för grundvattenflöden. Dessutom kan zonerna utgöra potentiella risker utifrån såväl grundvattentransport som bergmekanisk synpunkt. Detta förstärks genom förekomst av Palaeozoiska till Mesozoiska förkastningar på båda sidor av Moredalen och neotektoniska rörelser längs dalen. Pukedalen, å andra sidan, som har samma basala erosionsnivå som Moredalen, visar att glacial erosion av intakt berg kan vara mycket begränsad. Dalarnas utformning är förmodligen äldre än den senaste istiden och är bildade genom djup vittring och fluvial erosion (huvudsakligen av löst material, t.ex. vittringsprodukter och lösa fragment i sprickzoner).

Studien av Moredalen och Pukedalen ger eftertryck åt att en allmän kunskap om bildandet av nuvarande landformer kommer att förbättra strukturgeologisk kartläggning genom fjärranalys.

Nyckelord: *Deponering av radioaktivt avfall, bergblock, blockförkastning, geomorfologi, vittring, erosion, sub-glacialt flöde, neotektonik, GPR, resistivitetsmätning.*

Abstract

In south-eastern Sweden, there are a number of over-deepened narrow valleys, more than 20 m deep, formed in Precambrian bedrock located above the highest post-glacial shoreline. Canyon-like valleys, called ”kursu” or kursu-valleys, are generally interpreted to be formed by glaciofluvial erosion. An example of such a valley is Moredalen, a canyon in the Fennoscandian Shield, which has an implication on site selection for radioactive waste disposal. There are also more open over-deepened valleys along which sub-glacial flow has occurred, e.g. Pukedalen.

The main part of this paper discusses a combined geological and geophysical investigation of Moredalen, with the aim to investigate possible reasons for the formation of such an unusual feature formed in acid vulcanites and foliated tonalitic to granodioritic rocks. Moredalen is a marked, approximately 7 km long, E-W striking valley that cuts through a plateau (c. 140 m a.s.l.), and an elevated block of the sub-Cambrian peneplain. Glaciofluvial sediments can be found up-streams where the canyon widens to the west. Just east of the valley is a larger delta deposited at the highest post-glacial shoreline (c. 105 m a.s.l). Further east of, and in line with the Moredalen valley there is an esker. Rock debris in the valley is angular.

Pukedalen is a northwest-southeast trending valley incised in massive granite. The valley is in its northern parts relatively open and becomes narrow in its south-eastern part having partly a vertical south-western wall. Rock surfaces are smooth along the valley and rock debris in the valley consists generally of rounded blocks. In line with Pukedalen, on both sides at great distances though, there are eskers.

Geomorphological features of this kind indicate certain characteristics of the bedrock that need to be considered during safety analysis of repositories for nuclear waste. The distinct weakness zones along which the kursu-valleys are formed create prominent transport paths for groundwater flows. Furthermore, the zones may be potential hazards from ground water transport and rock mechanical points of view. This is emphasized by Palaeozoic to Mesozoic differential block faulting on both sides of the Moredalen valley and neotectonic movements along the valley. Pukedalen on the other hand, having the same basal erosion level as Moredalen, indicates that the glacial erosion of intact sound rock may be very limited. The shape of the valleys presumably predates the last glaciation and they are formed by deep weathering and fluviatile erosion (mainly of lose material, e.g. weathering pro-ducts and lose fragments in fracture zones).

The study of Moredalen and Pukedalen emphasises that a general knowledge about the formation of the present landforms will improve structural mapping performed by remote sensing.

Keywords: Disposal of radioactive waste, rock blocks, block faulting, geomorphology, weathering, erosion, sub-glacial flow, neotectonics, GPR, resistivity measurements.

1. Introduction

Sweden has now started the final reconnaissance studies for the location of storage for spent nuclear fuel at a depth of c. 500 m in crystalline bedrock. Selecting a site involves studying and drawing conclusions from vast amounts of data (SKB, 1999). For the geological and structural interpretation of the subsurface conditions, it is essential that the upper surface of the bedrock must be characterized well. Information gathered on a local scale should be integrated in the regional context (and vice versa). Exposed rock generally represents the more solid proportion of the rock mass, which better resists erosion while lows covered with soil may constitute more erosive rock.

One matter, a complex one, which has been considered, is the advantages of a coastal versus an inland location of a repository with regards to the regional flow of groundwater. Assuming a constant slope, inland areas generally recharge while the coasts are usually discharge areas. The coastal lowland, the target area for site selection by the Swedish Nuclear Fuel and Waste Management Co (SKB), is generally a smoother landform compared to land located above the highest post-glacial shoreline. This is partly as a result of difference in erosion and deposition of Quaternary sediments in the bedrock depressions. In spite of these differences in topographic relief, the structural framework in the bedrock is comparable.

This report discusses the existence and formation of over-deepened valleys, some characterized as "kursu" valleys found above the highest post-glacial shoreline and the apparent absence of such valleys in the lowland of south-eastern Sweden.

A study of one of the largest kursu valley in southern Sweden, Moredalen (Fig. 1 and 2), began in 1997. The objectives of the study were to consider:

- Is the E-W trending valley Moredalen (Fig. 2) related to any major basement structures?
- To unravel whether this valley, 7 km long with a 20 to 30 m wide flat bottom and up to 40 m deep, was formed at the rim of the retreating ice during the last glaciation, c. 12 400 years ago?
- If the formation of the Moredalen valley was the result of a single event, e.g. a jökulhlaup (Olvmo, 1989)?

Another valley, Pukedalen (Fig.s 1 and 3), located 15 km south-southeast of Moredalen and not classified as a kursu valley, was visited in April 2001. The objective of this visit was to compare the characteristics of the two valleys:

- Pukedalen is oriented in NW-SE, c. 5.5 km long with a 50 to 75 m wide flat bottom and up to 40 m deep. The valley is relatively open, narrower in its south-eastern part.
- Pukedalen is located just above the highest post-glacial shoreline and has about the same basal erosion level as Moredalen.
- Pukedalen acted as a sub-glacial melt water channel during the last glaciation. Eskers line up, at distance though, north-west and south-east of Pukedalen.

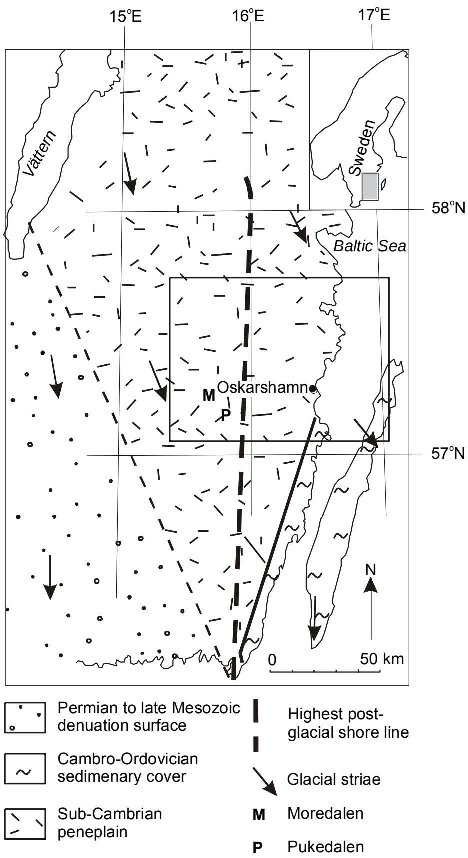

Figure 1. Map showing the location of the valleys Moredalen (M) and Pukedalen (P), south-eastern Sweden, and information about the denudation surfaces, distribution of Cambro-Ordovician sedimentary rocks, highest post-glacial shoreline and direction of ice striations. The location of regional terrain models (Figures 4 and 5) is given by the rectangle.

To understand the structural setting of the Moredalen valley, digital terrain models based on the LMV elevation database (The Land Survey of Sweden, LMV; 50 by 50 m grid), aerial photos (scale 1:30 000), airborne magnetic measurements and geological maps were used. Field studies comprised structural mapping and geophysical measurements. Resistivity surveys and ground penetrating radar measurements (GPR) were used to map the morphology of the bedrock surface and characterize the sediment cover in the valley and an alluvial deposit interpreted as an outwash delta just east of the valley.

The study of Pukedalen was based on the same digital terrain models (elevation presented as a grey-tone map and relief map) and airborne magnetic map as for Moredalen. The field study was restricted to mapping.

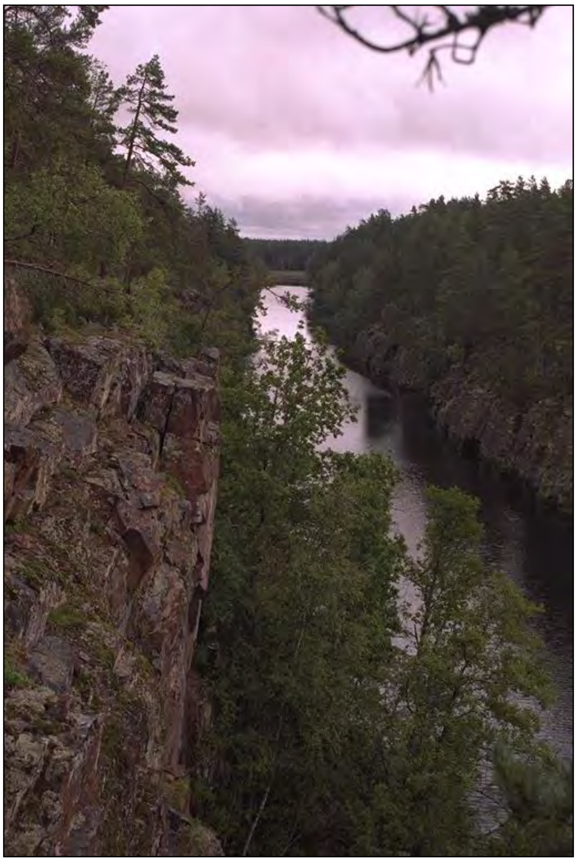

Figure 2. The eastern part of the Moredalen valley, looking eastward.

Figure 3. Southern part of the Pukedalen valley, looking south-eastward.

2. Previous work concerning over-deepened valleys

Olvmo (1989) has described the character and distribution of canyon-like valleys and related the formation of such valleys to glaciation. Talbot (1999) considered the formation of such valleys with respect to the long time safety of a repository for high level nuclear waste located at a depth of 500 m in crystalline bedrock. Talbot concluded that the effect of a retreating ice front is one of the greatest threats to a repository, especially the effect of the hydraulic gradient. He also stated for the off-shore located incisions that the regional drainage pattern better integrates with late glacial drainage pattern than with bedrock structures and lithologies. Olvmo, on the other hand, is a geomorphologist who noted the degree of fracturing within the canyons located above the highest glacial shore-line, as Rudberg (1949) before him, and considered them to be formed by glaciofluvial processes and classified them as kursu-valleys (Rudberg, 1949).

2.1. Kursu- and Fissure-valleys

Larger valleys are conventionally classified according to their shapes: U-shaped valleys formed by glacier erosion and fluvial V-shaped valleys. Two minor types of valleys do not fit this pattern: Kursu-valleys and fissure-valleys (Rudberg, 1949 and 1973).

2.1.1. Definition of Kursu-valleys

Rudberg introduced the descriptive term kursu-valley in 1949 to denote morphological features appearing as valleys distinctly cutting into the surrounding terrain, incised into bedrock along most of their traces, having a canyon-like appearance and flat bottoms. Sizes of the canyons vary considerably from just a few metres deep and some hundreds of metres long to 30-40 m deep, several tens of metres wide and up to seven kilometres long.

The word “kursu” has a Lappish origin and has been taken over by the Finnish-speaking people in northern Sweden and Finland, where this type of valley was first described at the beginning of the twentieth century. Many of the kursu-valleys are dry or have an insignificant flow of water in relation to the landform. Rudberg pointed out that the origin of kursu-valleys may differ, but he concluded that most are related to glaciofluvial erosion. The glaciofluvial origin has been favoured since (cf. Olvmo, 1989). Bergsten (1942) and Persson (1969) argued that kursu valleys might well be polycyclic formations. An argument for this (Persson, 1969) is that glaciofluvial sediments are often missing downstream of the valleys.

2.1.2. Character of Kursu-valleys

The formation of kursu-valleys according to Olvmo (1989) can be due to erosion by different type of streams:

- Sub-glacial streams; streams flowing in crevasses.
- Overflow of ice-dammed lakes.
- Proglacial fluvial system.

A peculiarity with kursu-valleys is that they only occur above the highest post-glacial shoreline (Rudberg, 1949, Olvmo 1989), i.e. they contain no marine sediments. Olvmo (1989) identified and mapped 30 kursu-valleys in the high-land of south-eastern Sweden. 75% of these valleys are large enough to be expressed on topographical relief maps (50 by 50 m grid) and c. 20 % is indicated as faults on bedrock maps (scale 1:250 000). Olvmo pointed out that the number of identified kursu-valleys is a minimum and the identified kursu-valleys represent just a small proportion of all valleys (cf. Fig. 4 and 5). All kursu-valleys in southern Sweden are located in Precambrian rocks. Sixteen of the Kursu-valleys are formed in granites, 9 in acid porphyries, 5 in foliated to gneissic granitoids, 2 along N-S trending dolerite dykes and one in meta-sedimentary rocks.

The direction of ice flow was southward in southern Sweden (cf. Fig. 1), in broad terms symmetrical and fan shaped (N-S in the highland and deflecting towards the east and west coasts, respectively). All kursu-valleys are located on the central and eastern side of southern Sweden and most drain between E to SSW, with south-east drainage being the most common.

Based on regional remote studies of northern Sweden, Nisca (1995) proposed neotectonic influences for the formation of kursu-valleys.

Occurrence of analogue incisions in the lowland, i.e. below the highest post-glacial shoreline, has generally not been described except for a submarine canyon crossing the Swedish East Coast (Tirén et al., 1996). However,bedrock fracture patterns in the lowland appear no different from those in bedrock above the highest post-glacial shoreline.

2.1.3. Character of Fissure-valleys

Fissure-valleys differ from kursu-valleys in two major respects according to Rudberg (1973). They are related to pre-existing brittle bedrock structures, e.g. fracture zones, and their shapes are affected by ice erosion. The ice erosion can, e.g. be expressed by striation along the walls of the valleys or, when the valley is oblique to the ice movement, plucking on the lee-side and polishing on the stoss-side.

3. Setting of Moredalen and Pukedalen

3.1. Geomorphology and sedimentary cover

Central southern and south-eastern Sweden is characterized topographically by plane surfaces; a central flat surface (above 200 m a.s.l.) and a very gently eastward tilted surface, c. 0.2°, along the east coast. The main part of the surface corresponds to a late Precambrian denudation surface, the sub-Cambrian peneplain (Rudberg, 1954). It had an extremely low relief (±20-30 m) and a regional extent, being traceable along the East Coast of Sweden for c. 1 300 km (Rudberg, 1954, Elvhage and Lidmar-Bergström, 1987). Parts of it are well preserved up to an altitude of 300 m in the inland in southern Sweden (Lidmar-Bergström, 1999). The peneplain was then distorted by restricted faulting during the Cambrian transgression and deposition of Palaeozoic and younger sediments. The thickness of the sediment pile was up to some kilometres thick (Tullborg et al., 1996).

Differential uplift along a N-S trending axis in the Jurassic caused denudation of sediments and basement rocks along the crest of the culmination (the South Swedish Dome) and a gentle tilting of the eastern flank eastwards (Lidmar-Bergström et al., 1997). Another transgression followed and Cretaceous sediments were deposited. A second pulse of uplift exposed the bedrock again in the Tertiary, by which time axis of the culmination had moved eastward.

Erosion during repeated Quaternary glaciations was the last main event of denudation. At present there are just a few remnants of Palaeozoic sedimentary rocks and a bedrock surface that approximates the sub-Cambrian peneplain to the east and the younger denudation facet in the central part. To the east, erosion of the sub-Cambrian peneplain is more or less restricted to erosion along fracture zones, which enhances the structural framework of the bedrock. To the west, erosion has affected much more of the peneplain resulting in wide troughs and open channel-like passages enclosing plateaux representing residual parts of the peneplain (Fig. 1, 4 and 5). The lows are locally excavated to a depth of c. 100 m below the peneplain. The present ground surface in the lows is flat. The lows contain a sequence of sediments starting with a few metres of basal till followed by glacial and post-glacial sediments (below the highest post-glacial line also including varved clay beneath thin-bedded silt and clay) with a thickness of up to c. 20 m (Johansson et al., 2000).

Note that the configuration of the open topographic structures resemble a drainage system draining generally SSE, via N-S and NW-SE trending lows; this is oblique to the present topographical gradient which is toward the ESE. Obviously, the morphology controlled the sub-glacial water transport above the highest post-glacial shoreline, 105 m a.s.l; the open valleys are the locations of glaciofluvial deposits (Fig. 5). At lower altitudes, or where there are no open valleys, the glaciofluvial deposits appear mainly as NNW-SSE to NW-SE trending eskers parallel to the late ice striation (Fig. 1). The inland ice retreated at c. 125 to 300 m per year (Kristiansson, 1986). Glacial erosion can have a small effect on the older landform (Lidmar-Bergström et al., 1997, Lidmar-Bergström, 1999, Olvmo et al., 1999) or the landform could locally be preserved through multiple glacial cycles (Fabel et al., 2002).

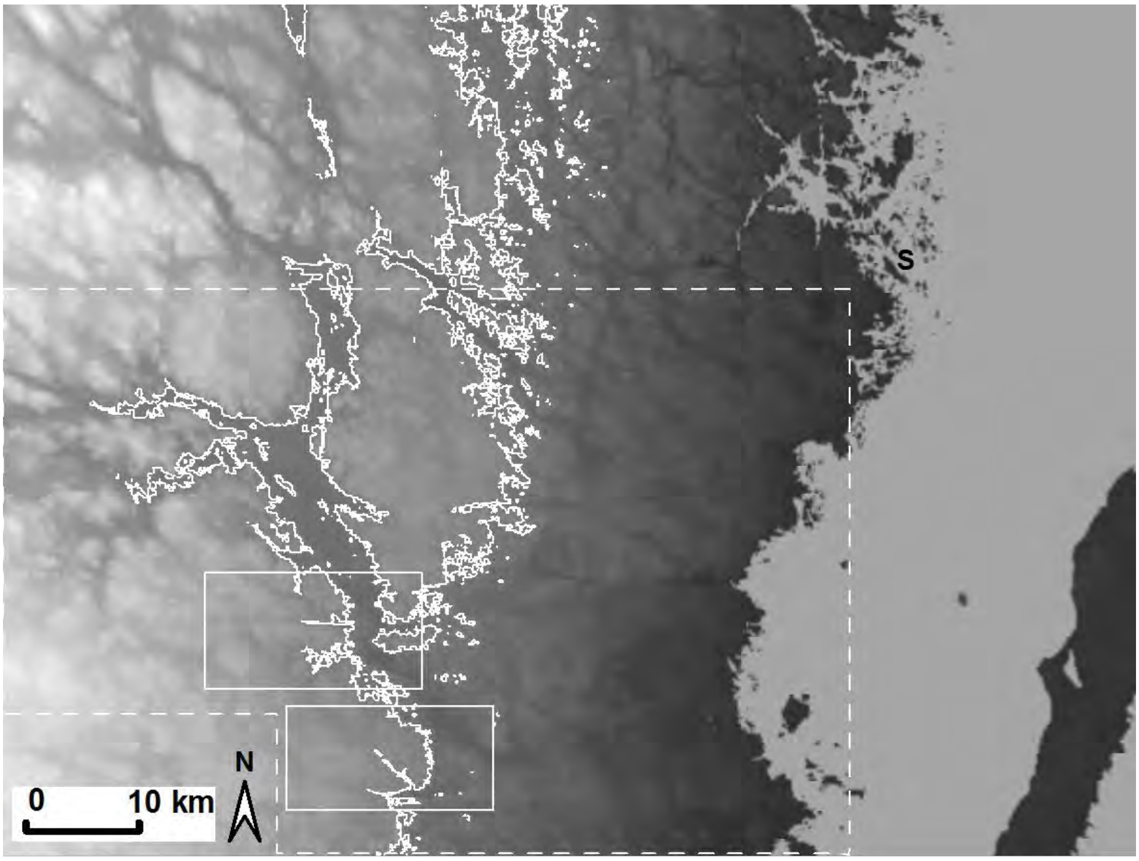

Figure 4. Digital terrain model, elevation presented as a grey-tone map, covering an area of c. 100 by 75 km (LMV elevation data base, 50 by 50 m grid). Larger “rectangle” gives position of airborne geophysical measurements presented in Figure 7 and location of the local area by the smaller rectangles (Moredalen, upper, and Pukedalen, lower; cf. Figures 1, 5 and 6). The highest post-glacial shoreline is represented by the 105 m contour. S is the location of Strupdjupet, a submarine canyon. Permission to publish by the National Land Survey of Sweden (I 2007/1092).

The location of the later study however, is in northern Sweden and it is assumed to have been cold based ices i.e. ice frozen to the ground.

The highest post-glacial shoreline followed a straight N-S line traceable 230 km northward and intersects the present shoreline of south-eastern Sweden where the latter swings on to E-W (Fig. 1). The angle to the present north-trending coastline, which parallels the strike of the sub-Cambrian peneplain, is c. 15º. The corresponding angle of the intersection line of the sub-Cambrian peneplain and the late Cretaceous denudation surface (Lidmar-Bergström, 1993) is c. 45º (Fig. 1). Minor block faulting and differential movements along faults probably accompanied periods with vertical movements.

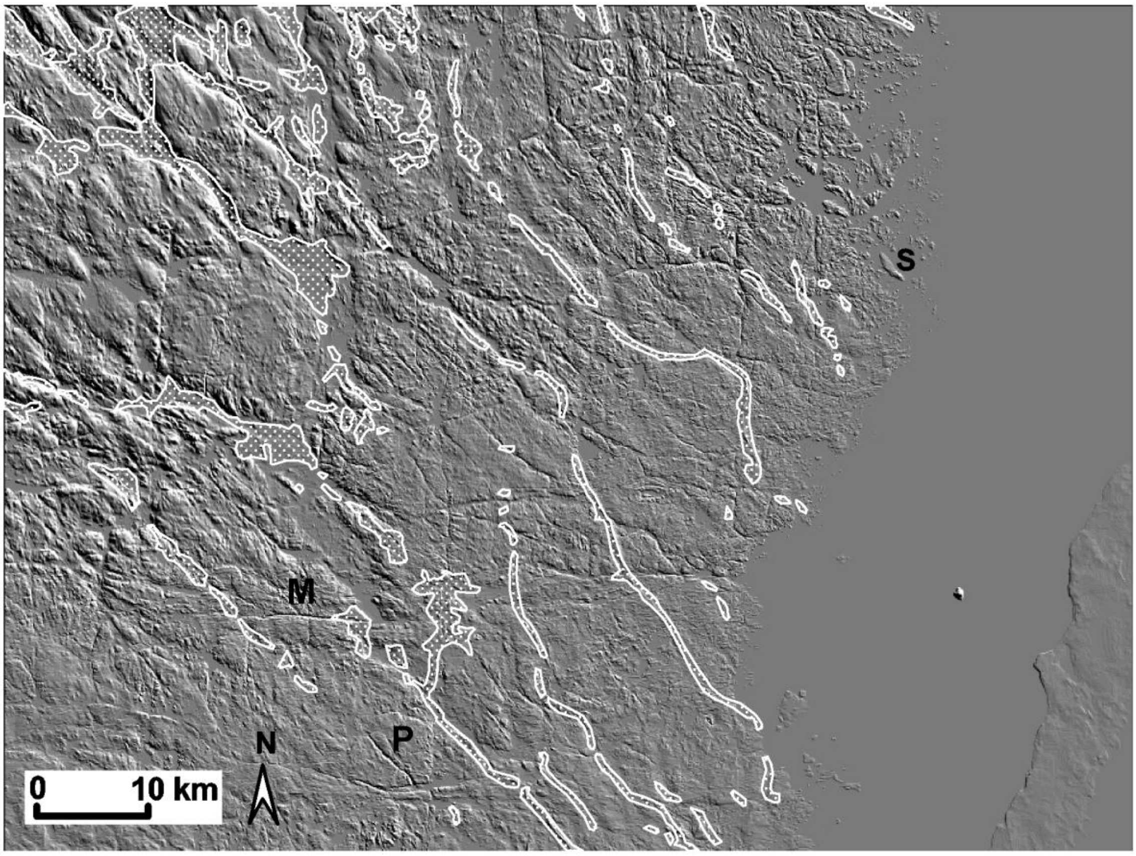

Figure 5. Digital terrain model, relief map (LMV elevation data base, 50 by 50 m grid), illuminated from NE, size of the area is 100 by 75 km. Distribution of glaciofluvial sediments, preferentially eskers, are displayed. Location of over-deepened valleys mention in text: Moredalen (M), Pukedalen (P), and a submarine canyon, Strupdjupe (S). Permission to publish by the National Land Survey of Sweden (I 2007/1092).

The rate of post-glacial (<10 ka) uplift (at present c. 1 mm a^{-1}, Ekman et al., 1982) is almost symmetrical across southern Sweden and somewhat higher in the central part, whereas most current seismicity is confined to south-western Sweden.

The coastline trends NNE-SSW south of Oskarshamn while to the north the coast trends more N-S. This indicates that the set of E-W trending linear land-forms (slopes and valleys), traceable from Oskarshamn and westwards, are tectonically significant (Tirén and Beckholmen, 1992). Land south of this line and below the highest post-glacial shoreline is planar To the north, still below the highest post-glacial shore-line, the relief is greater with plateaux, plains and valleys even though the relief rarely exceeds 30 m. The relief is still more pronounced above the highest post-glacial coast-line (located at c. 105 m a.s.l) and within the highland (above c. 200 m a.s.l) the relief is generally 50 to 100 m.

A topographical feature expressed as a slope at Oskarshamn, extends c. 25 km westwards and further to the west the same structure is expressed as a valley. Still further to the west it branches and the southern branch steps southwards and connects to a c. 30 km E-W trending topographical feature. Where the latter transects a plateau, c. 40 km from the coast, a 7 km long canyon (the

Moredalen valley; a kursu-valley), is found. A small brook, Morån, flows through Moredalen. Three kilometres east of Moredalen the brook meets a river, Emån. On the western side of the plateau the brook leaves the E-W structure for an intersecting WNW-ESE trending valley.

The NW-SE trending Pukedalen (the Swedish word "puke" is the same as Puck in English and according to Swedish folklore it is a mischievous or evil spirit/creature or a hunchback) appears more like a solitaire topographical feature. Still, it parallels extensive valleys in the region, e.g. the open valley/linear low through Högsby - Ruda – Långemåla expressed as a regional fault zone on the geological map (Lundegårdh et al., 1985). Bogs and minor lakes mainly occupy the lower part of Pukedalen. The airborne magnetic measurements (Fig. 6) only weakly indicate Pukedalen; it does not have a pronounced magnetic signature. Close to Pukedalen, to the east and northwest, there are some more distinctly expressed NW-SE trending magnetic structures.

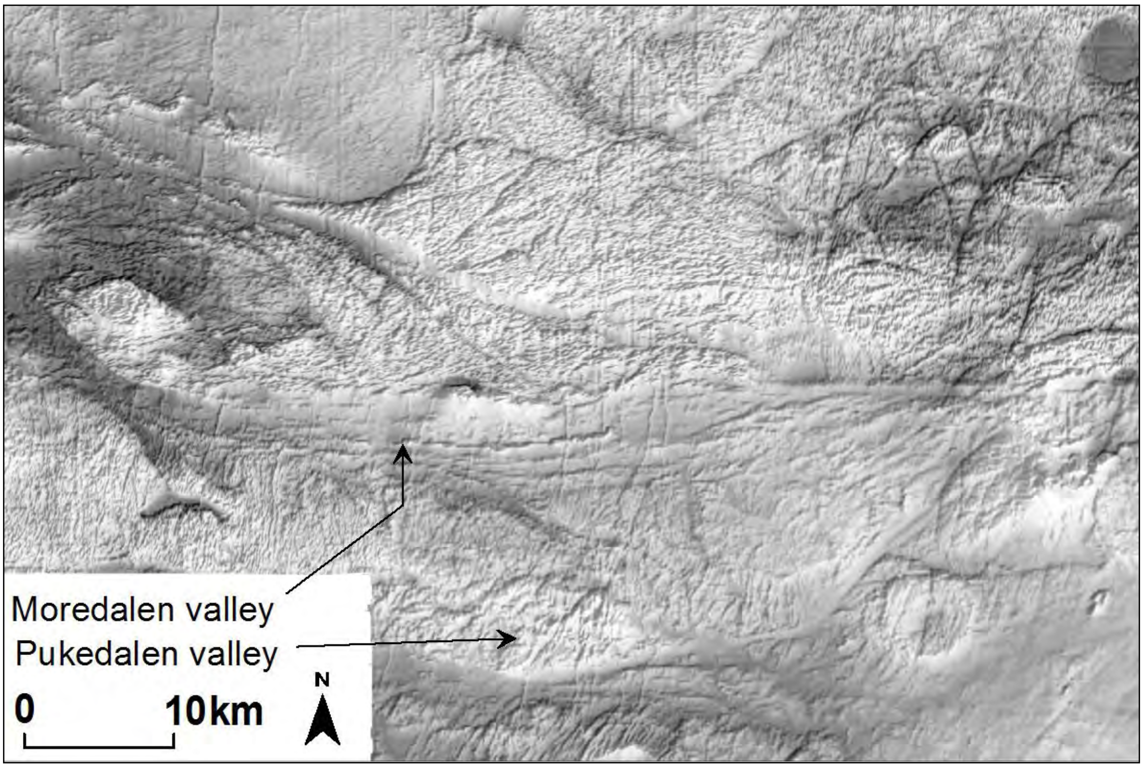

Figure 6. Airborne magnetic measurements, 75 by 50 km, a combined shaded relief and total field grey-tone map. Bright colours indicate high magnetic areas. Orientation of flight lines is predominately N-S. Flight line separation is 200 m, measurements were performed approximately every 16 m with a ground clearance of 30 m. Location of the area is given in Figure 4. Moredalen (trending E-W) has a well-expressed magnetic signature, while Pukedalen (trending NW-SE) is just weakly indicated. The winding N-S trending bright structures are c. 0.9 Ga old dolerite dykes. Permission to publish by the Geological Survey of Sweden.

3.2. Regional bedrock geology

South-eastern Sweden is a part of the Baltic Shield. It consists of continental crust formed more than 1.7 Ga (= 10^9 years) ago and is mainly plutonic to supracrustal acid rocks of the Trans-Scandinavian Igneous Belt (TIB; Patchett et al., 1987). This belt has a NNW-SSW regional trend. The TIB is transected by c. 10 to 15 km wide WNW-ESE trending belt (cf. Holst, 1893), the Oskarshamn-Vetlanda domain, containing foliated and presumably older rocks with a more basic composition (granodioritic to gabbroic Svecokarelian rocks, >1.8 Ga old). The spatial distribution of the older rocks in the domain is irregular. The structural relation between the foliated rock and the TIB rocks is not evident on existing geological maps (Lundegårdh et al., 1985, Persson and Wikman, 1986). However, the zone is well indicated by a deep seismic refraction sounding survey (Lund, 1983, and Guggisberg and Berthelsen, 1987).

The airborne magnetic map, Fig. 6, indicates that the Oskarshamn-Vetlanda domain coincides with an E-W trending major shear zone with anastomosing shears outlining lenses on various scales. In a part where the shear zone is only c. 7 km wide, several internal shear bands conform to orientation of the zone. Individual shears can be traced for more than 50 km (cf. Nisca, 1987). Berthelsen (1988) recognised the regional extent of this zone and assumed it to cross the Baltic Sea. The zone is one of three regional sinistral shear zones in the Baltic Sea region that are c. 100 km apart. The northern zone offsets a major Rapakivi massif at the Baltic coast and the southern one constitutes the northern border of the Blekinge coastal gneiss. Minor E-W trending structures occur between the major zones. Tirén and Beckholmen (1992) identified the southern boundary of the shear zone as a major tectonic boundary between regional scale rock blocks. Eastwards concave traces of large-scale structures in the northern block systematically stop at a high angle against the southern boundary of the E-W trending Oskarshamn -Vetlanda domain. These structures were interpreted as fracture zones dipping gently southward. Skjernaa (1992) and Mansfeld and Sturkell (1996) reported from studies of two localities just south-west and west of Moredalen that the individual E-W trending deformation zones are narrow and surrounded by undeformed rock. The zones were initiated as ductile shear zones characterized by grain size reduction and the development of a steep to vertical foliation. Structural mapping and gravity measurements indicate that the zones have steep to vertical dips and form a tectonic boundary to the TIB-rocks to the south. Tectonic striations indicate late normal faulting along the zones northern side down (Skjernaa, 1992).

The youngest rocks, c. 0.9 Ga old, are N-S trending dolerite dykes. Due to their magnetic character the dolerites show clearly on the airborne magnetic measurements, Fig. 6.

The trends of kursu-valleys conform to the trends of faults mapped in Precambrian rocks along the south-eastern coast of Sweden (SKBF/KBS, 1983). NE-SW is the dominant direction for early Palaeozoic clastic dykes (Nordenskjöld, 1944, Bergman, 1982) and also shear fractures, Fig. 7. No kursu-valleys trend NE-SW. However, most kursu-valleys are sub-parallel to

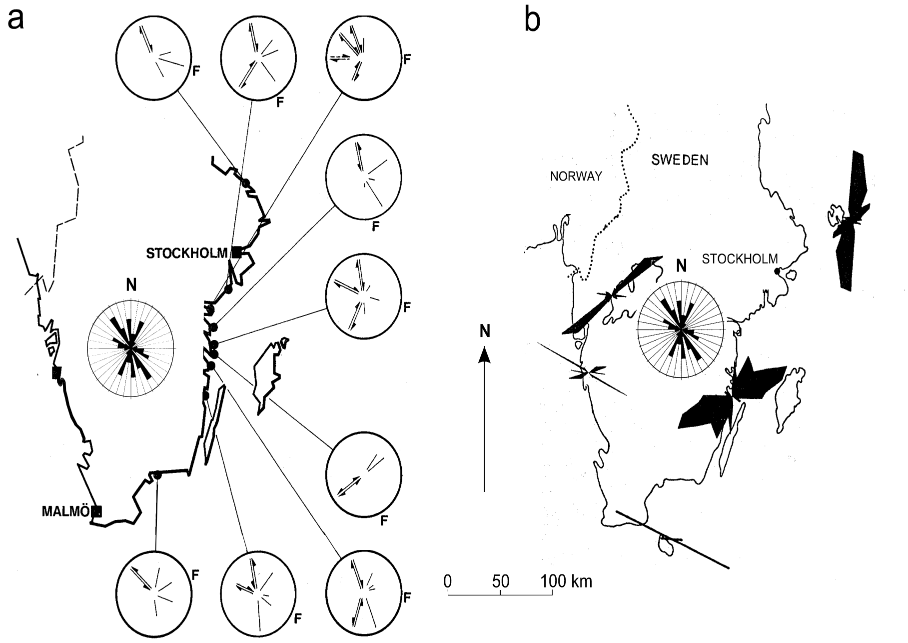

Figure 7. Orientation of tectonic structures: a. faults mapped along the Swedish East Coast (SKBF/KBS, 1983) and F is orientation of the foliation, and b. clastic Cambro-Ordovician dykes (Bergman, 1982). The rose diagram in the centre of figures gives the orientation of kursu-valleys.

the maximum current horizontal stress direction which is NW-SE (Stephansson et al., 1991) and has probably been so for at least 60 Ma. Notable is also the NW-SE trending fault relief in the region, Fig. 5; faults parallel the contact between the TIB-rocks and the Svecokarelian rocks (in the north-eastern corner of Fig. 4 and 5, at Strupdjupet marked S on the maps).

3.3. Local geology and morphological description of the Moredalen and Pukedalen valleys

According to the knowledge of the authors, only Moredalen has previously been subjected to studies concerning geomorphology or structural mapping.

3.3.1. Moredalen

3.3.1.1 Bedrock

Out of several extensive structural traces along and within a c. 5 km wide E-W trending ductile shear zone indicated on the airborne magnetic measurements, only one has a significant surface expression along a part of its trace; the canyon like kursu-valley Moredalen. The bedrock in the eastern part of

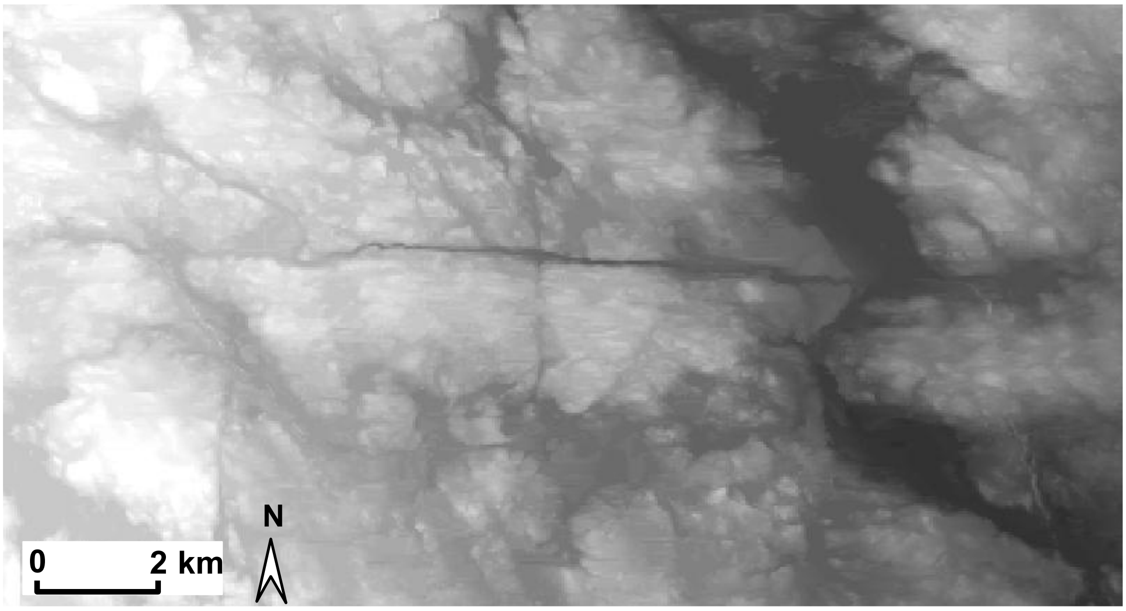

Figure 8. Digital terrain model showing the Moredalen valley, elevation presented as a grey-tone map, covering an area of c. 18 by 10 km (LMV elevation data base, 50 by 50 m grid). Location of the area is given in Figure 4. Permission to publish by the National Land Survey of Sweden (I 2007/1092).

Moredalen, where it has its most canyon-like appearance, is composed of dark reddish porphyritic rhyolite. This rock has a weak compositional vertical banding that strikes E-W, i.e. along Moredalen. Mylonitic derivatives and quartz-cemented breccias occur locally. In the western part of Moredalen the bedrock is composed of a foliated red-grey tonalitic to granodioritic rock.

Moredalen is 7 km long going westward. It is straight for the first 2.5 km then swings a 100 m northwards (Fig. 8 and 9) and continues another 1.5 km as a straight feature. From there the southern side of valley is relatively straight while the northern side is more irregular. The trace of the valley is related to the structural pattern in the bedrock (Olvmo, 1989).

The eastern parts of Moredalen have the simplest profile. The northern wall is sub-vertical to vertical (locally overhanging) controlled by extensive fractures and the upper parts of the southern side have a relatively moderate inclination, while the lower parts steepen to 60-70°, parallel to extensive fractures, Fig. 10, 11, 12, 13, and 15. This part of the kursu-valley has an asymmetric “valley in valley” or double valley character. Exposed bedrock is not found in the floor of the kursu-valley, which is just covered with rock debris and some rounded boulders. Thus the actual depth of bedrock in the valley is not directly observable.

In the westernmost part of Moredalen there is a central, c. 15 m high cliff with more or less vertical sides, the Moredalen Citadel (a tor-like pillar), composed of rhyolite.

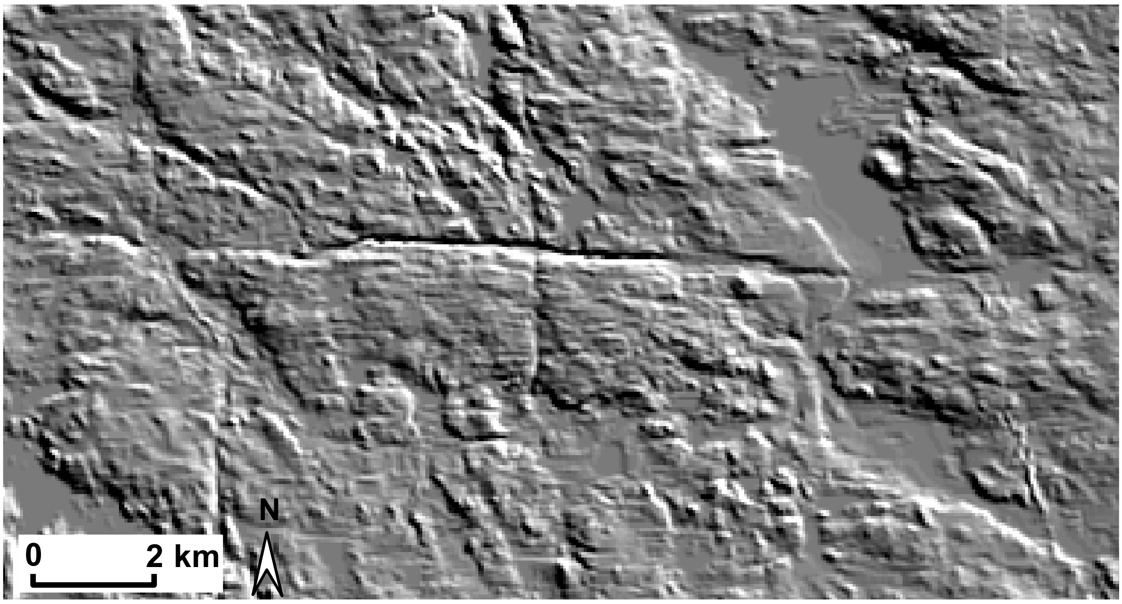

Figure 9. Digital terrain model showing the Moredalen valley, relief map, covering an area of c. 18 by 10 km (LMV elevation data base, 50 by 50 m grid), illuminated from NE. Location of the area is given in Figure 4. Permission to publish by the National Land Survey of Sweden (I 2007/1092).

N-S to NNE-SSW trending dolerite dykes, c. 0.9 Ga old, overprint the E-W fabric in the Moredalen bedrock. The dykes are magnetic and mappable for 5 to 10 km on the airborne magnetic map, Fig. 6. The dolerite dyke intersecting Moredalen at its midpoint has a negative topographical signature, Fig. 8 and 9. Where it intersects Moredalen the valley opens to a southern slope and on the northern side a minor terrace of rock debris rests on a moderately dipping bedrock surface. There is no indication of any lateral displacement of the dolerite dykes along the Moredalen structure.

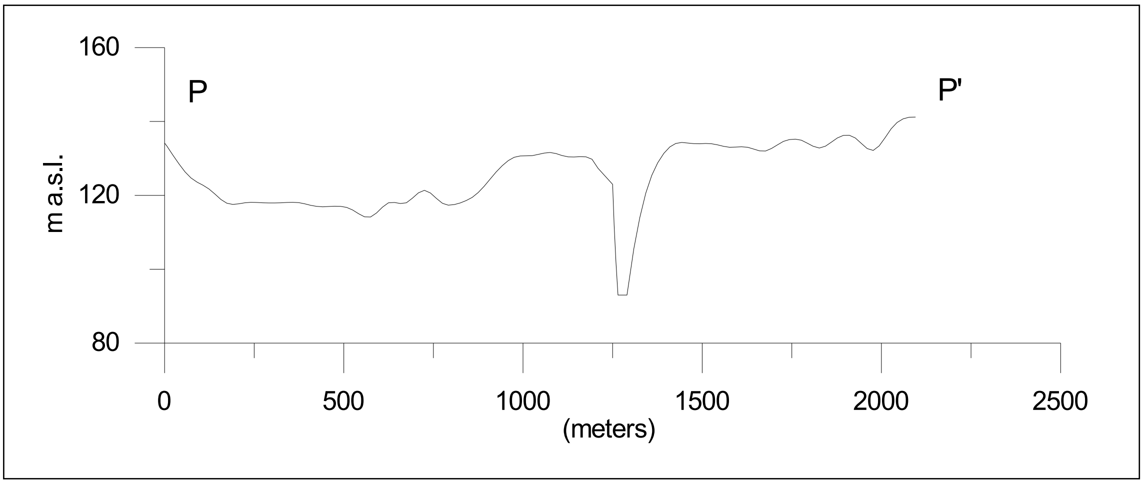

Figure 10. A N-S trending vertical profile across eastern part of the Moredalen valley showing the asymmetrical shape of the valley. Location of the profile is given in Figure 16.

Figure 11. N-S trending fractures expressed along the southern side of Moredalen.

Figure 12. Vertical lensoidal fracture pattern of E-W trending fractures and closely spaced horizontal fractures in the northern wall of the Moredalen kursu-valley, looking eastward.

Figure 13. Blocks in the northern wall of Moredalen

Figure 14. Scree at the foot of the northern wall of the Moredalen valley. Note the uniform size of the fragments. Length of hammer is 0.53 m. Same scree as in the lower part of Figure 13 above.

In the eastern part of Moredalen, three vertical dolerite dykes trend N-S. The weathering of these dykes (c. 5, 2.5 and 0.3 m wide, respectively) and the erosion of the bedrock along the dykes have formed two hollows or pockets in the northern canyon wall; the Giant's Pinfolds (enclosures for stray cattle) according to folklore. These two hollows are crucial for the interpretation of the formation of the Moredalen canyon. They are less than 15 m long and c. 5 m wide and separated by a c. 4 m wide rock bridge reaching out to the canyon wall. The floors are filled with debris and slope steeply toward the canyon. They do not reach down to the surface of the lake which is an 8 m deep surge pool (92 m a.s.l.) occupying the eastern part of the kursu-valley. There is no visible expression of any talus outside the hollows. The exposed wider dolerite dykes are fresh while the thin dyke is open a further 1.5 m deep leaving an open fracture. Stacked rounded boulders block the upper part of this fracture.

Dominant sets of fractures in the Moredalen kursu-valley are N-S/vertical and E-W/vertical, i.e. fractures are mainly parallel and perpendicular to the length of the Moredalen valley (Fig. 11, 12, 13 and 15). The N-S fracturing is pervasive and relatively regular with an estimated separation of one to five metres between extensive fractures (cf. Fig. 11). A N-S structural grain is typical for the whole of south-eastern Sweden (Tirén and Beckholmen, 1992), although the E-W fracturing is more intense along the Moredalen valley and occurs preferentially in the northern wall of the valley (Fig. 12 and 13). However, most fractures are closed and recent rock debris composed of rhyolitic porphyries along the northern side of the canyon generally has a uniform size, less than one decimetre, and regular form (Fig. 14). Larger blocks are unusual although, further degradation of the northern wall is likely to take place by rock glide as well as rock falls. Tabular rock blocks up to 10-15 m high and several tens of metres long and some metres wide form locally the northern side of the canyon.

The character of rock structures in the granitoid bedrock exposed in western Moredalen remain to be mapped. The rock debris in the western part is lager (cobbles to boulders) with more irregular shapes.

a. b.

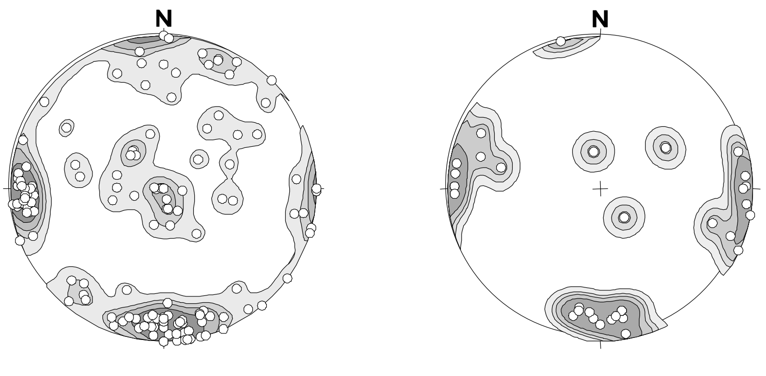

Figure 15. Orientation (poles) of fractures: a. Fractures mapped on the northern side of the Moredalen valley (n=150), and b. fractures mapped on the southern side (n=33). Schmidt projection, lower hemisphere, contours; 1, 2, 3, and 5 %.

3.3.1.2 Altitude of the bedrock surface

To check differences in altitude of the ground surface along Moredalen, four rock blocks have been analysed: two north of and two south of the valley (denoted NW, NE, SE and SW in Fig. 16 and Table 1). The data indicate moderate as well as defined shifts in altitudes both across and along Moredalen. The blocks south of the E-W trending Moredalen are higher. The blocks west of the crossing N-S trending structure (containing a dolerite dyke) are also higher. The absolute offsets in altitude of the top surfaces of the rock block are in the range of 2 to 24 m. The offsets relative to the "mean altitude" of the plateau (136.8 m, standard deviation 10.6 m; considering areas NW, NE, SW and SW in Fig. 16) are in the range of 0 to 18 m. The relief within all four blocks is similar.

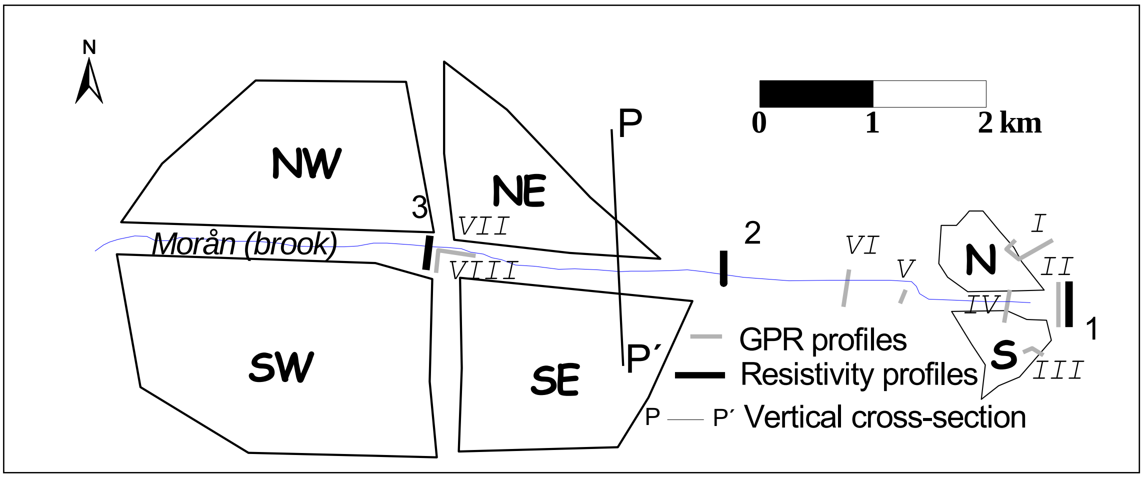

Figure 16. Simplified map showing the location of : a. four rock blocks (NW, NE, SE and SW) see text and Table 1, b. northern part and southern part of the delta (N and S) see text, Figure 17 and Table 2, c. GPR profiles (grey lines, I to VIII), see text and Figure 18, d. resistivity surveys (heavy lines, 1 to 3), see text and Figure 19, and e. vertical cross-section P to P´, see text and Figure 10.

Table 1: Altitude data of four areas, rock blocks, along the Moredalen kursu-valley (Figure 16, cf. Figure 8 and 9). Data points = number of grid points in the 50 by 50 m elevation database.

Area	Data points	Median value (m)	Mean value (m)	Standard deviation (m)	Max value (m)	Min value (m)
NW	1108	136	136.3	8.6	156	114
NE	612	119	118.9	5.6	132	109
SE	998	138	137.4	4.9	151	120
SW	1198	143	143.2	7.6	161	118

3.3.1.3 Sedimentary cover

Sediments are related to glaciofluvial transport through Moredalen (cf. Johansson, 1968). Moredalen therefore differs from most kursu-valleys which generally lack sedimentary deposits (Rudberg, 1949). South-east and east of the plateau transected by Moredalen is a NE-SW trending esker. Just east of Moredalen the esker swings to an E-W trend in line with Moredalen. The esker is then lost, eroded by the river Emån; it appears again at the mouth of Moredalen valley as high level ridges rich in rounded boulders (Olvmo, 1989).

However, the esker is there partly covered by the delta that consists of well-sorted fine sand in its distal parts and less sorted sediments with rounded boulders in its proximal parts. Glaciofluvial deposits of fine sand occur at altitudes just below the highest post-glacial shoreline (105 m a.s.l.) as far west as where the Moredalen valley has a canyon shape. Petrological composition of sediments from the delta is c. 55 % gneissic granite, 27 % red porphyritic rhyolite, 9 % greenstone, 7 % quartzo-feldspatic grains and 2 % unspecified grains (13 samplings sites, ca 13 000 counted 2-5.6 mm grains, Olvmo, 1989). Larger fragments (20-600 mm, 335 clasts) studied in a gravel pit have a similar composition: 50 % various sorts of granitoids (whitish to reddish), 31 % red porphyritic rhyolite, 6 % greenstones (gabbro, diorite, amphibolite, dolerite; the latter constitutes 2 %) and 13 % other rock types. Boulders larger than 0.6 m in diameter are rare.

Glaciofluvial deposits occur west of Moredalen. Further west there is a system of eskers trending NE-SE, some up to 40 m high. Washed ground surfaces at the edge of Moredalen are restricted to minor areas of the northern side of Moredalen.

Notable is the absence of glaciofluvial deposits, except for rounded boulders, in Moredalen.

The lowest part of the valley is located on the bottom of the 8 m deep surge pool or kolk lake in the easternmost part of Moredalen that is at c. 84 m a.s.l. This corresponds to a depth just less than 20 m below the top surface of the delta, the same level as the water table of the river Emån to the east. The delta has a relatively well-preserved palaeo-channel system and the brook Moreån-flowing along Moredalen, is located in a distinct deep channel across the delta. The original size of the delta is not known. Its eastern termination appears as well preserved foreset beds.

3.3.1.4 Altitude of the delta

The only well-defined datum surface at Moredalen is the top surface of the delta. The delta has a flat top surface with residual channels fanning out from the mouth of Moredalen. The channel of the present brook flowing through Moredalen divides the delta. The channel is straight E-W and parallel to Moredalen and its position is offset to the south. By comparing the elevation of the northern and southern parts of the delta it is found that the surface of the southern part of the delta is located 3.5 m below the surface of the northern part of the delta (Table 2 and Fig. 16 and 17).

Table 2: Altitude of the delta east of the Moredalen valley, Figures 16 and 17.

Part of the delta	Data points	Median values (m)	Mean value (m)	Standard Deviation (m)	Max value (m)	Min value (m)
Northern	164	99	98.8	1.7	101	95
Southern	145	96	95.3	2.0	98	88

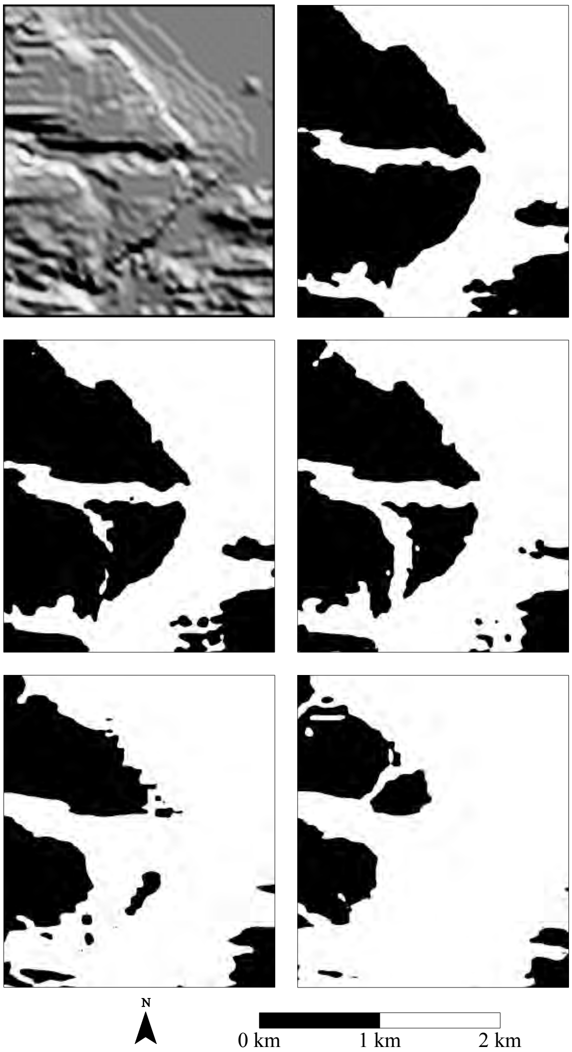

Figure 17. Illumination of the difference in elevation of the northern and southern part of the delta just east of the Moredalen valley. Altitudes above 92, 93, 95, 97 and 99 m a.s.l. are shown. Permission to publish by the National Land Survey of Sweden (I 2007/1092).

3.3.1.5 Geophysical measurements to map sediments and bedrock surface

Geophysical investigations were performed to characterize the sediments in the delta, the depth of rock debris in Moredalen and morphology of the bedrock below the delta.

GPR

GPR surveys (c.f. Maijala, 1994) were performed with antenna frequencies of 50 and 100 MHz. The antenna spacing was 2 m and the station spacing used was 0.5 m. Eight GPR profiles were measured (as indicated in Fig. 16) with a total length of 2700 m. In addition, several shorter GPR profiles were measured.

The depth of penetration achieved during the GPR measurements varied, e.g. depending on the soil material in the overburden. In most cases the radar signal was able to penetrate 20 meter. In areas where the bedrock is much shallower the penetration is also smaller. Soil containing clay material effectively attenuates the radar signal, thus decreasing the depth of penetration.

Four radar surveys were carried out in the delta area (Fig. 16 and 18). The main objective of these surveys was to get an understanding of the stratigraphy between the delta and the plain east of the delta area and furthermore to detect bedrock if possible.

In general, the depth of penetration was fairly high ranging from 25 metres in the deltaic sediments down to 5 to 8 metres in the section of the profile that intersects the plain east of the delta.

The most obvious feature in the data from profile I (Fig. 16 and 18a) is interpreted as a buried channel parallel to the north-eastern edge of the delta (150 to 220 m profile length). Due to the difference in elevation between the plains and the delta area, a possible extension of the buried channel westward below the delta material is difficult to trace. Cross-bedded structures can be identified throughout the delta. Notable is the attenuation of the radar signal (0 to 50 m profile length) which indicates the occurrence of glacial (?) clay deposits. This could indicate that the extension of the delta is actually larger than what is expressed by its distinct foreset-like slopes (cf. Fig. 17).

Profile 3 (Fig. 18 b) is from south to north just east of the delta (Fig. 16 and 18b) and indicates similar attenuation of the radar signal (c. 360 to 420 m profile length) and a buried channel feature (280 to 320 m profile length) as in profile I. The channel is however, not as pronounced. Depth of penetration is more than 25 m in the delta region. A possible bedrock surface dipping southward can be spotted in the last part of the profile (at a depth of c. 20 m at 180 m profile length to c. 12 m at c. 350m profile length).

The objective of radar profiles V to VIII (Fig. 16) was to follow the bedrock surface, which crops out in parts of profile VII. However, bedrock could not be followed beneath boulders.

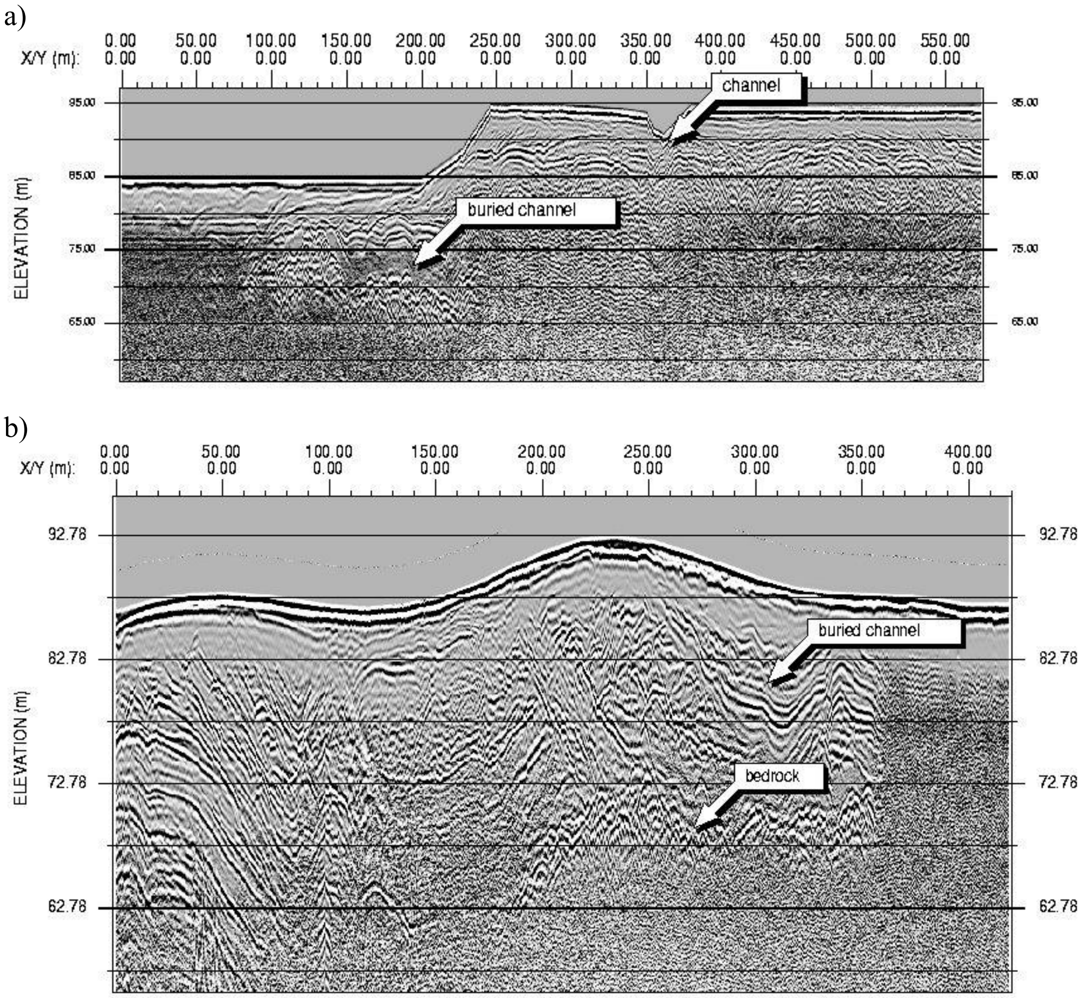

Figure 18. GPR profiles measured at the delta east of the Moredalen kursu-valley (location of profiles is given in Figure 16): a. Profile I is measured south-westward from the plainland up onto the delta, turns north-westward across a former channel and turns back north-eastward to the front of the delta, a U-turn, and b. Profile III is measured from south and northward across the Moreån brook, across a eastern wedge of the delta and thereafter out on the plainland north of the delta.

Resistivity survey

Resistivity methods measure the electrical resistivity distribution in the subsurface. Two electrodes are used to transmit direct current (DC) or low frequency alternating current (AC) into the ground while the potential difference between a second pair of electrodes is measured. Based on the specific electrode spacing and geometry, the apparent resistivity of the subsurface can be calculated. The apparent resistivity is mainly controlled by the presence, quality, and quantity of ground water together with the electrical properties of the soil and bedrock material (Haeni et al., 1993). The resistivity of fracture zones is controlled by the porosity induced by deformation, fracture fillings and the water content. The maximum penetration depth is directly proportional to the electrode spacing and inversely proportional to the subsurface conductivity (Edwards, 1977). The resistivity survey at the Moredalen kursu-valley was carried out using an ABEM Lund Imaging system which uses multi-electrode layouts to ensure fast and reliable data collection. Data were collected using a Wenner configuration.

Where conditions were good an electrode separation of 5 m was used with a single set-up length of 200 m. The maximum depth penetration was about 30 m.

2D depth models were generated using an inverse modelling program (RES2DINV). All data are collected in profiles going south (Fig. 19 a-c).

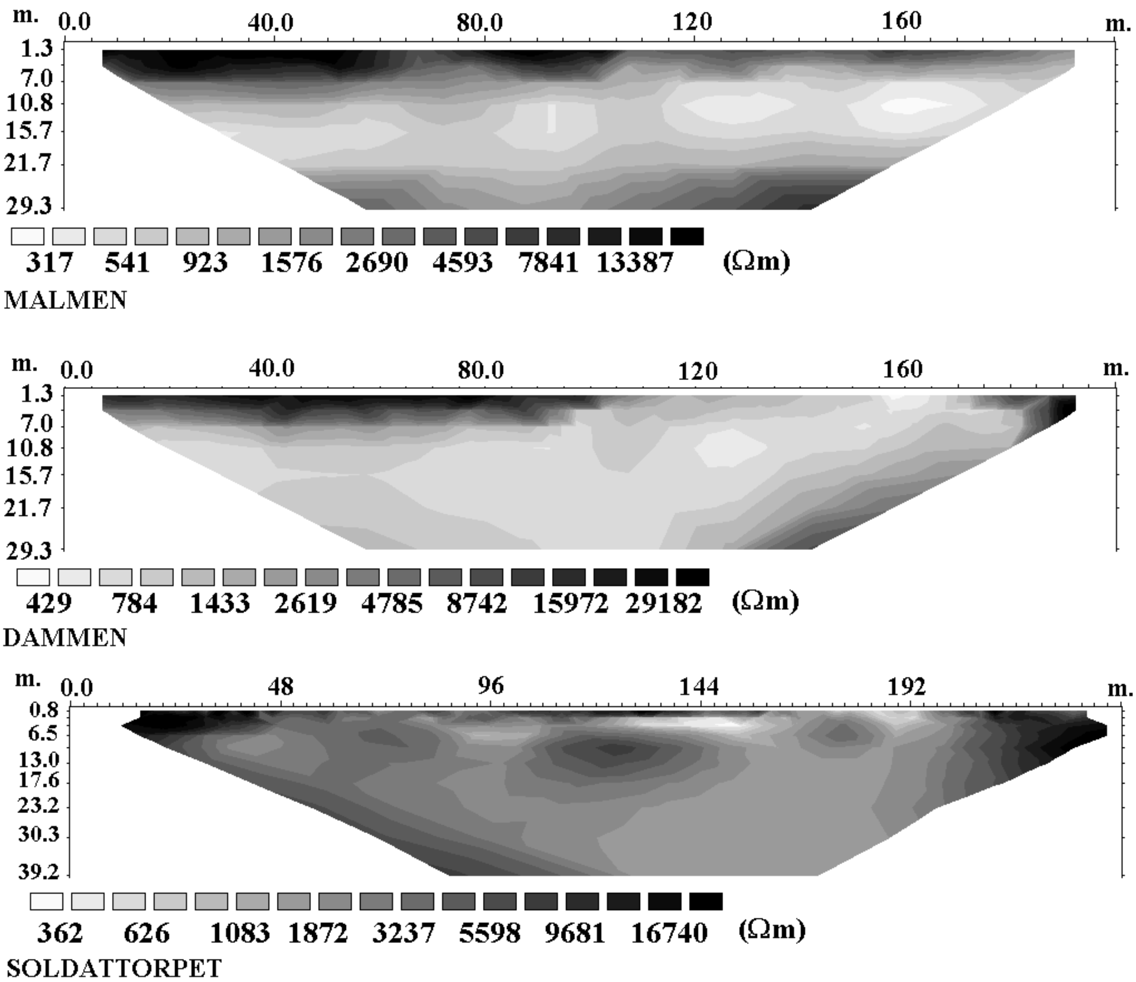

Figure 19. Resistivity inversion model sections, profiles 1 (Malmen), 2 (Dammen) and 3 (Soldattorpet). Location of the profiles is given in Figure 16. All profiles are measured from north to south.

All three 2D models (Fig. 19) show indications of (high resistivity) bedrock in the lower part of the sections.

In the bottom profile (Fig. 19) the bedrock is visible in the most southern part of the section. The high resistivity anomaly in the central part of the section could be correlated to a limb of the bedrock formation seen in the left part of the section.
The top profile (Fig. 19) is located just east of the delta. Bedrock surface may be visible deeper than 20 m. This bedrock surface is also visible in the radar data covering the same distance (Fig. 18 b).

3.3.2. Pukedalen

Pukedalen is located between two relatively flat and large rock blocks (Fig. 20, 21 and 28). Only the south-eastern part of Pukedalen (c. 1. 5 km; its total length is c. 5.5 km) has been visited during some rainy days in April 2001. The field record consists of some notes and as a sequence of photos.

The western side of Pukedalen valley consists of steep to vertical cliffs (up to more than 5 m high) while extensive gently westward dipping fracture planes form the eastern side of the valley (Fig. 26 and 27). The valley contains a small brook and only in its south-eastern part it forms a narrow valley (Fig. 22). The valley slopes slightly less than 3 m/km in its central and northern parts while the slope from the mouth of the valley and 1.5 km upstream is c. 5.3 m/km. At the time of the highest post-glacial shoreline (c. 105 m a.s.l. at c. 12 500 B.P) the central and south-eastern part of Pukedalen formed a narrow creek (Fig. 4).

3.3.2.1 Bedrock

According to the regional geological map (Lundegårdh et al., 1985) the NW-SE trending Pukedalen transects a sequence of rocks comprising granodioritic gneiss, younger granites (medium to coarse grained TIB granitoids) and young Småland porphyry (acid TIB supracrustals, c. 1.8-1.85 Ga).

The rock type in the south-eastern part of Pukedalen consists of a uniform, even-grained massive granite.

Outcrops are generally smooth and rounded (Fig. 23). Notable is that rock blocks exposed in the south-western wall of the valley display rounded corners and the fracture fillings consist of weathering products, a grus type of saprolite (Fig. 24, see below, section 4.1). In the neighbourhood there are well-rounded large block of the local granite (Fig. 25). This indicates that the area has been affected by deep weathering.

North of the central and northern part of Pukedalen there is a sub-parallel gully at a separation of c. 1 km (Fig. 20 and 21). Even though Pukedalen is a distinct topographical feature (Fig. 22) it is hardly discernible on the airborne magnetic measurements (Fig. 6). However, NE-SW trending structure crossing Pukedalen in its southern part is magnetically well expressed but these are vaguely distinguishable on the topographical relief map.

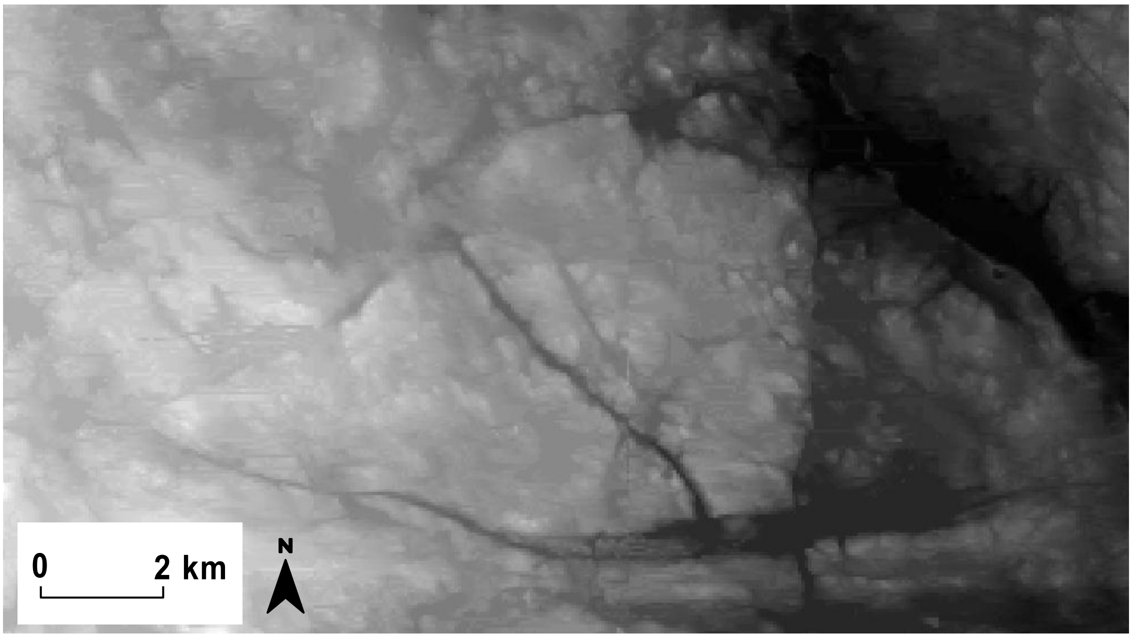

Figure 20. Digital terrain model showing the Pukedalen valley, elevation presenting as a grey-tone map, covering an area of 18 by 10 km (LMV elevation data base, 50 by 50 m grid). Location of the area is given in Figure 4. Permission to publish by the National Land Survey of Sweden (I 2007/1092).

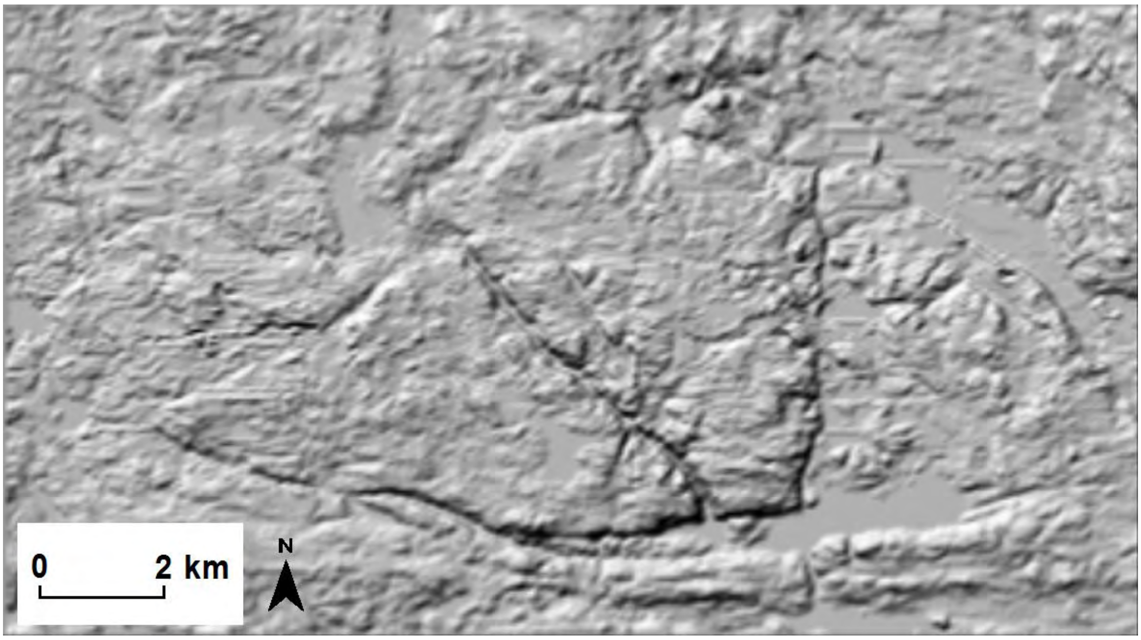

Figure 21. Digital terrain model showing the Pukedalen valley, relief map, covering an area of 18 by 10 km (LMV elevation data base, 50 by 50 m grid), illuminated from NNW. Location of the area is given in Figure 4. Permission to publish by the National Land Survey of Sweden (I 2007/1092).

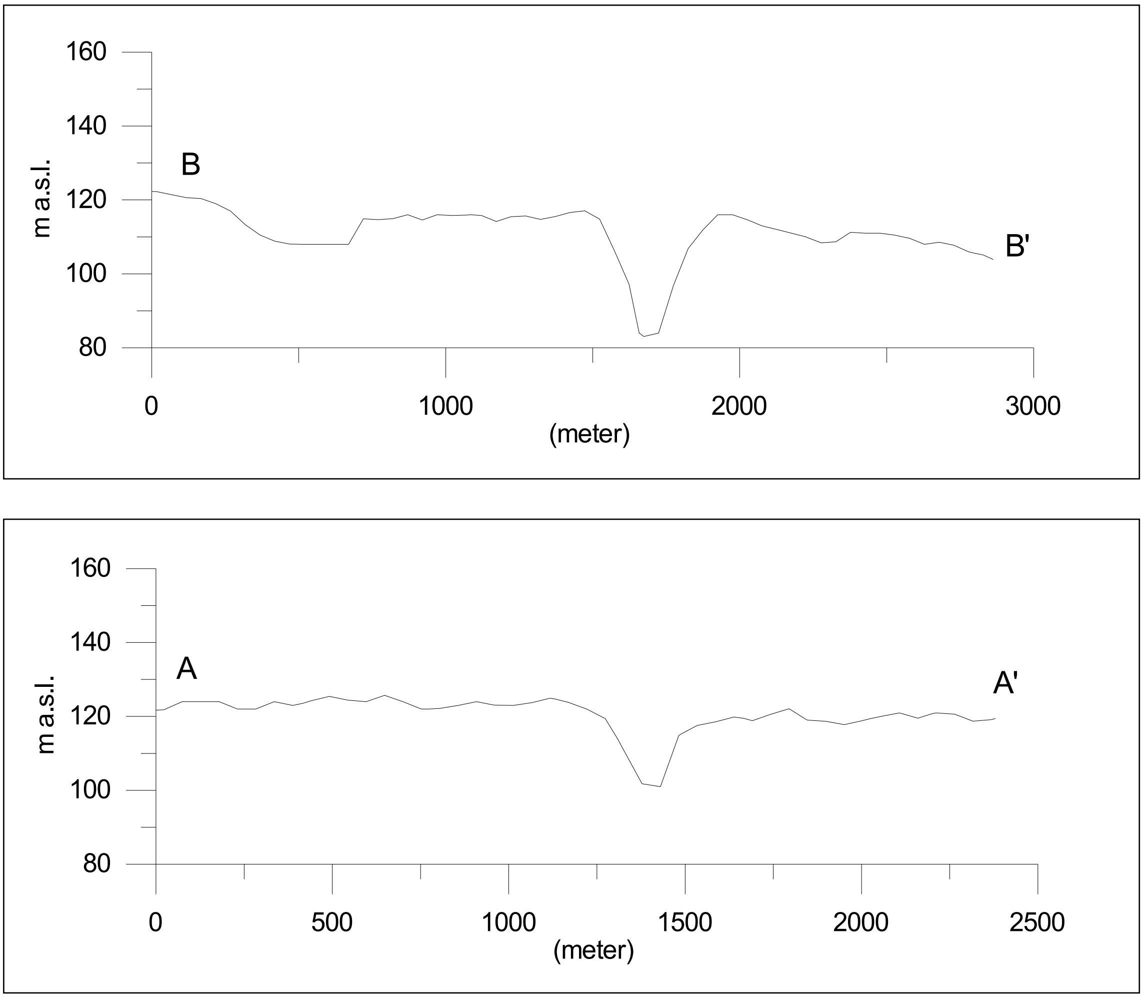

Figure 22. Vertical profiles: a. across the Pukedalen valley (B-B´) and b. across the E-W trending southern border of the major rock block west of Pukedalen (A-A´). Location of profiles and the demarcation of the major rock block are presented in Figure28, cf. Figures 20 and 21.

Figure 23. Granitic outcrops with rounded form, typical for the area.

Figure 24. In situ blocks with rounded corners and a fracture fill composed of grus weathering product (brownish in colour, see section 4.1).

Figure 25. Rounded local block of granite, presumably a glacially displaced “core-block” formed by deep weathering.

Figure 26. Spaced fractures along the south-western side of Pukedalen valley, looking north-west.

Figure 27. Planar and smooth fracture surfaces along the north-eastern side of Pukedalen valley, looking south-east, close to the location of Profile B-B´ (cf. Figure 28).

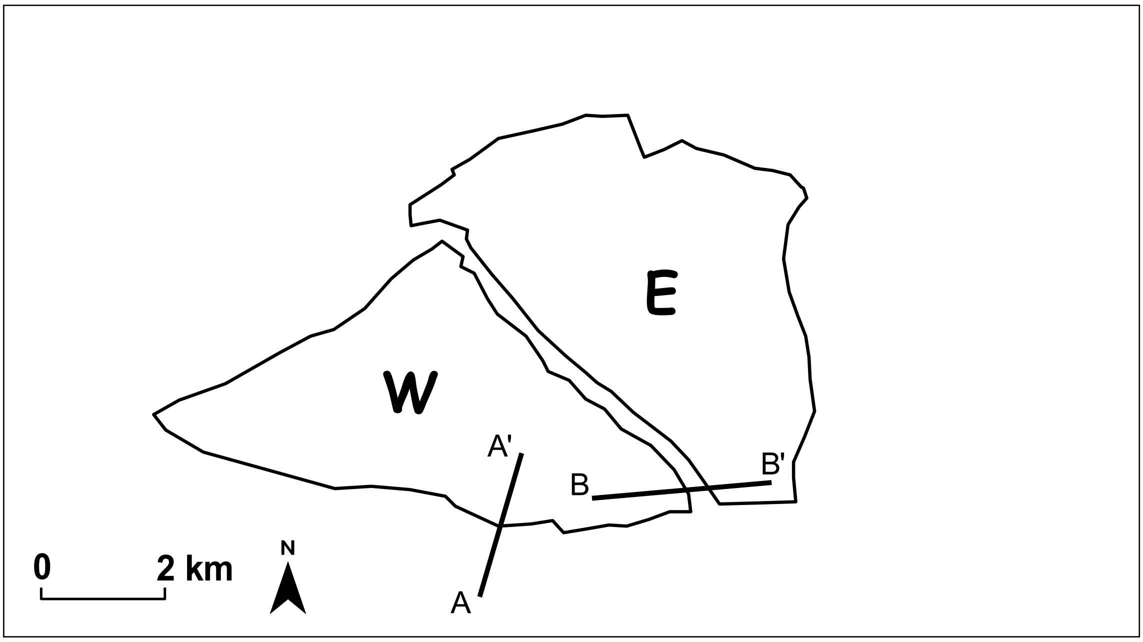

Figure 28. Simplified map showing the location of the two rock blocks (E and W, see Table 3 below) separated by the NW-SE trending Pukedalen valley. Profiles A-A´ and B-B´ are shown in Figure 22.

3.3.2.2 Altitude of bedrock surface

Detection of rock blocks based on relative elevation of the ground surface indicates that Pukedalen is located along an apparent NW-SE trending block border. The large-scale rock block east of Pukedalen is in its easterly part topographically well demarcated, located up to 20 m above the surroundings. Only the south-eastern boundary of the large scale block west of Pukedalen is topographically well expressed. Furthermore, there is not a distinct difference in altitude between the large bedrock blocks to the west and east of Pukedalen. Instead the ground surface has a very gentle inclination eastward, c. 4.5 m/km, and this may give the difference in mean altitude of the two bedrock blocks (c.f. Table 3, Fig. 28 and 20). However, the two large-scale bedrock blocks contain minor blocks outlined mainly by N-S, E-W and NW-SE trending deformation zones. This holds especially for the large-scale block east of Pukedalen. It should be pointed out that the local inclination of the ground surface within the two bedrock blocks is higher than the regional topographic inclination, which is slightly less than 3 m/km. Notable is that the airborne magnetic measurements (Fig. 6) indicates that the western block is divided by a N-S trending structure (Fig. 20). The western part of the block have uniform easterly slope while the eastern part appears to be relatively flat and horizontal (Table 3).

Vertical displacement along Pukedalen is indicated by an elevated minor elongate block along and north of the central and northern part of the Pukedalen structure. The age of displacement is unknown and may date back to Palaeozoic time.

Table 3: Altitude of the areas, rock blocks, west and east Pukedalen, Figure 28 and 22. Note that the ground surface has a gentle eastward inclination, c. 4 m/km, and the eastern area has a more irregular topography the western area (cf. Figures 20 and 21).

Rock Block	Data points	Median values (m)	Mean value (m)	Standard Deviation (m)	Max value (m)	Min value (m)
E	9010	116	115.8	7.2	138	83
W	7592	129	130.1	9.9	160	94

3.3.2.3 Rockslides

Along the steep southern -western side of Pukedalen there is a major block glide/ rockslide into the valley.

There is also a several hundred metres wide rockslide in the E-W trending slope just east of the mouth of Pukedalen. The down-slope displacement of the slide is restricted just some tens of metres (the vertical displacement is just a few metres) and the front of the slide is very steep. The original bedrock surface is still recognizable, strongly block faulted though (Fig. 28). Inside the rockslide block caves are formed (Fig. 29). The slide has taken place along an E-W trending and steeply southward dipping fracture.

Figure 29. Rockslide along an E-W trending fracture dipping steeply southward, southern side of the NE block and just east of the mouth of Pukedalen (cf. Figure 28). The original bedrock surface is the top surface of each block. The dull parts on the photo are due to condensed water on the lens.

Figure 30. Narrow passage and tunnel (block cave) in the rockslide.

3.3.2.4 Sedimentary cover

The bottom of Pukedalen is flat, although there a sequence of depressions occupied by wetland and minor lakes. Between the depressions the floor of the valley is covered with minor boulders. Boulder beds occur also locally on the eastern sides of the valley.

The Quaternary within the surroundings of Pukedalen valley is relatively thin and the degree of exposed rock is high, especially at Pukeberget located just west of the mouth of Pukedalen.

The mutual distance between eskers is generally in the order of 5 to 10 kilometres but in the vicinity of Pukedalen there is a lack of eskers within an area of approximately 30 by 25 km. The reason for this is not described but it could be related to that the area is located at the south-eastern spur of the highland i.e. on the lee side relative to the direction of movement of the inland ice. However, Pukedalen is aligning eskers on both sides. The esker on the north-western side is one of the major eskers in south-eastern Sweden, Virserumsåsen. The same esker as located west of Moredalen. The esker on the south-eastern side, Kåremoåsen/Kåsebergaåsen, is more moderate in size and extend to the Kalmar Straight.

4. Discussion

4.1. Surface morphology and bedrock structures

The morphology of an area is related to several destructive processes and the character of the bedrock. Elements that influence the morphology of an area are for example:

- Rock type.
- Structural framework in the bedrock.
- Tectonic and isostatic adjustments (including both seismic displacements and aseismic creep).
- Relative altitude, local to regional scale.
- Climate.
- Hydrography, including the sea level changes.
- Biotic environment.
- Time.
- Distribution of regolith (the layer of loose material covering the bedrock, comprising soil, sand, rock fragments, volcanic ash, glacial drift, etc.).

The morphological evolution of an area is in other words a complex time dependent function. One of the most profound morphological characteristics of the Fennoscandian Shield is the existence of the sub-Cambrian peneplain. This extensive paleo-surface with a relative altitude of some 20 m is not well explained (cf. Phillips, 2002). On this surface an up to two kilometres thick cover of Cambrian and younger sediments was deposits. During periods of dome-like uplift, denudation processes removed the sediment cover and also affected the core of basement rocks. Today there are only few remnants of the sedimentary rock-cover and the Fennoscandian Shield is today one of the best-exposed areas with Precambrian granites and gneisses. Notable is that the sub-Cambrian peneplain roughly constitutes the present ground surface within large areas, e.g. along the Swedish East-coast from the southern part of Sweden to the northernmost part of the Bottnian Bay (c. 1 200 km, Rudberg 1954) and in the inland (Västgötaslätten, south of lake Vänern).

The subject of erosion of the sedimentary rock cover and the Precambrian rocks in Sweden has been treated by Lidmar-Bergström in a series of papers (from 1982 and "summarised" in Lidmar-Bergström 1996 and Lidmar-Bergström et al., 1997). She identified three paleo-denudation surfaces and associated in situ weathering and soil formations (weathering mantle or saprolite): the sub-Cambrian (flat), the sub-Jurassic (undulating hilly relief) and the sub-Cretaceous denudation surface (hilly relief), respectively.

The sub-Jurassic and sub-Cretaceous denudation surfaces are typical etch surfaces, that is bedrock surfaces formed by subsurface differential weathering that acts selectively regarding bedrock type, state of deformation in the bedrock and local geomorphologic setting (Migon´and Lidmar-Bergström, 2001). Two types of saprolites have been distinguished in southern Sweden (Lidmar-Bergström et al., 1997):

- Clay- and silt-rich saprolite or mature saprolite.
- Grus saprolite (gravelly) or immature saprolite.

Due to inhomogenities in the rock (e.g. fractures) differential and incomplete weathering of the rock may result in rounded edges of blocks and where more progressed weathering occur it will give relict, generally rounded blocks (core-stones) embedded in saprolite.

Twidale (2002) pointed out that "the worlds landscapes were not formed at the Earth´s surface, but at the base of the regolith". This implies that the weathering is active on bedrock surfaces covered by a permeable cover and not on exposed fresh rock, i.e. weathering occurs where fluids (groundwater) are located or moister is kept. The formation of the landforms occur in two steps:

- Subsurface weathering at regolith-rock contact.
- Removal of regolith (the products of disintegration and alteration of the rock).

"A stripped etch surface is often characterised by close correspondence between bedrock structures and surface relief" (Migon´and Lidmar-Bergström, 2001, cf. Johansson 2000). The glacial erosion had only a limited affect on the prevailing relief (Lidmar-Bergström et al., 1997 and references therein, Johansson 2000). Notable is that Hobbs (1912) clarified his concept of lineaments (Hobbs, 1903) by describing lineaments as "Significant lines of landscapes which reveal the hidden architecture of the rock basement".

4.2. Valleys and bedrock structures

Do kursu-valleys and fissure-valleys exploit fracture zones? The erosion of a canyon in igneous rocks in a cool humid or polar climate must presumably be related to the fractures in the bedrock, especially where there is no significant sign of ice polishing or striation. To develop a canyon the eroded tectonic structure must have two parallel and distinct boundaries with “insignificant” external damage zones (cf. Fig. 30). Is it appropriate to classify valleys exclusively according to their shape, and can valleys avoid fracture systems in their rock? It is argued below that the difference between fissure-valleys and kursu-valleys is partially related to the fracture pattern in their eroded bedrock.

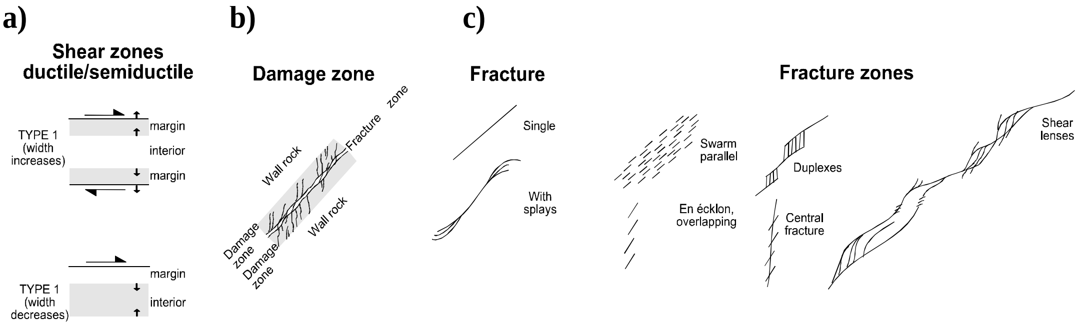

Figure 31. Geometry of deformation zones: a. deformation along shear zones (Means 1984 and 1995), b. wall rock damage zone at a shear zone or fracture zone, and c. deformation along fractures and fracture zones.

Means (1984, 1995) pointed out that Type I ductile to semi-ductile shear zones widen with time due to more resistant inner parts (work hardened) so that and deformation focuses along outer margins. Type II zones decrease in width with time as deformation narrows. Type III zones maintain constant width during deformation (Hull, 1988, Mitra, 1992). The walls of a valley eroded along steep to vertical examples of such zones, if the erosion of such structures is restrained to just removal of the actual shear zone, will be more or less parallel and show tectonic striations of the various types. Type I and III will show only minor deformation in the wall rock while the deformation decreases outward from Type II deformation zones. Tectonic and glacial grooves could be mixed especially if they are sub-horizontal.

Valleys, incisions or gorges may also be formed along brittle structures such as fracture zones. Once again, the morphology of the valley can be related to the internal fracture pattern in the zone and its wall rocks. Fracture patterns giving a well-defined zone with parallel borders can consist of a domain of clustered fractures parallel to the zone or a duplex formed at the overlap of two master fractures (Fig. 17). If the fracture zone has a pronounced central fracture and the density of the fractures decreases outward, then a V-type of valley can be expected. The profile of the valley will of course degrade with time. Renewed erosion along the valley may form a so-called “valley in valley” morphology.

4.2.1. Moredalen

4.2.1.1 The Moredalen kursu-valley and bedrock structures

Moredalen coincides with an extensive magnetic structure that winds slightly but is traceable for more than 70 km, 55 km on land. Structurally, it constitutes part of the southern border of an E-W trending mega-lens, Fig. 5, located in a 1.6 Ga old regional shear zone (Berthelsen, 1988). The magnetic structure correlated to Moredalen has a variable topographic expression
(Fig. 3, 4, 7 and 8):

- Moredalen itself, a 7 km long a canyon-like kursu-valley.
- An open and relatively narrow valley or gully extends c. 10 km west and east of Moredalen.
- About 10 km east of Moredalen, for c. 15 km, a poorly expressed trace curves through an area of low relief.
- A well-expressed W-E trending slope line c. 15 km long separates areas of variable relief and altitude north and south of Oskarshamn.

The topographical expression of the Moredalen lineament is interpreted as a function of the relative altitude of the ground surface on each side, offsets in altitude along it, and the local relief. However, there are also several other traces on the airborne magnetic map that run parallel to the Moredalen lineament although they are shorter and lack well-defined topographical signatures. Presumably, reactivation has been confined to the structure traceable as the Moredalen lineament. Furthermore, reactivation of the lineament was only partial as is indicated by, e.g. block faulting with variable throw along the zone. Intense fracturing occurs along Moredalen. The asymmetrical shape of this kursu-valley appears to be related to a change in dip of fractures across the valley; from sub-vertical along the northern side to steeply northerly dipping (c. 70°) at the southern side, a splay formed on the southern side of a sub-vertical tectonic zone dipping northward (?).

Is the shape of a valley related to the geometry of inhomogenities in the bedrock? This is evident in other examples of kursu-valleys. Two examples elsewhere are formed by selective erosion of 0.9 Ga old magnetic dolerite dykes like the N-S dyke crossing the middle of Moredalen. However, airborne magnetic measurements do not indicate any E-W trending magnetic intrusions along the Moredalen deformation zone. Nevertheless, other magnetic structures parallel to Moredalen are probably sheared and more or less oxidized magnetic (basic) rocks.

4.2.1.2 Block faulting - neotectonics

Four rock blocks form the plateau that the Moredalen kursu-valley truncates. The E-W trending Moredalen structure intersects a N-S trending c. 0.9 Ga old dolerite dyke. The top surface of the rock blocks may coincide or be close to the sub-Cambrian peneplain. If so, the offset in altitude between the bedrock blocks, using the sub-Cambrian peneplain as a datum surface,
indicates accumulated block faulting of Cambrian or younger age. The offsets

of these rock blocks are in the same range (up to 10-15 m) as faulting of Cambro-Ordovician strata in the Baltic Sea (Flodén, 1984).

The vertical offset between the northern part of the delta east of Moredalen and the southern part of the delta is interpreted to be late to post glacial, that is neotectonic and younger than 12 400 years old. The vertical offset occurs along the straight E-W tending channel across the delta, now used by the brook Morån. Furthermore, the channel is not perfectly in line with Moredalen as it is located c. 150 m south of the extrapolation of Moredalen. This offset is of the same sense and magnitude as the sideways shift along Moredalen proper. Notable is that there is no indication of displacement of the ground reworked by the river Emån sweeping along the south-eastern edge of the delta. A possible neotectonic distortion of the bedrock surface and sediments has been reported from an area c. 70 km south of Moredalen by Lagerbäck and Grånäs (1998).

Local block sliding has been observed in both Moredalen and Pukedalen. This type of feature has been interpreted to be formed by collapse (see section 4.3.2.3 below).

4.3. Kursu-valleys

4.3.1 The eroding agent

Many of the kursu-valleys are dry. It is noticeable that the water in kolk lakes or surge pools in many of the kursu-valleys is often fresh and cool (Lars Persson, Uppsala, personal comment 2000). The water represents groundwater flowing along the fracture zone along which the valley was formed.

It is argued by Olvmo (1989) that the canyon-like valley is melt water canyons. A closer look at the system of water transport associated glaciation is given below.

Sub-glacial water takes flows either along discrete systems (channels and tunnels) or in distributed systems (water film, linked networks at the base of the ice or pore-water flow in sub-glacial sediments). In this case the discrete systems are of interest and they are:

- Röhtlisberger channels (Röthisberger, 1972) – located in the ice.
- Nye channels (Nye, 1973) – incised into the substratum to the ice (bedrock, and sediments, consolidated and unconsolidated) and are in the order of some ten of metres to a few kilometres long and up to some ten metres wide.

Nye channels can be temporarily coupled with a superimposed Röthlisberger channel or vice versa. The frictional heat produced by the turbulent water melts the ice and the channel tends to close due to creep in the ice. The differential pressure caused by the ice load and the water pressure drives the ice creep. The melting of the ice and the ice-creep can balance each other and keep the channel open (Drewry, 1986). The transport of water along the channels is related to the hydraulic gradient. For equilibrium conditions most of the hydraulic gradient is related more to the slope of the ices surface than the gradient of the basal sediments or the bedrock surface (Ben and Evans, 1998). This implies that Rötlisberger channels can travel across highs and even up slopes. Nye channels imply that water flow and erosion of the ice are focused along the same route (Ben and Evans, 1998).

Tunnel valleys (cf. Grube 1979, 1983) are of larger magnitude than the Nye channels, up to hundreds of kilometres in length and up to several hundred metres deep. They have wide flat bottoms up to 4 km wide and may occur isolated or in an anastomosing or dendritic pattern covering extensive areas (Ben and Evans, 1998). These types of channels are known from several areas e.g. the North Sea (Wingfield, 1989, Ehlers and Wingfield, 1991), Denmark (Binzer and Stockmarr, 1985), northern Germany (Ehlers et al., 1984), and the Baltic Sea (Bjekéus et al., 1994, Monkevicius, 1999). Occasionally the tunnel channels are filled with glacial and non-glacial material leaving no morphological expression at the surface, e.g. North Germany (e.g. Ehlers, 1981, Ehlers and Linke, 1989), and they may overprint each other as in the North Sea (Ehlers and Wingfield, 1991). Tunnel valleys are of the same magnitude as the system of larger valleys, floored with glacial and post-glacial sediments, found inland above the highest post glacial shoreline in south-eastern Sweden (cf. western part of maps displayed in Fig. 3 and 4). However, tunnel valleys are not the subject of this paper but they are most likely poly-genetic and formed by poly-cyclic events. Perhaps some of them began as kursu-valleys? Binzer and Stockmarr (1985) and Bjerkéus et al. (1994) interpreted the tunnel valleys as pre-dating the last glaciation and to having formed along tectonic structures. Bjerkéus et al. (1994) and Monkevicius (1999) also stress that the valleys are restricted to easily eroded sedimentary rock.

Huuse and Lykke-Anderssen (2000) have made a map compilation and a review of Quaternary valleys (incisions) in north-west Europe, sea and land areas from Ireland to Poland. They presented a list of the main hypotheses proposed for the formation of incisions:

- Steady-state sub-glacial drainage of melt-water and groundwater driven by hydrostatic pressure gradients.
- Catastrophic melt water discharge (jökulhlaups).
- Glacial erosion.
- Erosion by rivers during glacioeustatic lowstand.
- Stacking of delta channels.
- Tidal scour.

Some diagnostic features of the incisions (over-deepened Quaternary valleys) are (for a complete list see Huuse and Lykke-Anderssen, 2000):

- Valleys are completely buried with sediment and they have no or insignificant topographical expressions, completely burred with sediments
- Valleys are incised to depths of more than 300 m below the present ground surface or the sea level
- Valleys can be traced for several tens of kilometres.

- Valleys generally begin and terminate abruptly.
- Longitudinal valleys show no consistent slope direction.
- Most deep valleys have relatively steep sides and flat bottoms.
- Valleys show significant over-deepening and contain internal ridges or sub-channels.
- Valleys post-date glaciotectonic structures in soft sediments.
- Deep valleys and eskers rarely co-exist, valleys are rare in areas where the substrate is consolidated while eskers are common and vice versa.

This implies that channels of glacial melt-water may not have a morphological expression where the soft sediment cover or regolith is thick.

The over-deepened Quaternary valleys or incisions may originate from the combination of three end-member erosion processes (Huuse and Lykke-Anderssen, 2000):

- Steady-state drainage of melt water.
- Catastrophic outburst of melt water (jökulhlaup).
- Glacial erosion.

Huuse and Lykke-Anderssen (2000) stated also that permeability variations in the substrate might produce sub-regional variations in the pattern of the incisions, while pre-existing rivers, faults are of local importance. This implies that transport of glacial melt water may find appropriate paths as bedrock valleys or gorges hidden below a moraine cover and may wash out saprolite and/or fault rocks in fracture zones. The refilling process typical for the incisions described above may only (?) take place in areas covered by water, e.g. below the highest post-glacial shore level.

In areas with hard rock as within the Fennoscandian Shield tunnel valleys are very rare and eskers indicates the sub-glacial flow system (Boulton and Hindmarch, 1987, Boulton et al. 2001).

4.3.2 Glacial water and erosion — the Moredalen and Pukedalen kursu-valleys

4.3.2.1 Moredalen — glacial water

There was structural control of the erosion responsible for Moredalen. The present water flowing along Moredalen in the brook Moreån is insignificant and cannot have eroded the valley or even affected its form. The delta east of Moredalen kursu-valley, the occurrence of rounded boulders and stones in the valley, and glaciofluvial deposits west of the valley, indicate that the water flow was once considerably greater than today. The surge pool at the eastern end of Moredalen also indicates fast flowing water. The bottom of the valley is flat, without waterfalls, and the drop is 9 and 8 metres per kilometre in the eastern and western part of the valley respectively. The altitude of the top surface of the delta is just above 100 m a.s.l. and located at the highest post-glacial shore level (c. 105 m a.s.l.). Washing of the moraine alongside the

kursu-valley is restrained to local narrow shoulders. This indicates that water flow, the Moredalen River, took place largely in the valley.
For a larger volume of water to flow through Moredalen the inland ice must have rapped a water supply. Either as a dam formed by residual ice or as a reservoir trapped below the ice sheet. The latter could have been located several kilometres north-west of Moredalen. The existence of an esker passing a few kilometres west of the Moredalen valley indicates that there was an open sub-glacial channel, at least during the supra-aquatic deposition of the esker. The other alternative, the existence of an ice-dammed lake should have caused reworking of the moraine in the area, an effect not looked for. However, low areas some kilometres north of Moredalen should have drained such a lake. If that pass was blocked and there was no precursor along the present Moredalen valley, lows at the middle of the Moredalen valley and a height in its eastern part should have affected the course of the escaping water. However, the esker east of the delta change from NE-SE to E-W to line up with Moredalen shows clearly that there must have been a path for melt-water along Moredalen within or below the ice.
In the case of Moredalen the moraines on either side of the valley indicate that the channel was roofed by ice and incised into bedrock. This requires that a bedrock channel already existed before the deposition of the delta to the east. Arguments for the existence of an early channel are:

- The existence of a topographical linear feature in the extension of the Moredalen kursu-valley, both to the east and west.
- The depression in the bedrock below the delta east of Moredalen kursu-valley as indicated by resistivity surveys and GPR.
- The esker which is traceable into Moredalen kursu-valley and located beneath the delta.
- The erosion of crossing structures, especially dolerite dykes (the depression in the middle of the valley and pockets in its eastern part).

The orientation of Nye channels generally aligns with the direction of ice transport. Moredalen is E-W, while the movement of the inland ice during its retreat was south-eastward or south-south-eastward as indicated by the ice striations and the larger eskers. The period when most Moredalen kursu-valley was covered by ice and the ice-front was to the east must have been short as the ice retreating at c. 125 to 300 m per year (Kristiansson, 1986).

A precursor to Moredalen is postulated; a lee-side cavity linkage forming an interconnected pass or short cut along an existing valley between two major sub-glacial floods west and east of Moredalen respectively. Such linkage was effective during the deposition of the c. 7 km long esker east of More-dalen, i.e. for a period of at least 25 to 50 years. This is based on the assumption that the eskers reflect the location of major sub-glacial floods and that their positions are relatively stable (Patrik Vidstrand, Göteborg, 1999, personal communication).

A proglacial formation of Moredalen is unlikely as it is formed at a high angle to the direction of ice transport and at a low angle to the ice front. Formation of Moredalen by overflow of an ice-dammed lake when forming the delta requires a precursor since otherwise the overflowing water would have found its way along lows offsetting from or crossing the present Moredalen. The topography west of Moredalen could have dammed a local ice lake if just a minor threshold at a major esker is blocked. However, it is possible that the last flooding was related to overflow of an ice-dammed lake along a channel that was already partially occupied by an esker.

4.3.2.2 Moredalen — glacial deposits

The esker clearly indicates that there was some sort of channel along Moredalen before the deposition of the delta to the east. The delta could have been deposited rapidly by a jökulhlaup or an outburst flood or both. Outburst flood deposits share such characteristics (Maizels, 1993 and 1997) as large-scale coarse-grained bed forms. If the flood eroded bedrock to deepen Moredalen and not just removed a sediment fill then some boulder or blocks should be expected. Such obstacles have not been found in the delta nor have traces of ice blocks. Gravel and boulders appear to be missing from the distal parts of the delta. Instead there are sandy cross-bedded layers (indicated by the ground-penetrating radar) and well-sorted fine-grained sand in the central distal parts of the delta. However, flooding along the valley must have ceased abruptly as the surge pool at the end of the valley has not been filled with sediments.

The location of the top surface of the delta more than 10 m above the valley bottom indicates pressurized or fast flowing water. However, the vertical drop from the western to the eastern part of the valley is c. 55 m. There is no need to add any pressure from an ice load.

Olvmo (1989) claims that the sediment in the delta could represent the rock removed when the Moredalen kursu-valley was formed. This assumption is based on the relative representation of different types of rock types in the sediments, the size of Moredalen and the volume of the delta. The delta is three times larger than the valley. Critical is the relative occurrence of reddish porphyritic rhyolite. However, this rock type is common and distributed over a large area. Furthermore, the cobbles and boulders are rounded and the foliated darkish granodiorite, which is the wall rock along the major part of Moredalen, does not dominate the granitoid clasts. To relate the sediments to the rock type along Moredalen they must have a unique charter.

An analysis of 83 clasts in the esker west of Moredalen resulted in c. 14 % dark-reddish porphyritic rhyolite, 65 % granites and 6 % greenstones. Only the quantity of porphyries is low compared to the sediments in the delta east of Moredalen. Additionally, the delta may have been larger at some stage. Meltwater flooding from the former embayment (Fig. 3) may have eroded the delta. The south-eastern side of the delta was eroded as the land rose due to post-glacial uplift and the embayment was transformed into a lake with an outflow along the delta. Buried channels along the north-eastern side of the delta are indicated by the GPR measurements. Detailed sedimentary studies of the delta would help to interpret whether or not the delta represents a catastrophic event, e.g. a jökulhlaup.

Glaciofluvial sediments located between a NW-SE trending esker and the western end of Moredalen indicate that water from the sub-glacial flood depositing the esker can have flowed through Moredalen.

4.3.2.3 Pukedalen — glacial water

The structural control of Pukedalen is not as obvious as for Moredalen. Exposed rocks along the valley sides are gently formed with rounded corners along the steeper western sides and large mildly undulation planes along the gently inclined eastern side. The valley is drainaged south-eastward by minor brook and this might have affected the shape of the valley. The bottom of the valley is relatively flat, with minor depressions resulting in a step-like form, without waterfall though, and the drop is 6 metres per kilometre.

Exposed rock away from Pukedalen also expresses rounded forms. The existence of apparently local rounded boulders and grus-weathered fractures indicate that a roundness of outcrops and boulders is related to deep weathering. Glacial erosion (ice + water) has presumably accentuated the shapes by removing weathered rock components. However, the existence of eskers at some distance along the extension of Pukedalen; in northwest Virserumsåsen and in south-east Kåremoåsen/Kåsebergaåsen. The separation of the two eskers is c. 30 km and notable is a general lack of glaci-fluvial deposits within an area of 30 by 30 km. This occurs within a region where the separation of eskers is in the order of 5 to 10 km.

4.3.2.4 Pukedalen — glacial deposits

Pukedalen formed as Moredalen a narrow creek during the time for the highest shore level. There is no delta formed in connection to Pukedalen and there is no glaci-fluvial deposit in the valley. There are local boulder beds (presumably washed glacial deposits) located along the sides of the valley and there also well rounded blocks of the same rock type as the local bedrock.

There are some local rock slides, composed of large blocks, along the steep western side of Pukedalen and one other rock slide along the steep major east-west trending block boundary just east of the mouth of Pukedalen. This rock-slide could have been caused by post glacial gravity collapses. However, the shape of the rockslide outside Pukedalen indicates that at least some of them were formed by differential stress (caused by a combination of groundwater pressure in the ice, ice load and drag) below the ice at a late stage of the glaciation (cf. Boulton et al. 2001) and that later block sliding has been insignificant (initial slide/glide was arrested by the ice inside the ice – a very high angle of repose and “more or less intact” top surface). Rockslides have been observed in other canyons in the region (eg. Skurugata canyon, close to Eksjö). In Moredalen a tabular major block was moved a few decimetres into the valley. In other valleys the block slides have collapsed and nearly filled up the valleys.

4.4. Location of Kursu-type of valleys and cyclic erosion

Why is there a change in the relief of south-eastern Sweden going towards the Baltic Sea across the highest post-glacial shoreline? There are at least two answers:

- Firstly, the relief is smoother where lows are filled by glacial and post-glacial sediment. This is analogous to the buried tunnel-valleys in northern Germany, see above. Areas with well-exposed bedrock rocks near the coast (cf. NE parts of Fig. 3 and 4), have well developed fracture patterns.
- Secondly, open large-scale depressions and valleys formed in the bedrock surface are exceptional.

Notable is the existence of a c. 50 m deep and 7 km long NE-SW trending submarine canyon eroded in Precambrian granites and gneisses and located off the Swedish coast (in the archipelago in the NE part of Fig. 3 and 4).
It is noticeable that the water level of the Baltic Ice Lake – Baltic Sea was no lower than now within this area (Svensson, 1989) and wave-washed (?) moraines along the Baltic shore and sandbanks are found at a depth of 13 m (Kjellin et al., 1986).
Furthermore, buried glacial incisions are found in Mesozoic sediments in central parts and the south-eastern parts of the Baltic Sea (Bjerkéus et al., 1994, Monkevicius, 1999).

However, it is obvious that the whole of the sub-Cambrian peneplain was not simultaneously exposed to erosion. The bedrock was beneath some kilometres of platform sedimentary rocks, e.g. quartzites, limestones and banded sedimentary rocks. This sedimentary cover was first eroded at the crest of the South Swedish Dome (Lidmar-Bergström, 1993 and 1994). The palaeo-landscape may well have resembled the present canyon-landscape of the western USA.

A canyon-like valley was formed at Moredalen. Rate of down-cutting of these valleys was presumably in the same range as for canyons in Utah, USA, i.e. up to c. 0.5 m per thousand years (Hamilton, 1995). In time the valleys became wider and were also incised into the underlying bedrock. As the regional gradient was low, erosion was most impressive in the upper part of the eastern flank of the South Swedish Dome. The system of open valleys and lows in the western part of the map area, Fig. 3 and 4, indicate a drainage system formed when the ground surface tilted south-eastward, not eastward as today and during the latest glaciation. Still, the sub-Cambrian peneplain can be traced up to the summit of the dome (Lidmar-Bergström et al., 1999).

A Permian to Late Cretaceous denudation surface developed in the southern part of the South Swedish Dome (Lidmar-Bergström, 1993). This was an etch-surface cut down into the Precambrian gneiss and granite core of the dome. Bedrock forms similar to roche mountoneés are found within this exhumed and etched sub-Cretaceous surface (Lidmar-Bergström, 1997). If these rounded weathering forms could be preserved then so could valleys. The shape of the valley could be a result of the weathering, erosion agent and the structural pattern in the bedrock. Finally, a flat landscape does not imply that the bedrock surface is completely flat – filled fracture valleys may be common.

5. Summary and conclusions

Airborne magnetic data show that Moredalen follows one of several accentuated E-W trending magnetic structures parallel to the contact between two rock complexes. A contact indicated by deep refraction seismics. Of these structures, Moredalen has the most extreme topographic expression. The shape of Moredalen with an aligned esker indicates that the valley predated the last glaciation. Resistivity and GPR surveys helped determine the depth to bedrock and investigate sedimentary sequences in the canyon and its delta. It is clear that Moredalen continues eastward beneath the delta. The formation of the canyon-like feature along Moredalen by a single catastrophic event is highly unlikely.

The following development of the Moredalen kursu-valley is proposed. A precursor was more or less filled with debris that fell from its rock walls before the glaciation and then by glacial sediments. The ice emphasised the asymmetry of the valley by plucking the northern (lee) side. The depth of the precursor was presumably down to the hollows in the northern wall at the eastern end of Moredalen, that is c. 8 m above the present floor of the valley. This implies that the precursor was more than 20 m deep. Fracture planes define the deeper levels on both sides of the valley. Terraces of fragmented rock also indicate a cyclic development of the valley. The precursor of the Moredalen kursu-valley was a water gap oriented at a high angle to ice-flow direction.

The effect of the Baltic Ice Lake on the distribution of the ice is not known. However, the delta east of Moredalen is deposited in the narrow mouth of a shallow bay, extending 50 km in NNW-SSE and up to 20 km wide, into which at least two major glacial floods discharged. The delta must have been rapidly deposited in a narrow passage through which melt-water flowed. The top of the delta displays a palaeo-channel system which is undisturbed by either flowing ice or by subsequent activity. However, the sides of the delta have been eroded by flowing water. The fact that the delta covers the esker and that only minor parts of the bedrock shoulders to Moredalen are washed may indicate that Moredalen was covered by ice when the delta was deposited. However, no sign of a channel west of Moredalen is known. Sub-glacial water flow occurred for a relatively long period of time, at least 30 to 50 years, and then ceased abruptly as the ice front left the area.

The deformation history of the E-W trending and steeply dipping structure along which Moredalen developed is long:

- Formation of a regional E-W trending shears zone across south-eastern Sweden at c. 1.6 Ga. Moredalen occurs along a southern branch of this zone.
- Differential block faulting along Moredalen, presumably during both deposition of Palaeozoic platform sediments and the Mesozoic uplift of the South Swedish Dome.

A vertical offset of the delta east of Moredalen (southern side down c. 3.5 m) indicates neotectonic displacement along the E-W trending Moredalen fault.

Neither the depth of Moredalen nor the character of the deformation zone along which the valley was formed is known. Such information requires drilling.

Kursu-valleys are like trenches cut into the bedrock and offer good exposures. The bedrock can be characterized in great detail. This information can be used as a reference when constructing three-dimensional geological and structural models of particular sites within the region and for planning borehole investigations. Especially if the site is poorly exposed, as usual for most coastal areas in south-eastern Sweden, especially south of Oskarshamn (Fig. 1).

The study of Moredalen and Pukedalen emphasizes that a general knowledge about the formation of the present landforms will improve structural mapping performed by, e.g. remote sensing. Topographical relief may within a short distance change rapidly from one regional rock block to the next. A devote of topographical relief (input data) does not necessary imply a sudden change in density of structures in the bedrock but may well reflect the time the rock has been exposure to erosion. Furthermore, a flat landscape does not have to imply that the bedrock is flat, buried bedrock valleys may occur. Sub-glacial rivers of coming glaciation may well find their way along such bedrock valleys.

The present study has significant implication for bedrock isolation of radioactive waste since it proves that significant displacement may occur along structures with unexpected orientations and locations (cf. Slunga et al., 1984, Slunga and Nordgren, 1990).

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Strålsäkerhetsmyndigheten
Swedish Radiation Safety Authority

SE-171 16 Stockholm
Solna strandväg 96

Tel: +46 8 799 40 00
Fax: +46 8 799 40 10

E-mail: registrator@ssm.se
Web: stralsakerhetsmyndigheten.se