A reconstruction of subglacial processes based on a classification of erosional forms at Ramsvikslandet, SW Sweden

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Master Thesis
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Cover Picture: Faceted roches moutonnées. Photo: author. The photos in this thesis are taken by the author, if not stated otherwise.

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Abstract: Ramsvikslandet on the Swedish west coast is characterized by exposed bedrock hills with numerous glacial erosional forms. Previous research in the area has mostly focused on individual forms and their relation to the larger forms, such as roches moutonnées. This study takes a more large-scale perspective and aims to reconstruct the subglacial processes based on the erosional forms and their distribution in the study area. In the reconstruction, both the distribution of the forms in relation to other forms and their distribution in relation to the large bedrock hills is considered. The erosional forms found in the area are: striae, crescentic fractures, crescentic gouges, pits, triangular pits, concoidal fractures, troughs, sickle troughs, comma forms, bowls, potholes, channels, roches moutonnées, faceted roches moutonnées (roches moutonnées with a sloping lee side), whalebacks and rock steps. The results show that the proximal slopes of bedrock hills are mostly dominated by roches moutonnées, striae, crescentic fractures, crescentic gouges and p-forms. Abrasion has been the dominating process here and the effective normal pressure on contact areas has been high. The subglacial water was concentrated in channels and had a high trough-flow velocity. The top surfaces and distal slopes of the rock hills are most commonly plucked, with rock steps descending in the direction of ice movement. Melt-water erosion was negligible since the water flowed in a linked-cavity system with low through-flow velocities. Large cavities made the ice-bed contact area smaller than on the stoss side. Towards the end of the bedrock hills the roches moutonnées normally reappear, these can be either classic roches moutonnées, but also faceted roches moutonnées and whalebacks. Crescentic fractures, crescentic gouges and p-forms also reappear again, indicating a channelized melt-water flow and abrasion as the dominating process with high contact forces and large contact areas. The abundance of p-forms and the many signs of cavities in the study area show that there has been much water under the ice. Ramsvikslandet is also part of a larger area that almost lacks till, beginning at the Vänern basin and widening towards the coast. This leads to the speculation that the water could have originated in the Vänern basin and with a continuous output could have created a fast-flowing ice stream towards the coast, sweeping away the till material and supplying the water for the formation of the p-forms.

Keywords: glacial erosion, subglacial processes, p-forms, roches moutonnées, Bohuslän

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En rekonstruktion av subglaciala processer baserad på en klassifikation av erosionsformer på Ramsvikslandet, mellersta Bohuslän

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Sammanfattning: Stora inlandsisar har vid upprepade tillfällen täckt Sveriges yta och den senast inlandsisen började dra sig tillbaka från Bohusläns kust för ca 15 000 år sedan. En inlandsis rör sig sakta framåt över underlaget och när den gör så kan stenar infrusna i isens botten skrapa berggrunden och bilda långa räfflor, flisor kan brytas loss ur berget och stora block kan också frysa fast i isen och transporteras bort. Räfflorna och de lösbrutna bitarna utgör erosionsformer, men erosionsformer kan också bildas av strömmande vatten under isen och har då mjuka, kurviga former (dessa former kallas plastiska former, eller kort p-former). Olika erosionsformer bildas under olika fysikaliska och hydrologiska förhållanden och de kan således användas för att rekonstruera de förhållanden som rådde och de processer som verkade under inlandsisen.

Det undersökta området är Ramsvikslandet som utgör södra hälften av Sotenhalvön, strax norr om Smögen i mellersta Bohuslän. Landskapet karaktäriseras av berghöjder utan jordtäcke med leriga sediment nere i dalarna. Studieområdet kartlades och delades in i åtta kategorier, här kallade glacialmorfologiska områden, beroende på vilka erosionsformer som fanns i området och var i topografin det låg. Syftet med undersökningen var att identifiera vilka erosionsformer som finns på Ramsvikslandet och med hjälp av dessa rekonstruera de processer som verkade under isen under senaste nedisningen.

De erosionsformer som identifierades på studielokalen var: räfflor, parabelriss, skärbrott, gropar, triangelbrott, musselbrott, glacialtråg, sichelwannen, kommaformer, kolkar, jättegrytor, kanaler, rundhällar, rundhällar med lutande läfacett, valryggsformade rundhällar och trappstegsformade hällar.

En analys gjordes av de glacialmorfologiska områdenas fördelning på studielokalen och en modell konstruerades över den mest sannolika sekvensen av glacialmorfologiska områden på berghöjderna. På de flesta berghöjdernas proximalsidor (sidan som vetter mot det håll varifrån isen kommer) hittas rundhällar, räfflor, parabelriss, skärbrott, gropar och p-former. De fyra förstnämnda formerna visar på att isen har haft god kontakt med underlaget över en stor yta och friktionen mellan is och underlag var hög. Isen har slipat bergsidan, ungefär som ett sandpapper kan slipa trä, och bildat rundhällarnas runda former och släta ytor. Isen har emellertid också brutit loss mindre bitar. P-formerna vittnar om att vatten har runnit under isen och har bildat kanaler i de lägre delarna av topografin. På grund av tryckskillnader kan vattnet pressas uppför berghöjderna och kanaler är vanliga på proximalsidorna. På toppen och på de svagt sluttande läsidorna av berghöjderna har isen oftast plockat med sig stora block av berget och skapat sluttningar som liknar trappor med låga, breda trappsteg. Avsaknaden av p-former tyder på att vattnet har haft en låg hastighet och därför inte kunnat erodera ner i berget. Vattnet har runnit i ett system av kaviteter (hålrum) som länkas samman av smala kanaler och stora delar av isen har därför inte haft direktkontakt med underlaget. Mot kanten av berghöjderna kommer vanligtvis de rundade formerna tillbaka; detta kan vara antingen vanliga rundhällar eller rundhällar med en sluttande facettyta och valryggsformade rundhällar. Parabelriss, skärbrott, gropar och p-former dyker också upp igen. Detta tyder på att isen åter har kontakt med stora delar av underlaget och att friktionen är hög. Vattnet har hög hastighet och strömmar i kanaler.

P-formerna och de vattenfyllda hålrummen visar att det fanns mycket vatten under isen när formerna bildades. Ramsvikslandet ligger också inom ett större område där det finns mycket lite lösa sediment. Detta sedimentfattiga område utgår från Vänernsänkan och breddas mot kusten, vilket föder en idé om att sedimenten kan ha blivit bortsköljda av vatten från Vänernsänkan, som kan ha utgjort en sjö under isen. Detta vatten kan också ha bildat p-formerna när det skyddande jordtäcket väl sköljts bort.

Nyckelord: glacial erosion, subglaciala processer, p-former, rundhällar, Bohuslän

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1 Introduction

1.1 Background

The landscape of Bohuslän (Bohus County) in SW Sweden is characterised by its exposed bedrock hills. Erosional forms, such as potholes and roches moutonnées, are common in the county. The erosional forms are formed subglacially under different physical and hydrological conditions and can thus be used to reconstruct the former subglacial environment. This opportunity, however, has not been much used and little research is done on erosional forms in bedrock today. Most research is from before the 1970's, even from the beginning of the 20th century. The research has also mostly focused on individual forms and their relation to larger forms, such as roches moutonnées. Some research also focuses on a regional perspective, but studies on a local scale are uncommon.

The Swedish scientists Erik Ljungner (1930) and Gunnar Johnsson (1956) have done comprehensive studies of erosional forms on the Swedish west coast and Ragnar Dahl (1965) has done the same from the coast of northern Norway. Ljungner (1930), Johnsson (1956) and Dahl (1965) all focus on individual forms and their relation to the small-scale topography. However, the Canadian scientist John Shaw (2002) and his colleagues have in the past 20 years been investigating large erosional forms in Canada. The erosional forms, together with other features such as drumlin fields and boulder lags, are put into a regional context and are explained by the drainage of enormous subglacial lakes over large areas (Kor *et al.*, 1991; Shaw, 2002). There are also Swedish studies from locations situated very close to the study area, focusing on weathering and its effect on the formation of the landscape (Olvmo *et al.*, 1999; Johansson *et al.*, 2001a; Johansson *et al.*, 2001b; Olvmo & Johansson, 2002). Lidmar-Bergström (1986; 1987) argues that some erosional forms are formed mainly by pre-Quaternary weathering.

1.2 Aim

As mentioned, the erosional forms are formed subglacially under different physical and hydrological conditions and can be used to reconstruct former subglacial environments. This can be done at a micro scale in the interpretation of single erosional forms, but also at a larger scale where the appearance of certain forms as well as their distribution in relation to each other and to the topography is taken into account. The focus of this thesis is on the larger-scale perspective, but the large-scale picture builds heavily on the small-scale pictures, which means that these too have to be studied.

The first aim of the study was to identify different erosional forms present in the study area and to compile a picture catalogue showing the variations of these different forms. The interpretation of the formation of the individual erosional forms has been based on literature.

The second and main aim of the study was to reconstruct the former subglacial conditions in the study area. The reconstruction should include the processes that were active in the study area and where these processes acted, such as on stoss or lee sides. The basis for this large-scale reconstruction is the different erosional forms and their relations to each other and the topography. Other features that could aid in the reconstruction of the subglacial environment were also to be studied, including boulder accumulations and the roundness of the clasts, the direction of striae and rock walls.

2 Study area

2.1 Description of the study area

The study area constitutes most of Ramsvikslandet nature reserve, which is situated at the southern half of the Sotenäset peninsula in Bohuslän, SW Sweden (Fig. 1). The size of the nature reserve is approximately 5 km^2 and about 4 km^2 of these have been studied; the most eastern and southern parts have been omitted.

The landscape at Ramsvikslandet is characterised by exposed bedrock hills with joint valleys or flat, sediment-covered areas in between. The bedrock hills are mostly ridge or plateaux shaped and they often have sides rising almost vertically for up to tens of metres. The relative relief in the area is usually around 20-30 m, but is close to 60 m at Sote Bonde and only a few metres in the south of the study area (Fig. 1b). The highest point is between 60 and 65 m. The flat areas in between the bedrock rises represent hollows filled with Late Weichselian deposits of marine silt and clay which can be up to 40 m thick (Johansson *et al.*, 2001b). Numerous wetlands and small lakes are also located between the ridges and plateaux. The joint valleys are aligned in the three main directions N-S, NNE-SSW and WNW-ESE (Olvmo *et al.*, 1999; Johansson *et al.*, 2001a; Johansson *et al.*, 2001b).

Northern Bohuslän and southern Dalsland are referred to as a bedrock and clay area (Johansson, 1982). Exposed bedrock constitutes 55% and clay 20% of the area. Only ten percent of northern Bohuslän and southern Dalsland have till cover (Johansson, 1982). In this area the till cover increases towards the east, but even here the till cover is usually thinner than 0.3 m. Deposits of till are usually found in the lee of bedrock hills or along the sides of valleys (Johansson, 1982). Below the highest shoreline, the till has usually been reworked by waves. Accumulations of blocks along the sides of hills can be a sign of till that has been reworked by waves for a longer time period (Johansson, 1982).

2.2 Geological history

The Bohus granite is coarse-grained and reddish in colour and is the dominating bedrock in the coastal areas of Bohuslän. It intruded older gneisses 920 million years ago and is now part of the Precambrian

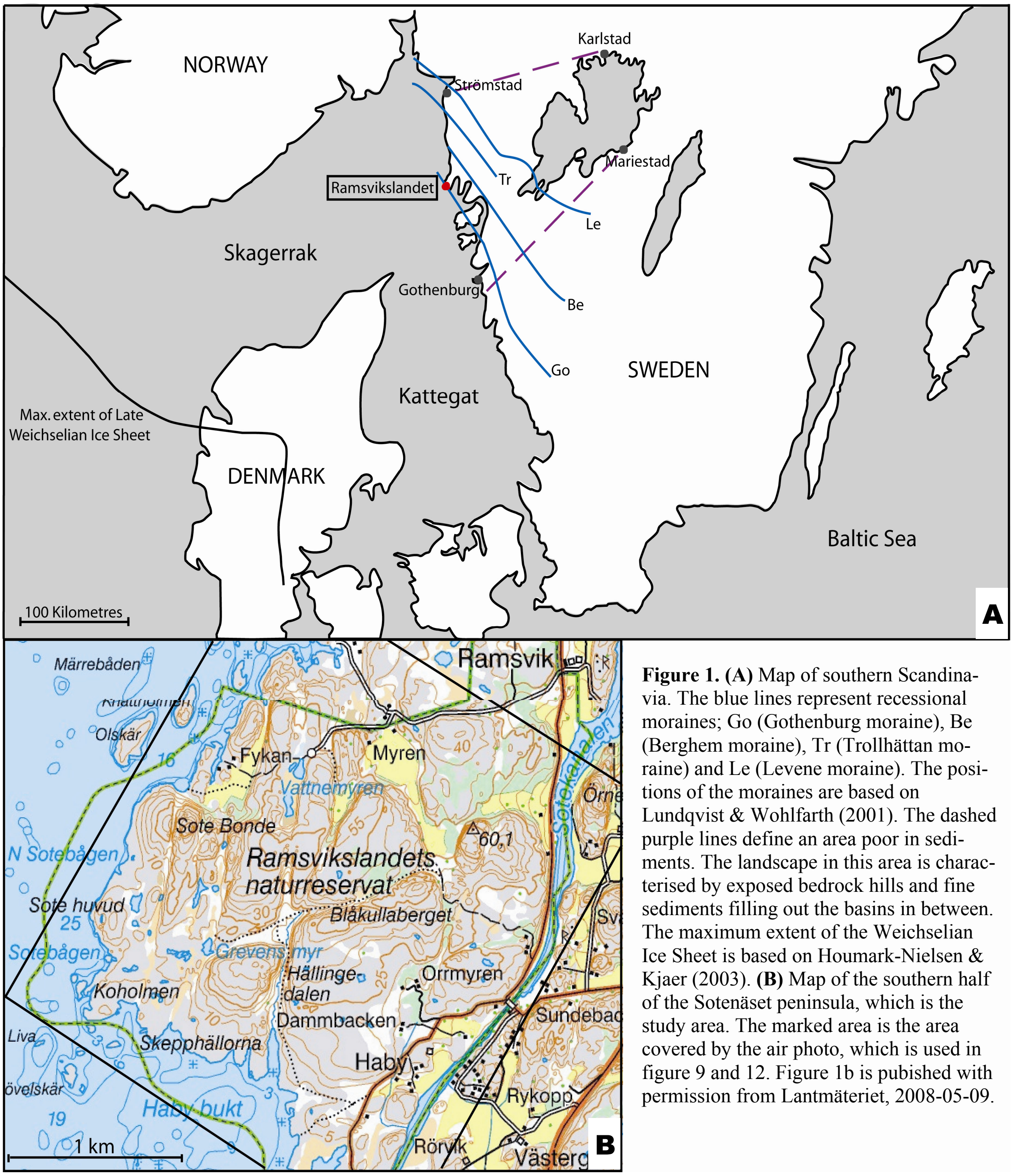


Figure 1. (A) Map of southern Scandinavia. The blue lines represent recessional moraines; Go (Gothenburg moraine), Be (Berghem moraine), Tr (Trollhättan moraine) and Le (Levene moraine). The positions of the moraines are based on Lundqvist & Wohlfarth (2001). The dashed purple lines define an area poor in sediments. The landscape in this area is characterised by exposed bedrock hills and fine sediments filling out the basins in between. The maximum extent of the Weichselian Ice Sheet is based on Houmark-Nielsen & Kjaer (2003). **(B)** Map of the southern half of the Sotenäset peninsula, which is the study area. The marked area is the area covered by the air photo, which is used in figure 9 and 12. Figure 1b is pubished with permission from Lantmäteriet, 2008-05-09.

crystalline basement (Johansson *et al*., 2001a). The crystalline basement was eroded to a nearly horizontal plane – a peneplain – in Precambrian time (Fredén, 2002). During the Palaeozoic and Late Mesozoic the peneplain was transgressed and shallow marine sediments were deposited on top of the crystalline bedrock (Fredén, 2002). Today, Palaeozoic and Mesozoic rocks can be found 50 km off shore in Skagerrak, where there is a continuous sequence (Johansson *et al*., 2001a). However, on land and for some 50 km off shore all cover-rocks have been eroded. The erosion took place when the area was uplifted and exposed to erosion in Mesozoic time and in the Neogene (Olvmo *et al*., 1999). Repeated glaciations during the Quaternary have also contributed to the erosion. The crystalline bedrock underlying Paleozoic sediments is flat, whereas the bedrock underlying Mesozoic sediments has a high relief which can extend to 200 m in extreme cases (Olvmo *et al*., 1999). Substantial deep-weathering must therefore have taken place during the Mesozoic when the climate was warm and humid (Olvmo *et al*., 1999; Fredén, 2002). The weathering was primarily concentrated to joints and fracture zones which created the joint valleys and the hilly landscape

(Olvmo & Johansson, 2002). Further weathering may have taken place during the re-exposure in the Neogene (Olvmo & Johansson, 2002). Glacial erosion during the Quaternary may have helped to remove the saprolites covering the granite hills and has also altered the shape of the hills by abrasion and quarrying (Olvmo *et al.*, 1999).

The landscape of exposed granite ridges and plateaux at Ramsvikslandet has been interpreted as a remnant Sub-Mesozoic etch-surface, which has later been modified by glacial erosion (Olvmo *et al.*, 1999). This interpretation is based on the facts that the Precambrian bedrock is covered by Mesozoic rocks further off-shore and that the weathering product kaolinitic clay has been found in joints in the area. The landscape is also similar to other Mesozoic weathered landscapes in southernmost Sweden (Olvmo *et al.*, 1999).

2.3 Glacial history

The last ice-flow direction was from the ENE (Johansson *et al.*, 2001a). The easterly direction prevailed from the last glacial maximum until the deglaciation (Kleman *et al.*, 1997). Two additional ice-flow directions have been observed on the west coast: one from the north and one from NW (Johansson *et al.*, 2001a). According to Kleman *et al* (1997) the northern direction is from a stadial 65,000 years ago and the NW direction from Early Weichselian, about 110,000 years ago.

The Sotenäset peninsula is situated more than 200 km inside the maximum extent of the Weichselian Ice Sheet, which extended south into Denmark and the North Sea to the west (Fig. 1a). The highest shoreline in the study area is at approximately 155 m (Fredén, 2002). Following the ice-retreat from the area the landscape was, therefore, an archipelago where the highest bedrock hills formed islands. The ice sheet retreated mainly through calving in water depth of about 100-150 m (Johansson, 1982), whereas on the islands the ice wasted away through melting at the surface. Extensive deposition of glaciomarine sediments occurred when the ice had left the area, from around 15.400-14.500 years ago (Fredén, 2002). Several recessional moraines are found in SW Sweden. These were formed at times when the ice came to a standstill during short periods of colder climate (Johansson, 1982). Through dating of these recessional moraines a time reconstruction of the deglaciation in SW Sweden can be made. The Gothenburg moraine terminates just SE of the Sotenäset peninsula and has been radiocarbon dated to an age of between 15.400 and 14.500 cal yr BP (Lundqvist & Wohlfarth, 2001). The Berghem, Trollhättan and Levene moraines are situated NE of the Gothenburg moraine and constitute the continuation of the deglaciation. The moraines have been dated to 14.400-14.200 cal yr BP, ≥14.100 cal yr BP and >13.400 cal yr BP, respectively (Lundqvist & Wohlfarth, 2001).

3 Methods and material

Before going into the field the entire study area was studied on aerial photographs. In the field, the different types of erosional forms were identified and photographed to be used in the picture catalogue. Five profiles were done in the study area. The profiles were laid approximately in the ice-flow direction. The exposed bedrock areas along the profiles were classified into eight categories, hereafter called glacial morphological areas. Each glacial morphological area represents a different type of bedrock landscape, i.e. areas with different erosional forms, or with the same forms but in different positions in the topography. The entire study area was also surveyed, but in less detail, and the exposed bedrock areas were classified using the same eight glacial morphological areas. The rock walls of some joint valleys were also studied for p-forms and signs of glacial erosion.

A survey was made of the boulder accumulations in the study area and these were classified according to the dominating roundness of the particles. As accumulations of boulders are numerous in the area and many of these are minor ones, only the larger accumulations discernible in aerial photographs were examined. Areas with scattered boulders on the bedrock surface were also omitted.

The directions of striae were measured in the study area to reconstruct former ice-flow directions. Striae of deviating directions are common. Efforts were made to avoid measuring the striae deflected by the small-scale topography. Where there were deviating striae, which were not caused by the ice's topographic deviation, the span of the directions was noted, but only the mean value of these spans is shown in Fig. 9.

All information was mapped on an enlarged aerial photo image using a map in the scale 1:12,500, a compass and a hand computer with a GPS tracking device.

4 Erosional forms

Erosional forms can be classified according to size into small-scale, intermediate-scale and large-scale erosional forms, also called micro, meso and macro forms (Benn & Evans, 1998). A specific type of form can vary enormously in size, but small-scale forms are normally less than 1 m in size, intermediate-scale forms between 1 m and 1 km and large-scale over 1 km (Bennett & Glasser, 1996). Smaller erosional forms occur on larger ones, creating several forms superimposed on one another. At Ramsvikslandet the small and intermediate-scale erosional forms are glacial (Olvmo *et al.*, 1999; Johansson *et al.*, 2001a). The large-scale forms are pre-glacial, but have a glacial overprint (Olvmo *et al.*, 1999). The shape of the bedrock ridges is determined by the bedrock and its jointing, as well as the extensive weathering in pre-Quaternary time. The sheeting pattern show that the

Figure 2. (A) Striae on stoss side cross-cutting finer striae on the lee-side facet. Two crescentic gouges on the stoss side. **(B)** Short striae in different directions. **(C)** Coarse striae on the stoss side of a roche moutonnée. **(D)** Striae inside p-forms. The striae inside the p-forms are finer than those on the rest of the stoss side. The arrows indicate the ice-flow direction.

topography once consisted of symmetrical dome-shaped hills (Johansson *et al*., 2001a). However, glacial forms are superimposed on the bedrock hills and have sometimes altered their profiles due to glacial plucking on distal slopes (Olvmo *et al*., 1999).

Each erosional form is described based on a literature review and it is followed by a description of the forms found in the study area, which is based on my own observations.

4.1 Small-scale erosional forms

4.1.1 Striae

A striation (sw. isräffla) is a thin scratch in the bedrock. It is normally only a few millimetres deep, but can be several metres long (Glasser & Bennett, 2004). There are, however, striae which are considerably larger. Laverdiére *et al.* (1985) classify a striation according to width and make a distinction between striae (≤5 mm) and small grooves (5-100 mm).

Striae are generally orientated parallel to the ice-flow over the bed and are therefore good indicators of former ice-flow directions (Glasser & Bennett, 2004). Several ice-advances over an area can produce cross-cutting striae, although older striae often are eroded by later ice advances (Glasser & Bennett, 2004). Since striae are parallel to the movements of the basal part of the ice they will deviate from the main flow direction if the basal ice does so due to deflection by local topography (Johnsson, 1956). Plastic ice can deviate from the main ice-flow direction with up to 90° and produce striae which closely follow the topography (Johnsson, 1956).

In the study area, there are fine, normal and coarse striae (Fig. 2). The coarse striae can also be referred to as small grooves. Striae are ubiquitous at the study site and are found in most places on the bedrock and in many different positions: on the stoss sides of rock bumps, on flat surfaces, on distal slopes, on lee-side facets, on rock walls, in open joints and inside p-forms (depressions into the bedrock). Coarse striae, or small grooves, are predominantly found on small-scale stoss sides (Fig. 2c). Note that small-scale stoss sides do not have to be positioned on the proximal slope of the hill. Fine striae are found inside p-forms (Fig. 2d). Normal striae are found in all positions mentioned above except in some p-forms where only fine striae are found. Short, fine striae with an en echelon pattern have been found on sloping lee-side facets (Fig. 2a). Striae which closely follow the topography and deviate around obstacles have been observed, as well as short striae going in different directions (2b). All striae are best preserved along the coastline and become more weathered further inland.

4.1.2 Crescentic fractures

Crescentic fractures (sw. parabelriss) are thin, slightly curved fractures orientated transverse to the ice-flow direction with the convex side of the fracture turned up-ice and the concave side pointing down-ice (Fig. 3a-c) (Ljungner, 1930; Johnsson, 1956). The orientation of single fractures is not always completely at right angle to ice-flow, but can deviate with up to 45° (Johnsson, 1956). The fractures can extend for decimetres into the bedrock. Johnsson (1956) has observed fractures that reached 30 cm into the rock. The size of crescentic fractures can vary from a few centimetres to 3-4 m in width (Johnsson, 1956).

Crescentic fractures are common in the study area. The fractures are mainly found on the stoss sides of rock bumps, but are also found on near-horizontal surfaces and on the side of rock bumps on surfaces that can be almost vertical (Fig. 3a-c). The form normally occur several together in a series or in a row. The size of the crescentic fractures at Ramsvikslandet is from a few centimetres to approximately 1.2 m.

4.1.3 Crescentic gouges

A crescentic gouge (sw. skärbrott; ger. sichelbruch) is a fracture in the shape of a crescent (Fig. 3d-g). The form is orientated transverse to ice-flow, but opposite to the crescentic fractures the crescentic gouge has its convex side pointing down-ice and its concave side pointing up-ice (Ljungner, 1930). The crescentic gouge has a proximal side, named the principal fracture, dipping into the bed in the ice-flow direction and a steep distal edge, the secondary fracture, resulting in the shape of a wedge (Fig. 3d) (Dreimanis, 1953). Just as the crescentic fractures, the orientation of single crescentic gouges can deviate up to 45° from the ice-flow direction (Johnsson, 1956). The size of crescentic gouges can vary from a few centimetres up to ca 1.5 m (Johnsson, 1956).

Crescentic gouges are common at Ramsvikslandet. The form is usually found on the stoss sides of rock bumps, but also on their sides, as well as on other ice-abraded surfaces (Fig. 3d-g). Crescentic gouges usually occur in rows or in pairs, but can also be found as single fractures. Forms up to about 0.8 m in size have been found.

4.1.4 Pits

A pit (sw. grop) is a small depression into the bedrock with a rough inner surface (Fig. 4a-b). Sharp & Shaw (1989) have observed pits in Canada. However, these pits have smooth edges and do therefore not fully fit the description of the pits found in the study area. The pits have a diameter of a few millimetres to some centimetres; the small pits are found on flat, lightly striated surfaces whereas the larger pits are located on smooth but irregular surfaces (Sharp & Shaw, 1989).

The pits in the study area are oval, nearly circular and irregular in shape. They are normally 0.5-2 cm deep and approximately a few cm to 1 dm long, but they can be larger. One pit has been found that is 6 cm deep and 50 cm long. Pits are most common on stoss sides in connection with striae or small grooves, but they are also found on lee-side facets and have also been observed in the transition from a stoss side to a sloping lee-side facet (Fig. 4a-b).

4.1.5 Triangular pits

A triangular pit (sw. triangelbrott) is a triangular depression bounded on each side by a joint (Fig. 4c-d) (Johnsson, 1956). The edges of the pits are sharp, where they have not been weathered or abraded. The size of triangular pits varies from a decimetre to over a metre (Johnsson, 1956).

At Ramsvikslandet triangular pits are found on the stoss sides of rock bumps (Fig. 4d). The forms are usually 1-3 dm large and have sharp edges.

4.1.6 P-forms

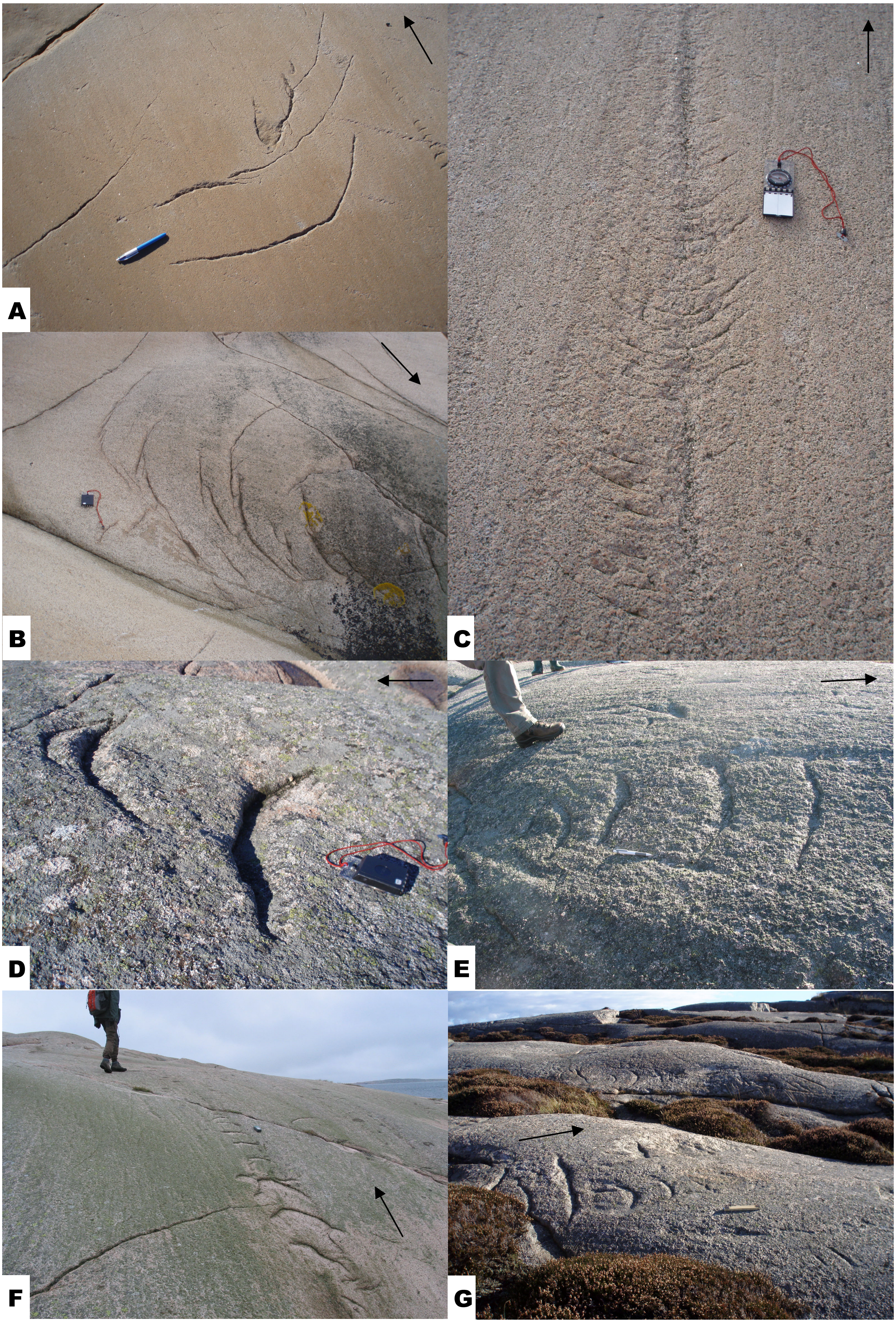
P-form is the collective term for a variety of different forms that have some common characteristics. P-forms are smooth depressions into the bed of different shapes and sizes. Dahl (1965) describes them as having "sharp edges and a beautifully curved course".

The name p-form was introduced by Dahl (1965) and stand for plastically sculpted form. The name means to describe the smooth and curved appearance of the forms. Kor *et al.* (1991) associate the name with an ice scoured origin and instead proposed the name s-form as a neutral name in terms of formation. I will, however, use the term p-form as I do not see the name as an indication of a glacially abraded origin and since p-form is also the most widely used name.

The p-forms found at Ramsvikslandet are concoidal fractures, sickle troughs, comma forms, oval, almond and irregular troughs, bowls, potholes, channels and cavettos (Figs. 5-7). P-forms occur in the lower parts of the detailed topography. However, they do occur on high locations, as on the top of bedrock hills, but then in the lower parts between the rock bumps. The exception is some troughs which occasionally can be found on top of low roches moutonnées. The p-forms are generally most well-preserved along the coast and become more weathered further inland. The insides of p-forms are either smooth or finely striated and these striae can be both long and parallel (Gjessing, 1967). The striae have puzzled scientists and different theories have been suggested to explain their formation inside p-forms.

4.1.6.1 Concoidal fractures

A concoidal fracture (sw. musselbrott; ger. musselbruch) is a shallow depression into the bedrock (Fig. 5a-b). Its up-ice side is curved with the convex side of the curvature turned up-ice and the down ice side of the form is diffuse and merges with the bedrock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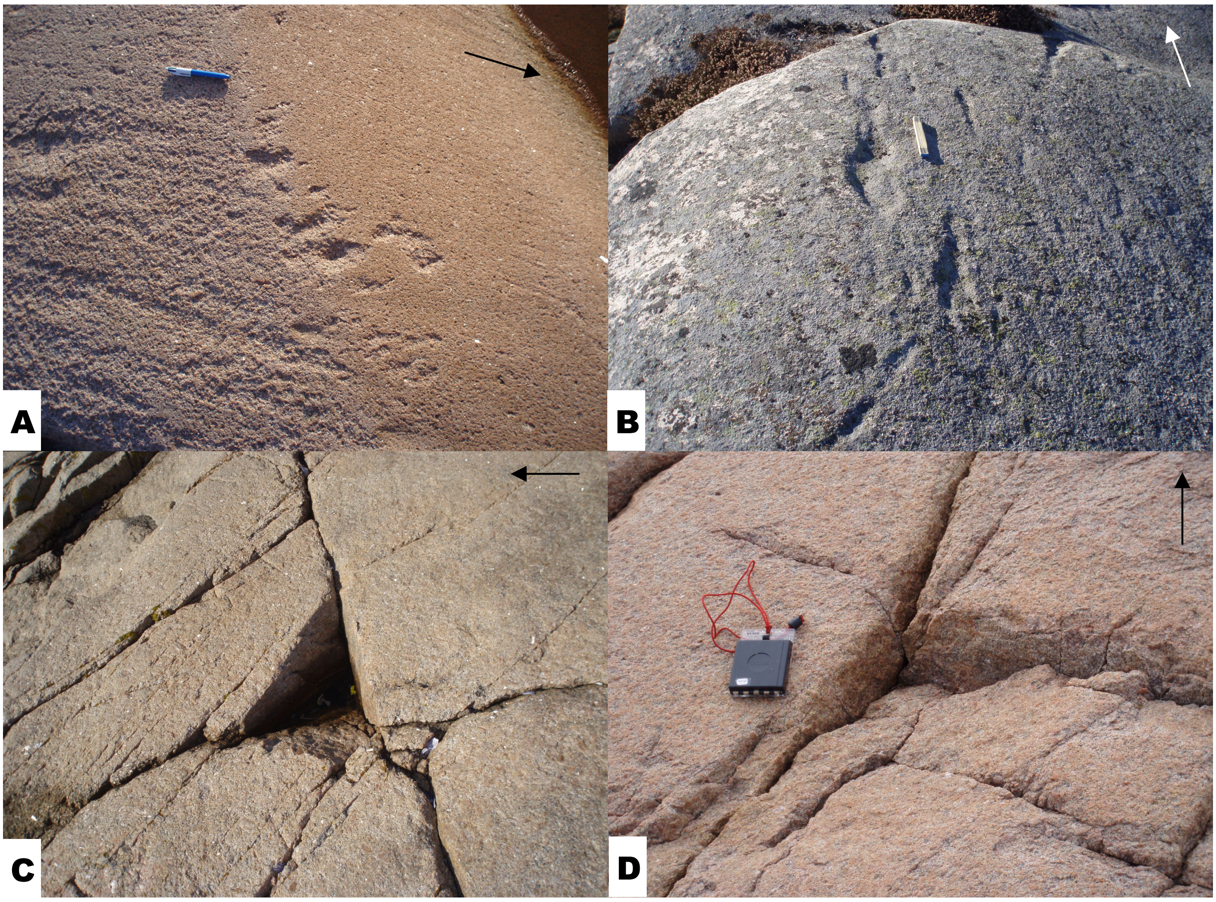


Figure 4. (A) Pits at the transition between a stoss and lee side **(B)** Large pits on the stoss side of a roche moutonnée. **(C)** Triangular pit in the shape of a prism; bounded by three joints. The photo is from Rossö, Strömstad kommun, northern Bohuslän. **(D)** Triangular pit situated on a very well-jointed roche moutonnée. The arrows indicate the ice-flow direction.

(Ljungner, 1930). The inside of the form can be anything from rough to smoothly polished and can also be striated (Johnsson, 1956).

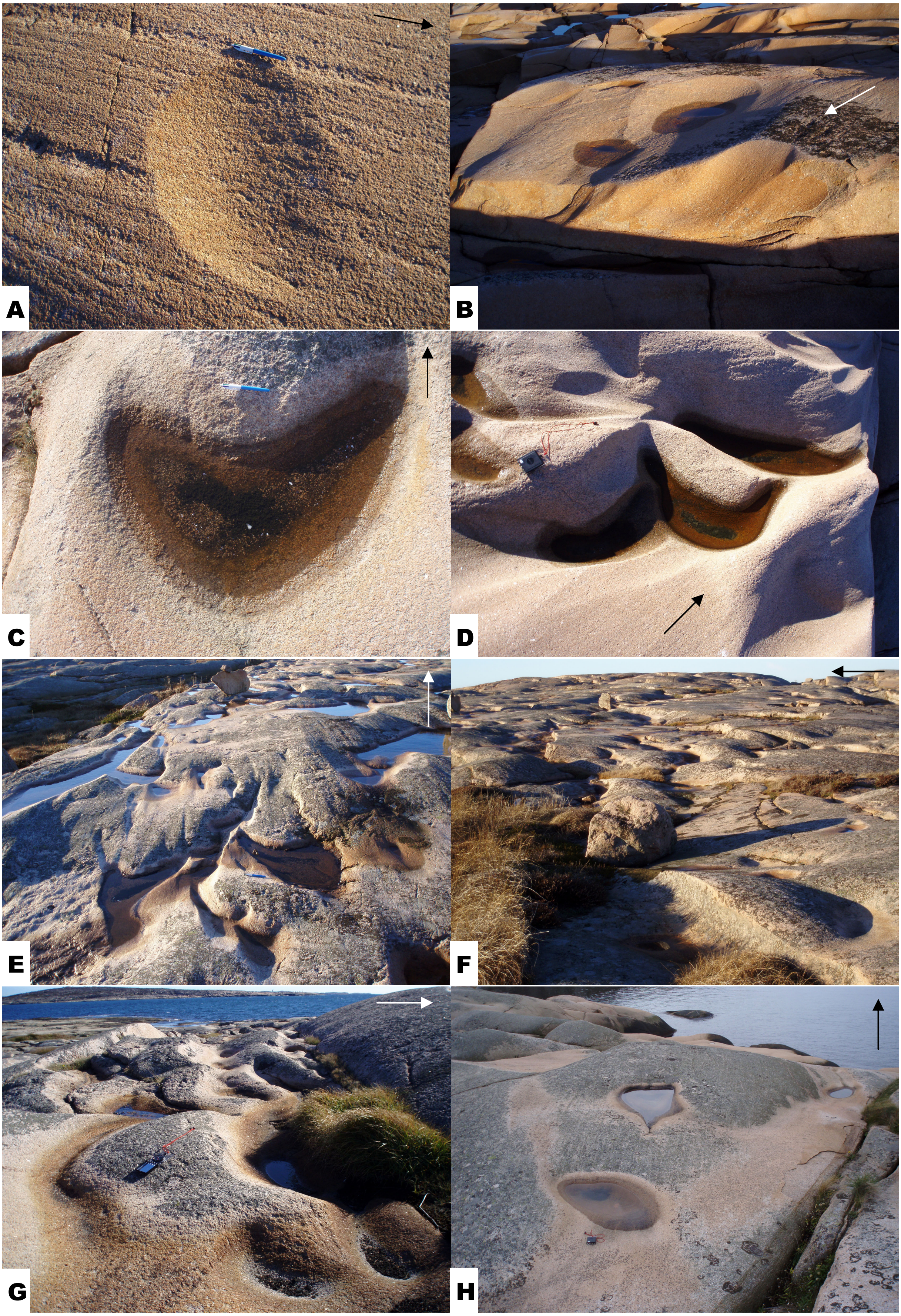
Concoidal fractures are common in the Koholmen area in the SW corner of the study site, but their distribution in the rest of the study area is unknown. They often occur at lee-side edges where they can be of importance in the formation of lee-side facets (Fig. 5b) (Johnsson, 1956). They can also be found on lee sides and flatter ice-abraded surfaces (Fig. 5a). All concoidal fractures found in the study area were smooth with striae and sometimes pits inside.

Ljungner (1930) and Johnsson (1956) consider the form a fracture, thereof Ljungner's name musselbruch. The smooth appearance is thought to have been acquired later from ice abrasion, but the inside of the form may, as mentioned earlier, also be rough if the abrasion has been incomplete (Johnsson, 1956).

4.1.6.2 Sickle troughs and comma forms

A sickle trough (sw. skärtråg; ger. sichelwanne) is a sickle-shaped or bean-shaped depression with the two ends, called horns, pointing down-ice (Fig. 5c-g) (Ljungner, 1930; Kor *et al*., 1991). A comma form is a sickle trough with only one horn (Fig. 5e-g). The insides of sickle troughs and comma forms can be either smooth or finely striated. Sickle troughs and comma forms are oriented transverse to the ice-flow direction (Kor *et al*., 1991). The forms vary in size from a few decimetres to many tens of metres in width (Kor *et al*., 1991; Kor & Cowell, 1998). The typical location of a sickle trough or comma form is at the base of a roche

Left: Figure 3. (A) Crescentic fractures on a fairly flat surface. **(B)** Large crescentic fractures on a nearly horizontal wall. **(C)** A row of crescentic fractures on a stoss side. A coarse striation cuts across the fractures in approximately the same direction as the row of fractures. **(D)** Crescentic gouges. Note the primary fractures dipping gently into the bed and the steep secondary fractures. **(E)** A row of crescentic fractures and coarse striae on a stoss side. **(F)** A row of crescentic fractures on a stoss side. The lowermost fracture is off angle with the rest of the row; the second and third fracture from the bottom have had their up-ice side ripped up. **(G)** Crescentic gouges on the sides of roches moutonnées. The arrows indicate the ice-flow direction. Photos E and F by Lena Adrielsson.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moutonnée, sheet edge or other rock bump, on the upstream side (Fig. 5e-g) (Ljungner, 1930; Johnsson, 1956). Sickle troughs can also occur in depressions on stoss sides. They rarely occur on flat rock surfaces (Johnsson, 1956).

Sickle troughs and comma forms are common in the study area. The typical location of a sickle trough or comma form is at the base of a roche moutonnée or other rock bump, on the upstream side. Sickle troughs can also occur in depressions on stoss sides and occasionally on smooth stoss sides. The size of the sickle troughs and comma forms vary from about two decimetres to over one metre. The insides of the sickle troughs and comma forms are either smooth or finely striated.

4.1.6.3 Troughs

Trough (sw. glacialtråg) is the collective term for all troughs that are not sickle troughs or comma forms (Fig. 5g-h). They can be oval, triangular, almond-shaped or irregular in shape and are further subdivided according to these shapes (Johnsson, 1956). Triangular-shaped troughs are grouped together with the almond-shaped troughs. Almond-shaped troughs are also called spindles (Kor *et al*., 1991). Troughs may be striated on the inside.

Troughs are common in the study area and occur in many positions: on the upstream side of roches moutonnées, along sheet edges, on near-horizontal bedrock surfaces and on top of low roches moutonnées and low faceted roches moutonnées (Fig. 5g-h). The size varies from about one decimetre to approximately one metre. The insides of the troughs are either smooth or finely striated.

4.1.6.4 Bowls

A bowl (sw. kolk) is a small, smooth depression in the bedrock (Johnsson, 1956). There are no sharp boundary between troughs and bowls, nor between bowls and potholes (Johnsson, 1956). Bowls occur in areas where p-forms are abundant, such as along sheet edges and upstream of roches moutonnées and other rock bumps. Bowls may be striated on the inside. The sickle troughs in Fig. 5d are bowl-like).

Bowls occur sporadically at Ramsvikslandet in areas with many p-forms. Their insides are either smooth or finely striated.

4.1.6.5 Potholes

A pothole (sw. jättegryta) is a circular, deep depression into the bedrock (Fig. 6a-f) (Kor *et al*., 1991). The walls of the pothole are smooth and can have spiralling striae (Gjessing, 1967; Kor *et al*., 1991). The shape of the hole can also be oval or two or more potholes can be merged together, creating double or multi-potholes (Fig. 6c-d). Some potholes have an over-hanging wall and some are open, i.e. they are situated at the edge of a cliff and therefore only have one wall. The size of individual potholes can vary from a few decimetres to over five metres across, and from a decimetre to at least four metres deep (Dahl, 1965). Most potholes occur in connection with joints (Johnsson, 1956). Potholes usually occur in lee-side positions, often underneath a sharp drop in the topography. In a study by Johnsson (1956) 76% of the potholes were in a lee-side position.

Approximately 110 potholes were observed at the study site (a double pothole is counted as two). The diameter ranges from ca 0.2 to 2 m for single potholes and up to approximately 5 m for multi-potholes. Depth can be from a few decimetres to several metres. Most potholes occur in connection with joints and several also in connection with channels leading towards or between potholes (Fig. 6b,f). Well-rounded boulders are found in several potholes, but also angular ones are found (Fig. 6e). The vast majority of the potholes occur in two areas, or clusters (Fig. 12). Also, within these two areas the potholes often occur two or more just alongside each other. Between these two areas only four potholes, situated in three places, have been found.

4.1.6.6 Channels and cavettos

A channel (sw. kanal/ränna) is an elongate depression into the bed, much longer than it is wide (Fig. 7a-d) (Kor *et al*., 1991). A cavetto is like a channel, but eroded into a rock wall (Fig. 7d-f) (Kor *et al*., 1991). Channels and cavettos can be both straight and sinuous (Sharp & Shaw, 1989). The size of channels varies enormously, from about 1 dm to some tens of metres wide and up to thousands of metres long (Laverdiére *et al*., 1985; Benn & Evans, 1998). The inside of channels and cavettos may be striated (Benn & Evans, 1998). There are many different names for channels, such as large grooves (Laverdiére *et al*., 1985) and furrows (Kor *et al*., 1991); although furrows are not one channel, but a network of intertwining channels (Fig. 7b). Nye channels are channels that are of a definite melt-water origin (Benn & Evans, 1998).

Channels are common in the study area and are situated in the lower parts of the topography, such as around the base of roches moutonnées. Channels are common on proximal slopes of bedrock hills, although they are again situated in the lower parts on the rise.

Figure 5. (A) A concoidal fracture with striae inside and small pits close to the down-ice edge. **(B)** Concoidal fractures at a lee-side edge. **(C)** Bean-shaped sickle trough on the up-ice side of a small rock bump. **(D)** Well-defined sickle troughs which were formed up-ice of a sheet edge. **(E)** Sickle troughs and comma forms on the up-ice side of small rock bumps in a low-relief area. **(F)** The same area seen from the side. **(G)** Troughs, sickle troughs and comma forms in front of a rock bump. **(H)** Two troughs on top of a faceted roche moutonnée. The arrows indicate the ice-flow direction.

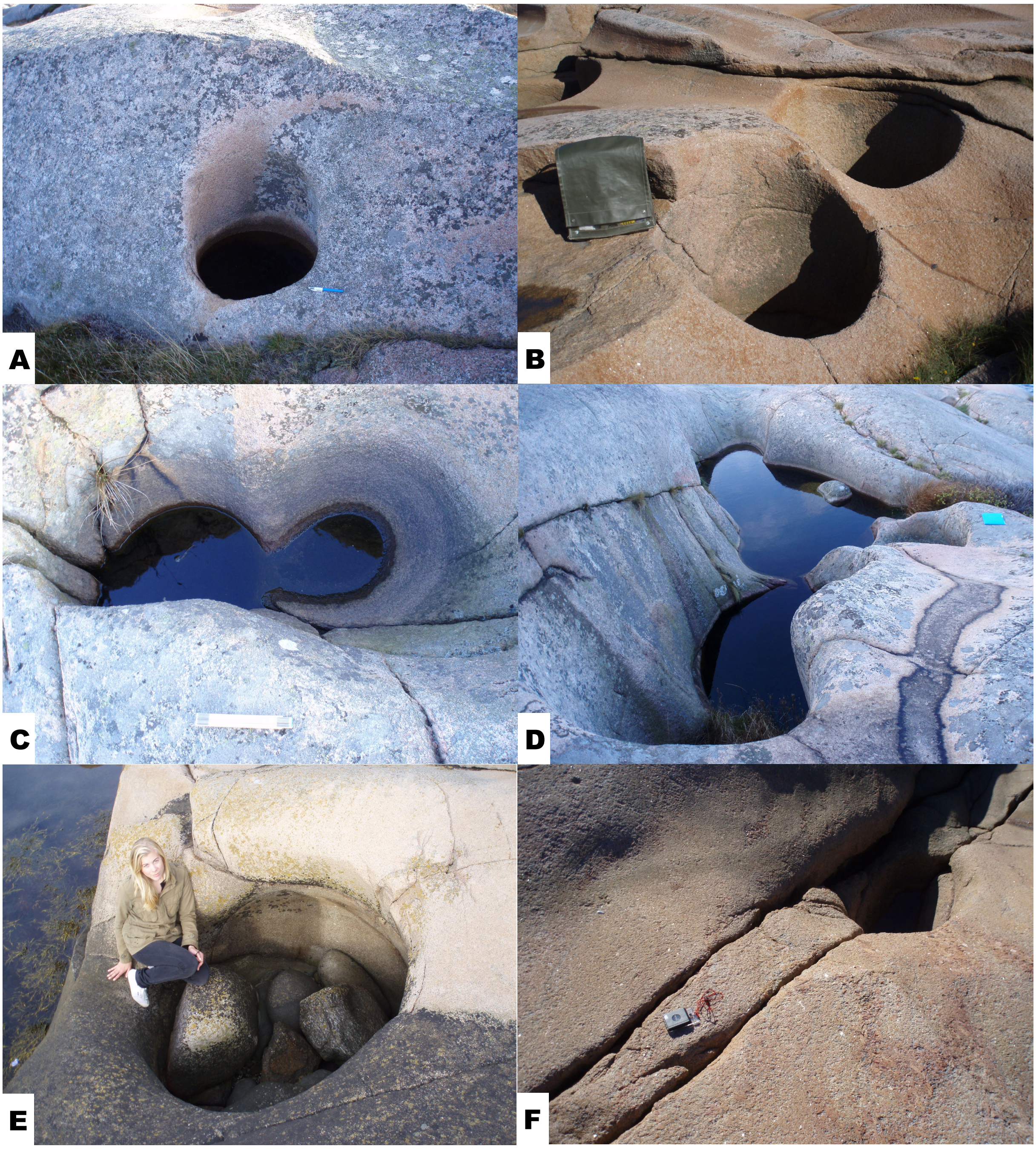


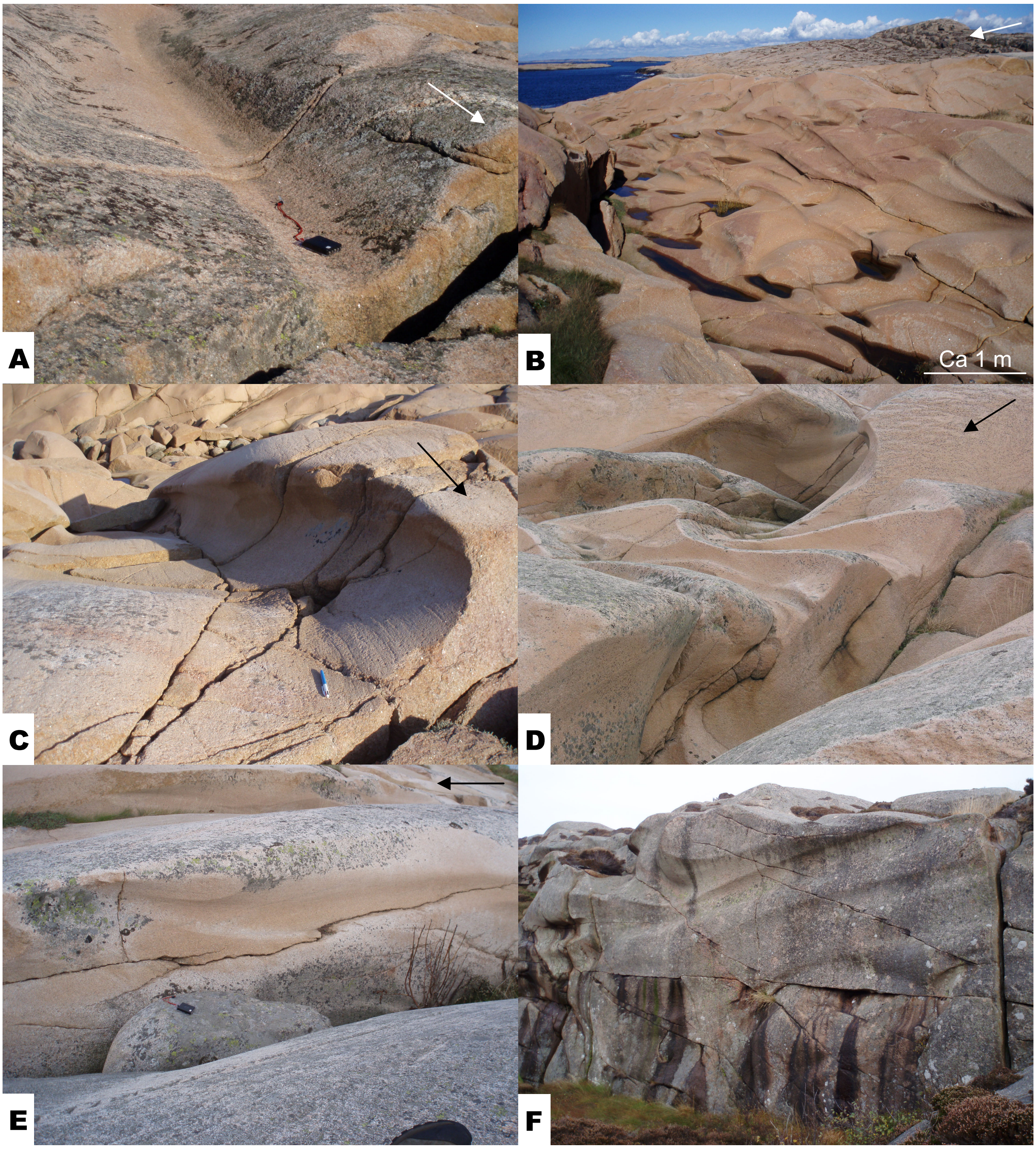
Figure 6. (A) Pothole formed into the wall of the rock. **(B)** A cluster of three potholes with a channel leading towards the potholes in the foreground. **(C)** A double pothole. **(D)** A multi-pothole. **(E) A** large pothole with rounded and angular boulders inside. **(F)** A small pothole in connection with joints.

Cavettos are common on the walls of bedrock rises. They are most common on walls striking in the last ice-flow direction, but are also common on walls up to 90 degrees from the last ice-flow direction. The size of the channels and cavettos vary from about 1 dm to approximately one metre in width and the length could be anything from around one metre to tenth of metres. The inside of channels and cavettos are often striated and can also be pitted.

4.2 Intermediate-scale erosional forms

4.2.1 Roches moutonnées

A roche moutonnée (sw. rundhäll) is an asymmetric bedrock bump with a rounded, abraded stoss side and a rough, steep lee side (Fig. 8a-b) (Benn & Evans, 1998). Roches moutonnées can be anything from 1 m up to several hundred metres long and over one hun-



Above: Figure 7. (A) A single channel. **(B)** A clustering of channels (furrows) at the lee side of a rock bump. **(C)** Channel with an over-hanging wall with striae visible inside. **(D)** Two open joints cut through the area with small cavettos visible inside them. There are also channel-like structures along the sheeting of the bedrock. **(E)** Close-up of an open joint with a small cavetto. **(F)** Cavettos on a rock wall; the wall is orientated perpendicular to ice flow. The wall is approximately 5 m high. The arrows indicate the ice-flow direction. Photo D by Lena Adrielsson.

dred metres high (Benn & Evans, 1998). The shape of roches moutonnées can differ a great deal due to the jointing of the bedrock. Smaller erosional forms can be superimposed on top of roches moutonnées (Benn & Evans, 1998).

The roches moutonnées at Ramsvikslandet vary a lot in both shape and size. There are roches moutonnées with both vertical and step-like lee sides. The size ranges from under a metre to approximately 5 m in height, and up to some tenth of metres in length. Smaller erosional forms superimposed on roches moutonnées are common. These are striae, grooves, crescentic fractures, crescentic gouges, pits, triangular pits, troughs, sickle troughs, comma forms, channels and cavettos. The roches moutonnées in their turn are superimposed on the larger bedrock hills.

4.2.2 Faceted roches moutonnées

A faceted roche moutonnée is a special type of roche moutonnée with a gently sloping lee side instead of the plucked lee side of the classical roche moutonnée (Fig. 8c-d). Faceted roches moutonnées are somewhat similar to the small unsymmetrical rocks (roches dissymétriques) described by Laverdiére *et al.* (1985). Johnsson (1956) describes the sloping lee sides, calling them lee-side facets, but he does not assign them to a specific landform.

The faceted roches moutonnées have a smooth, rounded stoss side and a gently sloping, usually smooth lee side (Fig. 8c-d). The transition from the rounded to the sloping part of the rock bump is sharp, creating the appearance of the lee side as a facet. The rounded part of the bump is often short compared to the sloping facet. The faceted roches moutonnées are usually less than 2 m in height, and less than 10 m long, but they can be larger. The facet can be striated; these striae are short and finer than the striae on the stoss side. The stoss sides are striated and may also have friction marks superimposed on them. Faceted roches moutonnées are common in the study area, but occur in specific areas, mainly on the distal slopes of bedrock hills.

4.2.3 Whalebacks

A whaleback is a symmetrical rock bump with a smooth, rounded stoss and lee side (Fig. 8e-f) (Benn & Evans, 1998). Whalebacks, like roches moutonnées, can vary in size and can be up to 1 km long. Smaller erosional forms, like striae, friction marks and p-forms, can also be superimposed on whalebacks (Benn & Evans, 1998).

Whalebacks occur sporadically in the study area, in the same areas as faceted roches moutonnées, on the distal slopes of bedrock hills. The whalebacks are striated and may have friction marks superimposed on them.

4.2.4 Rock steps

Rock steps are not described in the literature as a specific erosional form. Bennett & Glasser (1996) show examples from Scotland and Greenland in connection with their description of plucking. Olvmo *et al.* (1999) and Johansson *et al.* (2001a) discuss rock steps in a larger context as having reshaped bedrock hills by creating gently sloping, step-like distal slopes.

A rock step has a horizontal or gently down-ice sloping top surface that can be rough or striated and a vertical long quarried edge (Fig. 8g-h). They appear many after one another, which create the appearance of flat steps descending in the direction of ice-movement. The top surfaces are rough or striated, and striated top surfaces can also have a slightly rounded shape. The top surfaces can also change from rough near a vertical edge to striated a few metres further down-ice and remain striated until the next vertical step. The height of the vertical edges is determined by the sheet joints in the granite and ranges from a few centimetres to over 1 m, but the average height is ca 0.2-0.5 m.

5 Formation of erosional forms

The formation of erosional forms is described below in three sections, based on the dominating process of formation. Understanding the dominating processes is important not only for the formation of single erosional forms, but also later for the understanding of their distribution. The most important processes are therefore described before the descriptions of the individual forms.

5.1 Processes of erosion

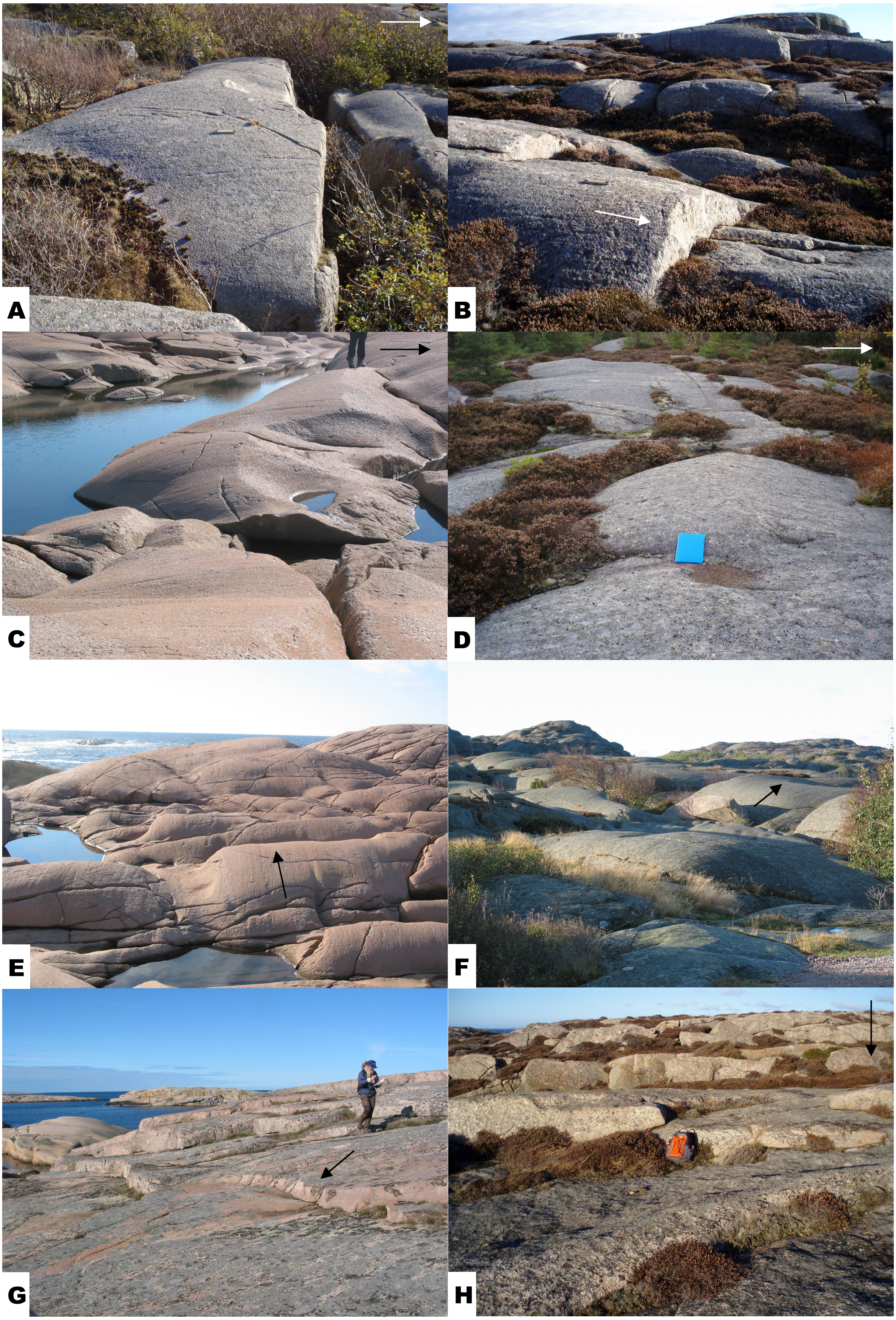
A pre-requisite for any erosion, either by ice or melt-water, is that the base of the ice is at the pressure melting point (Benn & Evans, 1998). If the base of the ice is below the pressure melting point, the base of the ice will be frozen to the bed, preventing sliding and also preventing the existence of melt-water at the ice-bed interface (Benn & Evans, 1998).

The base of an ice sheet sliding over an area can be either in direct contact with the bed, i.e. coupled, or be separated from the bed, i.e. decoupled (Benn & Evans, 1998). In the case where the base of an ice sheet is decoupled from the bed the cavities formed may be filled with water. Different erosional forms are formed in places where the ice is in direct contact with the bed and in places where the ice and bed are separated. Accordingly, the erosional forms can be used to reconstruct whether the ice has been coupled or decoupled from the bed.

5.1.1 Glacial abrasion

Abrasion is the wearing down of the bedrock by particles entrained in the ice. The three main factors controlling abrasion are (1) the contact pressure between the particles at the base of the ice and the bed, (2) the sliding velocity, and (3) the concentration and supply of new debris to the base of the ice (Bennett & Glasser, 1996). The contact pressure is likely the most important controlling factor of abrasion and there are three theories for which are the main factors controlling the contact pressure. The “friction model” has the effective normal pressure as the main controlling factor of abrasion (Bennett & Glasser, 1996). The effec-

Figure 8. (A) A small roche moutonnée. **(B)** Roches moutonnées at the edge of a bedrock hill. **(C)** Faceted roches moutonnées at the coast. **(D)** Faceted roches moutonnées further inland. **(E)** Small whalebacks. **(F)** Whalebacks. **(G)** Plucked, sloping area along the coast with rock steps a few dm high. **(H)** Plucked area with about 1 m high rock steps. The arrows indicate the ice-flow direction. Photos C, E, F and G by Lena Adrielsson.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tive normal pressure according to Bennett & Glasser (1996) is “the force per unit area imposed vertically by a glacier on its bed”. The effective normal pressure, in its turn, depends on (1) the thickness (weight) of the ice, and (2) the water pressure at the bed acting as an opposite force by helping to carry the weight of the ice (Bennett & Glasser, 1996; Benn & Evans, 1998). When the water pressure exceeds the ice pressure, a water-filled cavity is formed as the water carries the entire weight of the ice. When the ice pressure is greater there is ice-bed contact. An increased effective normal pressure increases the friction as the ice and bed are pressed harder together. The abrasion also increases with increased effective normal pressure up to a limit where the friction becomes so high that the dragging frictional force decreases the sliding velocity of the ice and thus also decreases abrasion (Bennett & Glasser, 1996). When the friction is too high the particle will stop and lodge against the bed, resulting in till deposition. The ”Hallet model”, on the other hand, says that the contact pressure is created as the ice around the particle melts, thus lowering it to the bed (Bennett & Glasser, 1996; Benn & Evans, 1998). The main controlling factor is the rate of melting, not the effective normal pressure, the rate of melting being mainly favoured by high ice-flow velocity and thick ice. The ”sandpaper model” is a variation of the ”friction model” in which water-filled cavities between the particles concentrates the effective normal pressure, and thus the abrasion, at the smaller area that is in direct contact with the bed (Benn & Evans, 1998).

The second main controlling factor of abrasion is sliding velocity. An increased sliding velocity increases abrasion by transporting more particles over the bed in a certain time (Bennett & Glasser, 1996). Debris content is the third controlling factor. Abrasion increases with increasing debris content at the base of the ice, but only up to a certain degree where the frictional forces become so large that the sliding velocity is reduced enough to decrease the abrasive wear. As the abrading particles are quickly worn down it is important for continued abrasion that new clasts are incorporated by plucking; particles can also be lowered to the bed by basal melting (Bennett & Glasser, 1996).

5.1.2 Glacial plucking

Glacial plucking (quarrying) is the removal of large pieces of rock from the bed. This involves loosening followed by transport (Benn & Evans, 1998). The loosening of blocks is facilitated if the bedrock is well-jointed. However, new cracks can develop and joints can widen if the bed is subjected to stress concentrations (Benn & Evans, 1998). Cavities cause stress variations over the bed and with a fluctuating water pressure these variations are magnified. As water pressure falls, the weight of the ice is transferred from the pressurized water to the bedrock on its side (Benn & Evans, 1998). Hence, lee-side cavities and a fluctuating water pressure causing repeated stress concentrations on the up-ice side of the cavities provides ideal conditions for plucking.

The loosened blocks are removed by freezing on to the base of the ice. The freezing occurs in low-pressure areas where the melting point is locally increased creating a cold patch (Bennett & Glasser, 1996). Cavities are typical low-pressure areas. Cavities with a high water pressure can also facilitate the removal of blocks by helping to lift the blocks and by pushing them forward. If a block has frozen to the ice over a cavity, a rising water pressure that becomes high enough to support the weight of the ice will lift the ice, and also the block frozen to it, and transport it forward (Bennett & Glasser, 1996).

A high sliding velocity favour cavity formation as the cavities cannot close as quickly when the ice is moving at a higher speed. A thin ice sheet also favours cavity formation, by reducing the normal pressure exerted by the weight of the ice and by making it easier for supra-glacial melt-water to reach the bed and causing water pressure fluctuations (Benn & Evans, 1998).

5.1.3 Melt-water erosion

Mechanical melt-water erosion may occur as either corrosive wear or cavitation erosion (Dahl, 1965). Corrosive wear (also suspended-load abrasion) is the result of mechanical erosion by minerogenic particles in the water when they hit the bedrock (Benn & Evans, 1998). Suspended material is required for melt-water erosion, since water in itself cannot erode bedrock. Cavitation erosion is when air bubbles contained in the water stream collapse in areas with higher water pressure and sending out chock waves as they do so (Sharp & Shaw, 1989). If the collapse is close to the bedrock surface erosion can take place. Cavitation erosion can only take place in rapidly streaming, turbulent water; where a water velocity of 8-10 m/s is required (Sharp & Shaw, 1989).

Melt-water underneath an ice sheet flows in accordance to the hydraulic potential, which is mainly controlled by the ice sheet’s surface slope, and to a lesser degree to the local bedrock topography (height above sea level) (Benn & Evans, 1998). The fact that the surface slope of the ice is the main determining factor of water flow and topography only secondary, means that water is able to flow uphill (Benn & Evans, 1998).

5.2 Formation of small-scale erosional forms

5.2.1 Ice-contact forms

Striae, crescentic fractures, crescentic gouges, pits and triangular pits are all formed where the ice is in direct contact with the bed and thus mostly occur in the higher parts of the detailed topography. Triangular pits are primarily related to quarrying, whereas the other four forms are related to glacial abrasion. Striae, crescentic fractures, crescentic gouges and pits (located on stoss sides) are formed when particles, which are frozen into the ice, move over the bed (Bennett &

Glasser, 1996; Benn & Evans, 1998). To create striae the effective normal pressure must be sufficiently high to keep the base of the ice in contact with the bed, but not high enough to cause the particles to lodge. In the formation of friction marks, the small-scale topography or effective normal pressure varies locally, which causes the particle to varyingly lift and be in contact with the bed (Bennett & Glasser, 1996). However, the effective normal pressure must be generally high since it requires a high contact pressure between the particle and the bed to cause fracturing. Brittle fracturing is caused by tensile stresses which are concentrated underneath the particle, promoting crack growth (Benn & Evans, 1998). Many small, continuously repeated fractures cause a striation, whereas larger particles, which are only temporarily in contact with the bed, cause crescentic fractures, crescentic gouges and probably also pits found on stoss sides (Benn & Evans, 1998). The pits probably represent a fracture where an irregular piece of the bedrock has been pried loose, as opposed to crescentic gouges where the missing piece is in the shape of a wedge. Triangular pits form where three tilted fracture planes interconnect to isolate a block in the shape of a pyramid or prism. When this block is quarried a triangular pit is formed (Johnsson, 1956). Triangular pits are thus primarily related to glacial plucking and the jointing of the bedrock, but the passing of large particles over the bed can cause the joints to grow and therefore make the plucking more efficient.

5.2.2 P-forms

There are three theories on the formation of p-forms, involving the three different scouring agents ice (Boulton, 1979), melt-water (Kor *et al*., 1991) and soaked deforming till (Gjessing, 1965). All theories state that p-forms form subglacially.

Erosion by turbulent melt-water has been proposed by several authors (Ljungner, 1930; Dahl, 1965; Kor *et al*., 1991) and is probably the most widely accepted theory for p-form formation (Rea *et al*., 2000). Both concentrated melt-water flows in channels and large scale catastrophic sheet floods underneath the ice sheet have been proposed (Dahl, 1965; Kor *et al*., 1991). The p-forms are explained to have been formed by vortices, rotating streams of turbulent water, which when they are loaded with suspended material can erode bedrock (Sharp & Shaw, 1989; Kor *et al*., 1991). Depending on whether the vortex impinges on the bedrock with a high or low angle, different p-forms are formed. A low angle creates a thinner longer p-form, such as an almond-shaped trough, whereas a higher angle makes the vortex spread out and creates a broader, but shorter p-form, such as a concoidal fracture (Kor *et al*., 1991). Sickle troughs are formed when the vortex split in two, referred to as flow separation, and potholes when the vortex impinges vertically on the bed. P-forms tend to occur in similar positions in the topography, for example they frequently occur on the up-, and down-ice side of roches moutonnées. Topography is therefore proposed to be of great importance for the formation of p-forms (Ljungner, 1930; Kor *et al*., 1991). Evidence in favour of a melt-water origin of p-forms includes their similarity to erosional forms formed in fluvial environments (Sharp & Shaw, 1989; Tinkler, 1993). Sharp upper rims are another characteristic typical of flow separation (Munro-Stasiuk *et al*., 2005). Striae are also missing in some p-forms and any p-forms formed by ice should undoubtedly be striated (Shaw, 1988; Sharp & Shaw, 1989). The striae found inside and in connection with p-forms are thought to post-date the p-forms themselves and may have formed either by ice abrasion or by scouring of a viscous substance, such as a soaked till (Sharp & Shaw, 1989; Munro-Stasiuk *et al*., 2005).

In a study on fluvial erosion, Whipple *et al*. (2000) state that cavitation erosion is more common in fluvial systems than previously thought. An obstacle, such as a moraine boulder, could possibly cause cavitation erosion to form a sickle trough by causing flow separation (Dahl, 1965). Indeed, cavitation experiments have produced erosional forms very similar to some common p-forms. Cavitation experiments have also shown that the erosion can be very rapid, even in hard materials like quartz (Dahl, 1965). In a dam spillway cavitation eroded 46 cm into concrete in just 23 hours (Dahl, 1965). Due to the rapidity to which cavitation is able to take place some researchers have claimed that some p-forms could have formed almost instantaneously (Dahl, 1965). Erosional forms produced by cavitation erosion have rough surfaces, implying that if p-forms are created by cavitation their surface must later have been smoothed by some process, such as suspended-load abrasion (Dahl, 1965). Erosional forms created by cavitation are, however, rapidly destroyed by erosion, so the smothering process cannot have been too severe. Favourable conditions for p-form formation by cavitation would be short, violent melt-water outbursts or melt-water flows with low minerogenic content which makes the effect of the suspended-load abrasion restricted.

Gjessing (1965) argues that a soaked till created both the p-forms and the striae. A soaked till should be viscous enough to have a laminar flow and create the long and parallel striae.

Plastic ice has also been proposed as a formative agent (Boulton, 1979). Observations by Boulton (1979) has shown that ice passing over an obstacle contains less debris than the ice passing on the side of the obstacle, thus the erosion will be larger on the sides of the obstacle and on its down-ice side. Rea *et al*. (2000) has found striated p-forms in front of a modern Norwegian glacier which are interpreted as being formed by debris-rich ice. Rea *et al*. (2000) stress that all p-forms are probably not formed by ice but show that this possibility should not be disregarded.

For the formation of the p-forms at Ramsvikslandet, it is my opinion that they are formed by melt-water erosion. There are numerous sharp edges and overhangs which are best explained by rotating vortices (Munro-Stasiuk *et al.*, 2005). Scouring by a soaked till is not an equally satisfactory explanation as it does not explain the sharp rims and similarity to fluvially sculptured features as well as the erosion of melt-water. The fact that there is no till in the study area is another problem to explain. If the p-forms were indeed formed by the erosion of a soaked till it is reasonable to assume that some till would have been deposited in the narrow valleys between the bedrock hills. Ice, like a soaked till, cannot explain features like the sharp edges and overhangs as well as melt-water (Munro-Stasiuk *et al.*, 2005). However, Rea *et al.* (2000) has observed that ice can deform plastically and fill out depressions, so it is possible that ice has contributed slightly to the p-forms by scouring. The striae are considered to be late ornamentations created by glacial abrasion during a period when the ice made contact to the bedrock and filled the p-forms (Munro-Stasiuk *et al.*, 2005; Rea *et al.*, 2000).

5.3 Formation of intermediate-scale erosional forms

Intermediate-scale forms are created by a combination of several erosional processes, which together produce the final form. Small-scale erosional forms are often formed on top of or around the intermediate-scale forms (Benn & Evans, 1998). The formation of smaller and larger erosional forms is not a question of the larger forms being formed first and the smaller forms being created later on top or around these. It is instead a simultaneous process where the small-scale forms and the processes forming them also contribute to creating the shape of the intermediate-scale forms.

5.3.1 Roches moutonnées, faceted roches moutonnées and whalebacks

There are two main theories for the formation of roches moutonnées, faceted roches moutonnées and whalebacks. Either they are formed by glacial erosion or by weathering (Lindström, 1988).

The glacial theory states that a roche moutonnée is formed by glacial erosion; abrasion on the stoss side and plucking on the lee side. The initial rock bump constitutes an obstacle to the ice-flow raising the effective normal pressure on its stoss side and thus increasing abrasion. On the lee side of the rock bump the ice is moving away, lowering the effective normal pressure and favours the formation of lee-side cavities and thus plucking (Benn & Evans, 1998). The granite in the study area is well-jointed and the joints are often weathered, which provides optimal conditions for plucking as the blocks are easily loosened.

Faceted roches moutonnées have an abraded stoss side, just as roches moutonnées, but differ on the lee side. The gently sloping facet may have been formed by plucking along a sloping joint (Johnsson, 1956) or by melt-water erosion, as water flows through a lee-side cavity. Faceted roches moutonnées are found on distal slopes, where the effective normal pressure is lower. P-forms are also abundant in connection with faceted roches moutonnées, indicating that melt-water could have been related to their formation. Johnsson (1956), however, thinks that the facet has been formed by plastic ice that has been deflected by the topography. He refers to the striae, but these could just as well have been formed later, as in the case of p-forms.

Whalebacks are formed by abrasion over the whole rock bump. This requires an ice that is plastic enough to deform around the rock bump, and/or an effective normal pressure that is sufficiently high to keep the ice in contact with the bed (Benn & Evans, 1998).

The weathering theory states that roches moutonnées, faceted roches moutonnées and whalebacks are mainly pre-glacial, formed by deep-weathering and later modified by glacial erosion (Lindström, 1988). The rounded form of the stoss side is formed by weathering of the rock bump and the plucked and faceted lee side is later formed by glacial quarrying and melt-water erosion, thus giving the weathered rock bump an asymmetric form (Lindström, 1988). The ice would also have abraded the stoss side to some degree, forming striae.

It is likely that the forms are a result of both weathering and glacial erosion. It is reasonable to think that the extensive weathering, preferentially concentrated to joints, would have created an undulating topography with the massive areas forming rock bumps and larger joints breaking up the higher areas. The rock bumps will then have formed obstacles in the ice-flow and glacial erosion could then reshape them into the final form.

5.3.2 Rock steps

Rock steps are formed as large blocks are quarried from the distal slope or the edge of a bedrock hill. The sheet joints in the granite are weak zones and the plucking therefore follow these joints (Bennett & Glasser, 1996). The fact that the joints in the study area were deeply weathered made quarrying of blocks easier as many were probably more or less loosened by weathering already when the ice overrode the area. The location of the rock steps on distal slopes, edges or top surfaces show that a low normal pressure and cavities are a pre-requisite for rock step formation. The areas between the cavities, where the ice has been coupled to the bed, have been abraded. The abraded areas are larger where the cavities have been small and opposite.

6 Survey of the area

The small-scale erosional forms have a systematic distribution in relation to the intermediate-scale erosional forms. The intermediate-scale erosional forms, and the related small-scale erosional forms, also have a systematic distribution in relation to the large-scale bedrock forms. The relationships between micro,

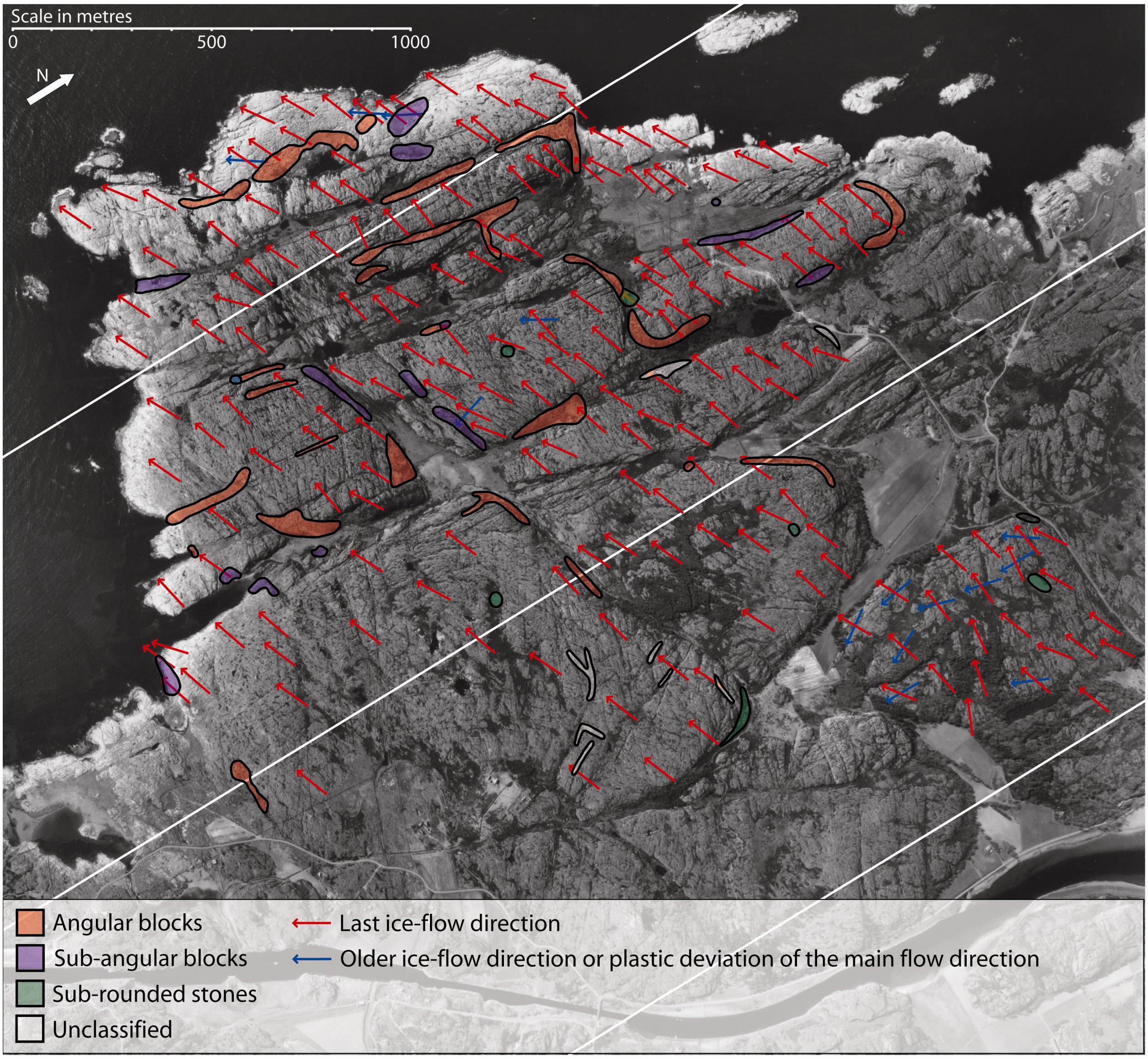

Figure 9. Map of measured striae and sediment accumulations. The white lines strike north-south and the distance between the lines is 1 km. Published with permission from Lantmäteriet, 2008-05-09.

meso, and macro forms have been used in the survey of the study area as the basis for the classification of the area into different glacial morphological areas.

6.1 The large-scale bedrock topography

The large-scale bedrock forms consist of ridges, or bedrock hills, striking approximately N-S. The ridges are bounded sideways by joint valleys and are also dissected by joint valleys in an E-W direction. The E-W striking joint valleys are not as continuous as the N-S striking valleys, which constitute the main direction. The relative relief varies within the study area, but is generally 20-30 m between the top of the bedrock hill and the valley floor. However, in some areas is the relative relief only one or a few metres, mainly in the SW part of the study area. The ridges are situated nearly perpendicular to the last ice-flow direction from the ENE, which means that the bedrock hills have developed a distinct stoss and lee side.

6.2 Ice-flow directions

The results of the measured striae are shown in figure 9. Two ice-flow directions are recognised in the study area, one from the ENE and one from the NE. At the coast, in the western part of the study area, the ENE striae on the stoss sides cross-cut the NE striae on the sloping lee-side facets. This means that the ENE striae are younger than the NE striae. A few striae with a more northern direction have also been measured, but it is not clear whether these are just deviations from the NE ice direction or represent an independent ice-advance.

6.3 Morphological classification

The entire study area was surveyed and divided into eight glacial morphological areas, which are described below. A sketch of how the area was classified is shown in figure 10 and the results of the classification in figure 12. The classification is based on which erosional forms are present in the study area and on the systematic distribution and relationship between the small and intermediate-scale erosional forms to the large-scale bedrock forms. Table 1 list different erosional forms and state for each glacial morphological area if they are common, occurs sporadically or are rare. All erosional forms found in the study area are not used in the classification, for example triangular pits, since they are too rare. P-forms are considered as a group in the table since the result is the same as when you regard them individually.

Each glacial morphological area has a descriptive name, and each name has an abbreviation consisting of two, and in one case three, letters. The first letter stand for stoss side (S), top surface (T) or lee side (L), depending on where on the ridge the area is found. The second and third letter stands for a descriptive word which characterizes the area; this word is given for each area below.

Sr Roches moutonnées on stoss side (r: roches moutonnées). The Sr-areas are dominated by roches moutonnées which terminate in fractures where quarrying has taken place along vertical joints (Fig. 11a). Open joints, ca 0.1-2 m wide and up to about 5 m deep, break up the proximal slope of the bedrock hill and create larger differences in topography. Most of the joints are aligned in an E-W direction and in some places there is an additional set of joints aligned in a N-S direction. The difference in height between the bottom of the open joints and the top of the roches moutonnées is usually about 2 m, but can be anything from 1 to more than 5 m. This area is only located on the proximal slopes of bedrock hills.

Ss Step-shaped, glacially abraded sheet edges (s: steps). The area is only located on the proximal slopes of bedrock hills and has the shape of large, curved steps (Fig. 11b). The stoss sides of the bedrock steps are smooth and curved similar to the stoss side of a roche moutonnée, but instead of a curved top there is a flat top surface, resulting in the step-like form. There are a few roches moutonnées, but they are not nearly as common as in the Sr-areas. As in the Sr-areas, the proximal slopes are usually broken up by open joints aligned in an E-W direction. The joints are about 0.1-2 m wide and ca 0.5-2 m deep. The height from the bottom of the open joints, or the bottom of a bedrock step, to the top of the step is on average 1-2 m, but can be higher as in figure 11b. The height of the steps is dependent on sheet joints, although the height of a single step is not necessarily the height of one single sheet slab. This can be seen from small notches or shelves, which follow sheet joints, that are often eroded into the edges of the sheet slabs.

Tr Low roches moutonnées on top surface (r: roches moutonnées. The area is dominated by low roches moutonnées and low faceted roches moutonnées (Fig. 11c). There are also roches moutonnées where the lee sides have been eroded into smooth, curved channel-like forms. Open joints are missing or shallow, and if present they can sometimes be seen as long, straight depressions with heather growing in them. The area is relatively flat with a height from the bottom to the top of the roches moutonnées being about 0.5-1 m. The area is located at top surfaces of bedrock hills or at their gently sloping proximal or distal slopes, but can also occur in low relief areas.

Lp Plucked lee side (p: plucked). The area is dominated by flat, rough to polished surfaces, with long quarried edges (Fig. 11d). Quarrying has taken place along sheet joints in the granite, which gives the areas the appearance of flat steps in the direction of ice movement. Rough and polished surfaces often intermix in a patchy appearance, where the surface up-ice of a step is striated and the surface in front of an edge

Table 1. The erosional forms used in the classification of the different glacial morphological areas. For each area the table states if the erosional form is common (C), occurs sporadically (S) or is rare (R).

	Sr	Ss	Tr	Lp	Lf	Lr	Ls	Lss
Roches moutonnées (r.m.)	C	R	C	-	R	C	-	-
Faceted r.m. & whalebacks	R	R	C	-	C	R	R	R
Striae	C	C	C	S	C	C	R	R
Coarse striae	C	C	C	R	S	C	-	-
Pits	S	S	R	R	R	S	-	-
Crescentic fractures	C	C	C/S	R	S	C	-	-
Crescentic gouges	C	C	C/S	R	S	C	-	-
P-forms around rock bumps	C	C	C	R	C	C	-	-
P-forms in open joints	C	C	-	-	C	C	-	-
Troughs on top surfaces	-	C	S	R	S	-	-	-

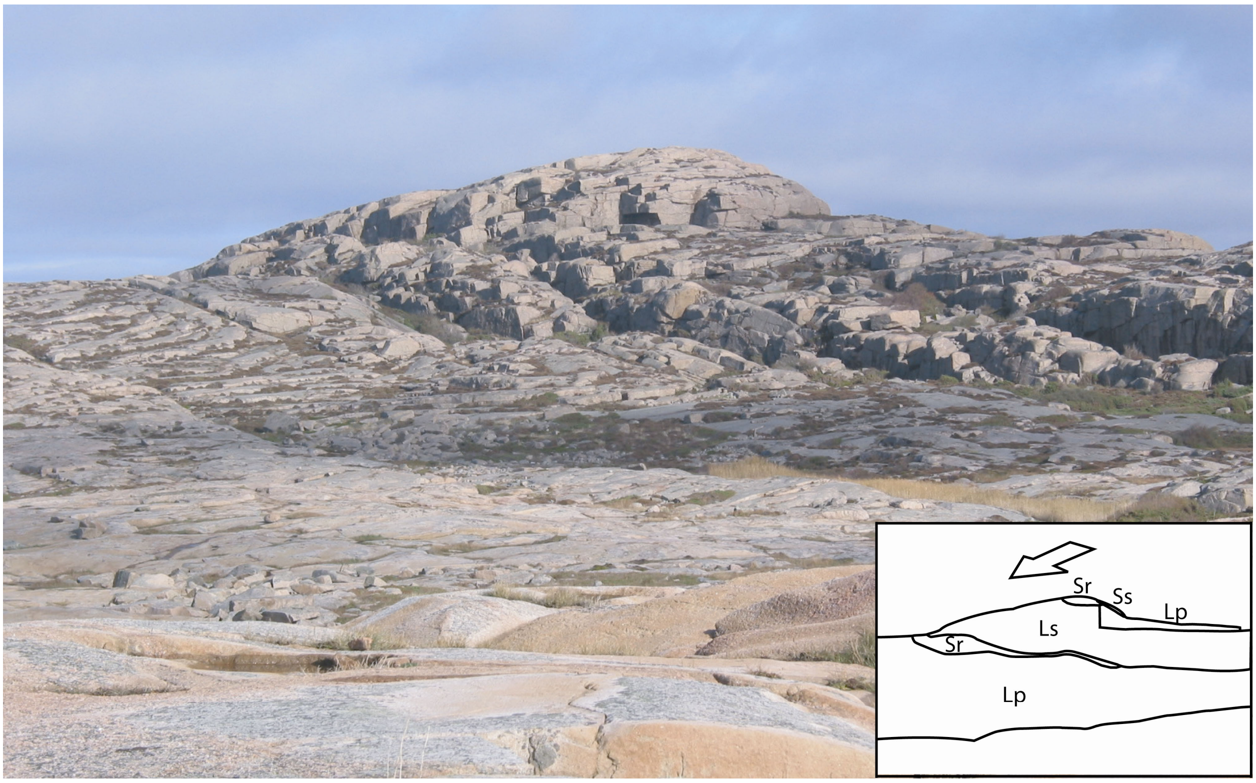

Figure 10. The picture shows the west side of the Sote Bonde ridge; the area west of the ridge slopes towards the sea. The picture illustrates how the area was classified by using the eight glacial morphological areas. Profile 3 (see Fig. 13) passes across the left side of the picture; crossing the highest part of the Sote Bonde ridge and continues towards the coast.

is rough. The rough surface continues for a distance, usually a few metres, where the surface becomes polished and striated again. Some plucked areas are similar to Tr-areas, where the surfaces are mostly polished and slightly rounded, but there are still the long, quarried edges and step-like appearance. The height of the sheet edges ranges from only a few centimetres to about one metre, but the average height is ca 0.2-0.5 m. The flat quarried areas are normally located on the distal slopes of bedrock rises, but can also be found on top surfaces.

Lf Faceted roches moutonnées on lee side (f: facet). The area is dominated by faceted roches moutonnées and whalebacks (Fig. 11e). Where the area is in a slope, the top surfaces of the faceted roches moutonnées may tilt down-ice. Classical roches moutonnées can occur, but are in minority. Open joints occur sporadically, but are not as common as on the proximal slopes. The height from top to bottom of the faceted roches moutonnées, or from the bottom of the open joints to the top of the faceted roches moutonnées, varies between approximately 0.5 and 2 m. The area is located on the distal slopes of bedrock hills or in low relief areas.

Lr Roches moutonnées on lee-side edge (r: roches moutonnées). This area is essentially the same as the roches moutonnées on stoss side (Sr). The primary difference from Sr is its location at the down-ice edge of a bedrock hill, instead of at its proximal slope (Fig. 11f). Another difference is that, in most cases, the open joints are not as well developed as in Sr-areas. Where the area is in a down-hill slope, the top surfaces of the roches moutonnées may be tilting down-slope.

Ls Lee-side edge resembling large steps (s: steps). The area is located on the lee-side edges of bedrock hills. The area is steep, in most cases nearly vertical, but with a step-like appearance (Fig. 11g). The height of the lee-side wall of the bedrock ridge, constituting the entire Ls-area, is about 5-30 m. The individual steps are approximately 1-3 m high and have been quarried along sheet joints in the granite.

Lss Lee-area in stoss-side position (ss: stoss side). The area resembles the Ls-area in that it has a step-like appearance (Fig. 11g). The steps are ca 1-3 m high and tilt towards the west. The stoss sides of the individual steps are vertical and have not been rounded into a form resembling roches moutonnées. However, the upper edges of the steps are commonly rounded. The area is located in a stoss-side position on the bedrock ridge, but is in the lee of a higher bedrock ridge to the east, which in this case creates a lee-side position on the eastern side of the lower ridge.

6.4 Rock walls

The rock walls of some joint valleys were observed for p-forms and signs of glacial erosion. The rock walls are divided into four categories: glacially quarried walls, plastically sculptured walls, slightly plastically

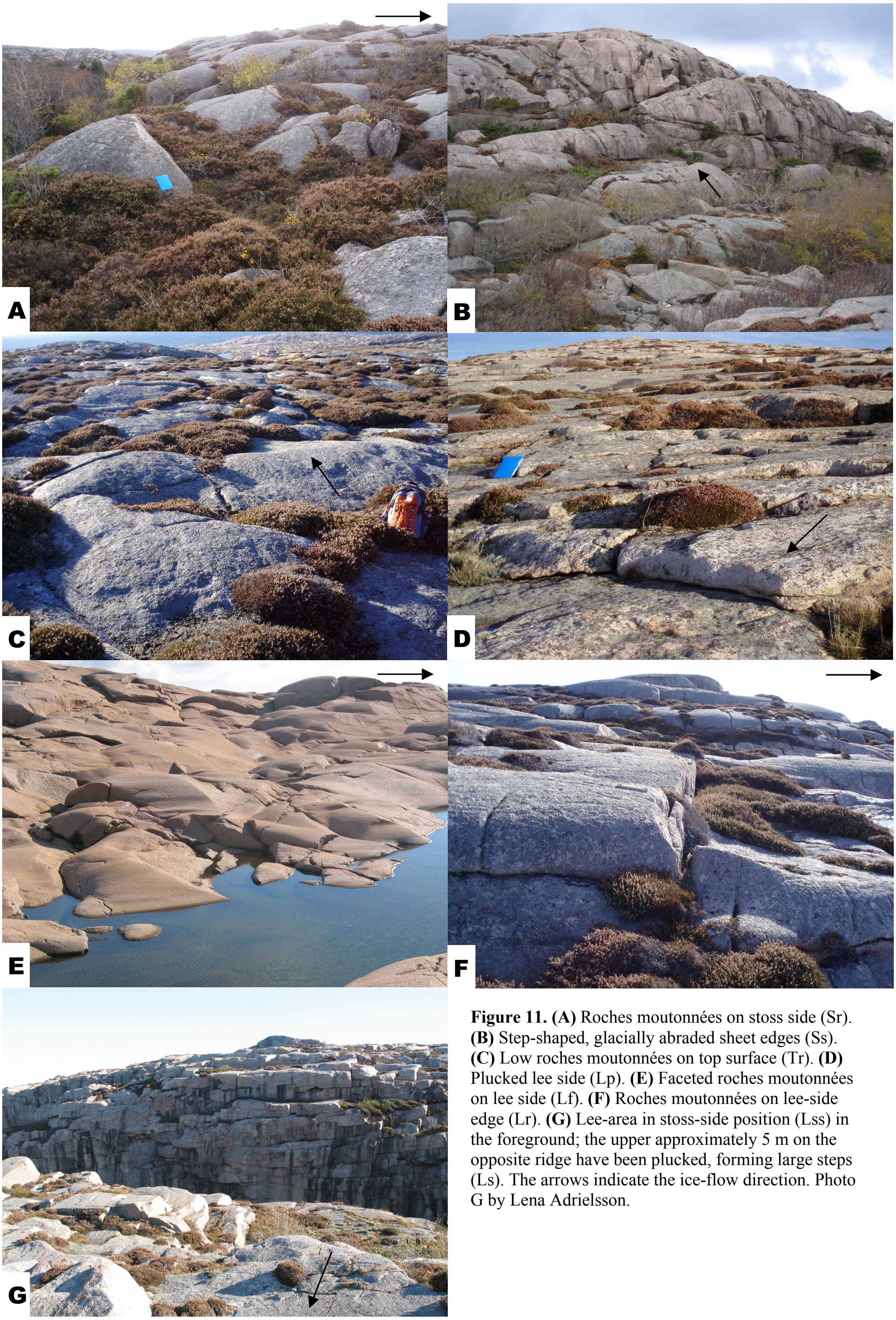

Figure 11. **(A)** Roches moutonnées on stoss side (Sr). **(B)** Step-shaped, glacially abraded sheet edges (Ss). **(C)** Low roches moutonnées on top surface (Tr). **(D)** Plucked lee side (Lp). **(E)** Faceted roches moutonnées on lee side (Lf). **(F)** Roches moutonnées on lee-side edge (Lr). **(G)** Lee-area in stoss-side position (Lss) in the foreground; the upper approximately 5 m on the opposite ridge have been plucked, forming large steps (Ls). The arrows indicate the ice-flow direction. Photo G by Lena Adrielsson.

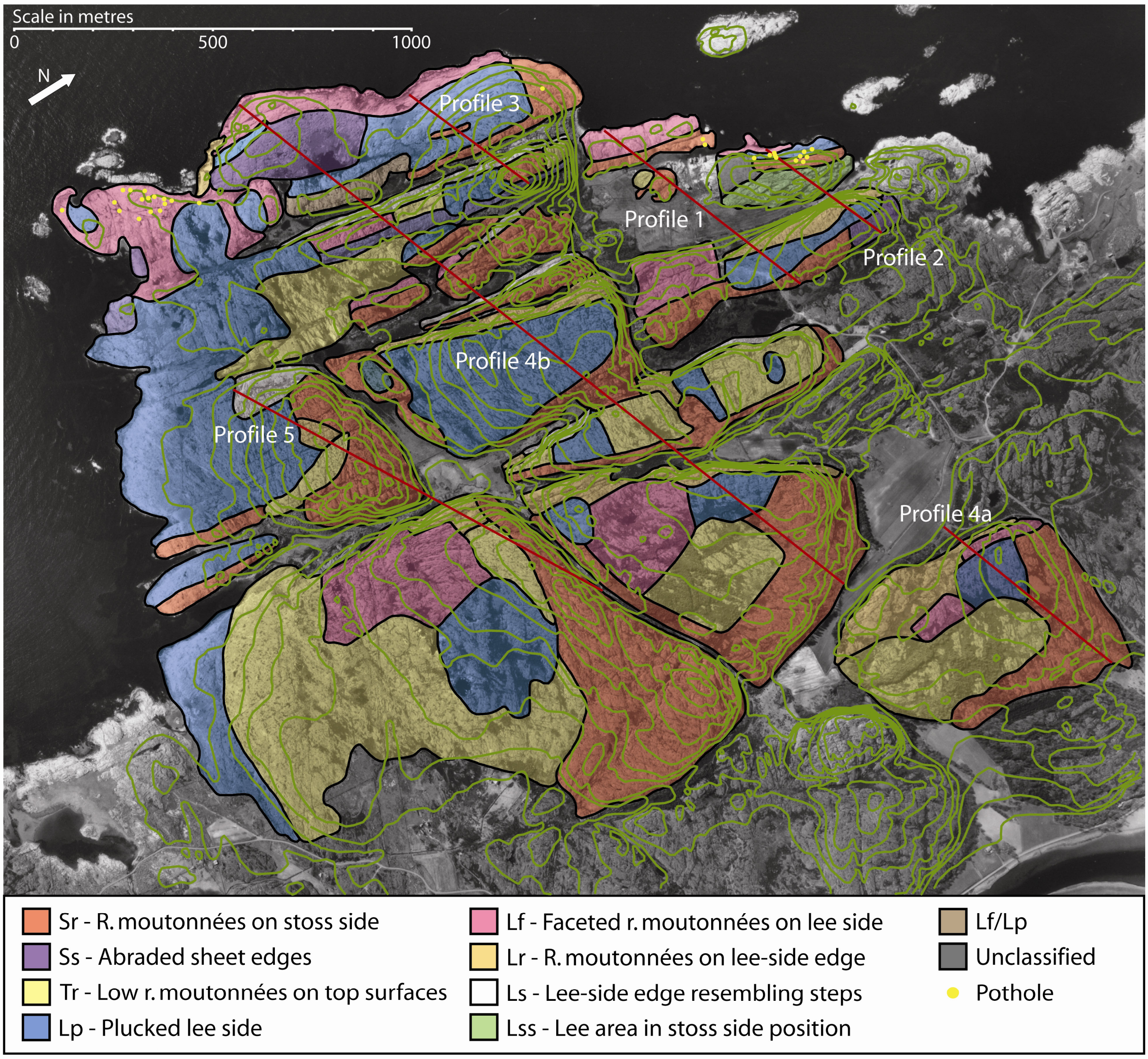

Figure 12. Map showing the results of the classification of the study area into eight glacial morphological areas. The profiles begin in the east and follow approximately in the ice-flow direction; profiles 1 to 4 strike 70° ENE and profile 5 strikes 60° ENE. Potholes are plotted as yellow dots and occur in the SW and NW part of the study area. The 25th and 50th metre of

sculptured walls and glacially unaffected walls. Glacially quarried walls have been subjected to glacial plucking and they often coincide with the Ls-areas described above. Plastically sculptured walls are striated and cavettos and facets are common whereas slightly plastically sculpted walls are striated with only a few cavettos and facets. In both former categories there have often been some blocks plucked at small-scale lee sides. Glacially unaffected walls are not striated and lack p-forms, facets and glacial plucking. They may be extensively weathered.

The sides of bedrock hills follow the main joint directions. The surveyed walls strike in N-S, NNE-SSW, ENE-WSW and E-W directions. 22 locations were studied and classified, a few along the same wall but with some distance apart. Plastically sculptured walls are most common in joint valleys trending in the ice-flow direction, i.e. in an E-W or ENE-WSW direction. However, there are also plastically sculptured walls striking in a N-S direction, which is at a right angle to the ice-flow direction. Almost all slightly plastically sculpted walls strike in a NNE-SSW direction, i.e. perpendicular to ice-flow, except one where the wall trend E-W. Quarried and glacially unaffected walls normally also strike perpendicular to ice-flow, i.e. N-S or NNE-SSW. Smaller quarried areas of walls occur in lee-side positions on walls which otherwise have plastic sculpture. Glacially unaffected walls occur in narrow joint valleys, from about one metre to approximately ten metres wide.

6.5 Sediment accumulations

Most accumulations are dominated by angular boulders, but there are also accumulations of subangular to subrounded boulders and subrounded to rounded stones. In the accumulations of angular boulders, large, flat, rectangular clasts are common, an appearance which is inherited from the sheeting of the granite. The boulders are mostly of the local bedrock Bohus granite. These accumulations are mostly located in the lee of a bedrock hill, but can also be located along the proximal slopes of ridges. The subangular to subrounded boulders have a similar distribution, although they are usually in a slightly weaker lee position. These accumulations have a more varied composition of bedrock types. Accumulations of subrounded to rounded stones are found in various positions: on the top surfaces of bedrock hills and on their distal slopes, in the lee of a hill and along its proximal slope.

7 Analysis of the areal distribution of glacial morphological areas

In addition to the less detailed areal survey, the study area was also surveyed by walking along straight lines, profiles, which were laid approximately in the last ice-flow direction. Five profiles were spread over the study area; profiles 1 to 4 strike 70° ENE and profile 5 strike 60° ENE. The exposed bedrock areas along the profiles were classified using the eight glacial morphological areas (Fig. 13). A statistical analysis based on the profiles was performed with the purpose of detecting any pattern in the arrangement of the glacial morphological areas. The analysis focuses on the number of transitions from one glacial morphological area into another, i.e. the probability on which for example an Sr-area changes into an Lp-area (Table 2). The analysis showed that areas without exposed bedrock, i.e. ground with for example thin soil cover, heather or bushes (classified as other ground), or basins filled with water or sediment, changes into either Sr-areas or Ss-areas. Sr-areas dominate most proximal slopes and commonly change into Lp-areas, but also in some instances into Tr-, and Lf-areas. The plucked (Lp) areas, in their turn, have most transitions to Lr- and Lf-areas. The Lr-areas usually occur at the end of exposed bedrock hills and thus mostly change into sedimentary or water covered areas or some other lower ground. Ss-, and Tr-areas only have four transitions each, and Lf-areas only three (not counting the four instances where an Lf-area ends in the sea) which makes it difficult to draw any conclusions. The most common transitions are shown in figure 14.

A model of a bedrock ridge was constructed which shows the most common form associations according to the analysis of possible transitions (Fig. 15). The mean length of each area has also been calculated from the profiles. The length of the Lr-area includes the sloping wall of the lee-side end of the bedrock hill and is longer than the actual morphological area itself. According to the model, the proximal slope of the bed-

Table 2. The table shows what the probability is for a glacial morphological area to change into any of the others. The probability is given both as number of transitions and as a percentage. The percentage is calculated separately for each glacial morphological area, i.e. for each horizontal line. The table is read horizontally; the vertical column to the left show each glacial morphological area and the the horizontal line shows the glacial morphological areas that the ones in the vertical column turn into. To read the table: start by, for example, reading the first horizontal line, the Sr-areas; in four instances a Sr-area change into a Tr-area, in eight instances into a Lp-area, twice into a Lf-area and once into a Ls-area. The table was constructed using the profiles, tracing them in the ice-flow direction and noting every transition from one glacial morphological area to another. The transition to the first glacial morphological area of a profile (from an unclassified area) is not counted, nor is the "transition" from an area to the sea.

	Sr	**Ss**	**Tr**	**Lp**	**Lf**	**Lr**	**Ls**	**Lss**	**Lf/Lp**	**S**	**G**	**W**
Sr			4 (27)	8 (53)	2 (13)		1 (7)					
Ss			1 (25)	1 (25)	2 (50)							
Tr	1 (20)					2 (40)	1 (20)					1 (20)
Lp	1 (9)	1 (9)			3 (27)	4 (36)	1 (9)					1 (9)
Lf						1 (33)	1 (33)					1 (33)
Lr				1 (14)						3 (43)	2 (18)	1 (14)
Ls											1 (33)	2 (67)
Lss	1(100)											
Lf/Lp				1 (100)								
S	2 (67)							1 (33)				
G	3 (60)	2 (40)										
W	4 (67)	1 (17)										1 (17)

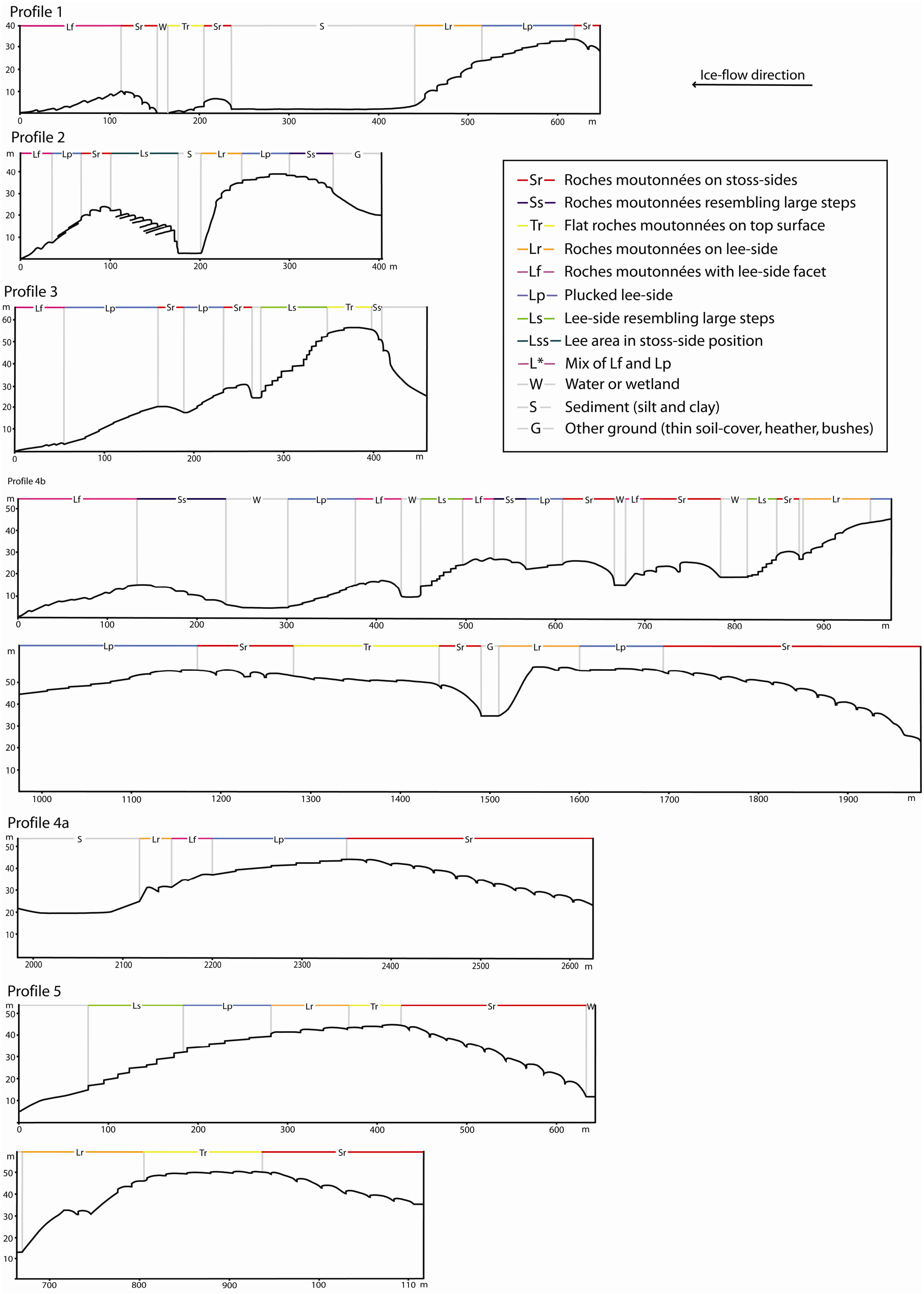

Figure 13. The five profiles in the study area. The profiles were laid approximately in the ice-flow direction; profiles 1 to 4 strike 70° ENE and profile 5 strike 60° ENE. The profiles are read in the ice-flow direction from right to left, and when reading profiles 4 and 5, start with the lowermost profile.

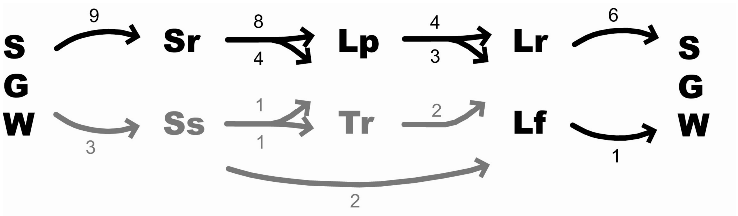

Figure 14. The most likely transitions from one area to another (based on table 2). The figures above and below the arrows are the number of transitions counted from the area to the left to the area to the right. The transition to the first glacial morphological area of a profile (from an unclassified area) is not counted and this results in a smaller number of transitions to the Sr-, and Ss-areas. Similarly, the "transition" from an area to the sea is not counted either. This effects the number of transitions from Lf-areas as these extend into the sea on four occasions.

rock hill is covered by roches moutonnées (Sr-area). At the top of the hill this changes into a plucked area (Lp-area) with rock steps sloping gently in the down-ice direction. Towards the end of the hill, roches moutonnées, faceted roches moutonnées and whalebacks reappear (Lr-area and/or Lf-area). Lr-, or Lf-areas end the bedrock hill and thereafter follow an area without exposed bedrock, for example a small lake or wetland, a sediment-, or vegetation-covered area or the sea.

A calculation of the quantitative distribution of the glacial morphological areas, i.e. how many percent of the study area each morphological area represents, was made based on the profiles (Fig. 16). The profiles miss one large Tr-area and only capture a smaller part of the largest Tr-area, as well as only capturing the narrower sides of the two largest Lp-areas. This makes the calculated percentage for these two areas too low and it can therefore only be seen as a minimum.

8 Interpretation of the areal distribution of glacial morphological areas

8.1 Areal distribution of glacial morphological areas

The model predicts that most bedrock hills have roches moutonnées on their proximal slopes (Sr-areas) (Fig. 14 & 15). Sr-areas also have the largest areal distribution in the study area according to the profiles (Fig. 16). At the intermediate-scale the areas are partly related to Pre-Quaternary weathering. The weathering, which was predominantly concentrated to joints, formed the large open joints dissecting the stoss sides and created a greater relief (Olvmo et al., 1999).

The stoss sides of roches moutonnées may be remnants of smoothly weathered rock bumps, formed as a result of differential weathering along joints in the bed. However, the most characteristic process connected to the area is glacial abrasion (Fig. 17). The effective normal pressure is high on stoss sides, resulting in ice-bed contact at large parts of the bed (Bennett & Glasser, 1996; Benn & Evans, 1998). This can be reconstructed from the striae and the many friction marks found, as well as the roches moutonnées. P-forms are also common and occur around roches moutonnées and in open joints, which indicate that there has been channelized water at the bed during at least some period. The hydraulic gradient has been high to create the water velocities necessary for p-form formation and to press the water up the proximal slopes (Benn & Evans, 1998). Quarrying took place at the lee sides of roches moutonnées, but is subordinate to the process of abrasion.

About 20% of the proximal slopes are step-shaped with abraded sheet edges (Ss-areas) (Fig. 14). The Ss-areas resemble a site at Hunnebostrand which is described by Johansson *et al.* (2001a) to resemble deep-weathered sheet edges in India. The few roches moutonnées, despite the presence of open joints in the ice-flow direction, indicate that the landscape has not been subjected to severe glacial abrasion, but has kept much of its preglacial weathered character and only received a glacial over-print of small-scale erosional forms, such as striae, friction marks and p-forms.

According to the model, a proximal slope with roches moutonnées (Sr-area) will change into a plucked area (Lp-area) (probability 53%; Sr-, into Tr-area – probability 27%) (Fig. 14 & 15). Lp-areas also have the second largest areal distribution after Sr-areas (Fig. 16). Lp-areas are situated at near-horizontal top surfaces and gently sloping distal slopes. Quarrying was the dominating process and the height of the blocks being quarried was determined by the sheet joints in the granite (Fig. 17) (Olvmo *et al.*, 1999; Johansson et al., 2001a). The effective normal pressure is lower at the top of the hill than on its proximal slope and even lower on its distal slope (Bennett & Glasser, 1996). The lower effective normal pressure favour cavity formation and cavities are common, occurring in front of the edge of every rock step, which can be seen from the lack of striae in front of the edges. More cavities mean that the ice is coupled to a smaller part of the bed. Where concentrated flows reappear again in the down-stream direction (which is predicted by the model) and parts of the ice recouples to the bed the Lp-area will constitute an area of cavities surrounded by more concentrated flows (Fig. 17). The water-flow

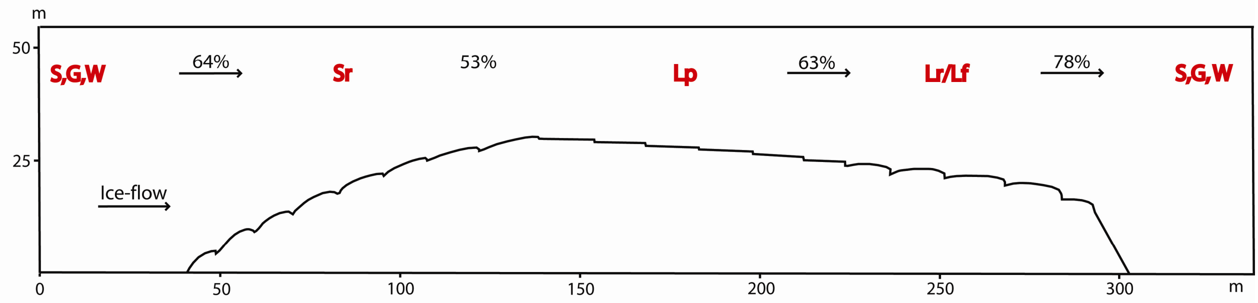

Figure 15. Model of a bedrock hill showing the most likely transitions, based on table 2. Areas with sediment, water, or other ground (S,G,W) do in 64% of their transitions change into a Sr-area; Sr-areas change into Lp-areas in 53% of the cases; Lp-areas change into either an Lr-, or an Lf-area in 63% of the transitions, and Lr-, and Lf-areas change into S,G,W-areas in 78% of the transitions.

diverges as it passes from the channels in the Sr-area to the cavities in the Lp-area and must converge again as it exits the cavities. The channels in the downstream direction of the cavities may function as bottle necks and make water build up in the cavities. This throttling will slow down the water flow and build up a high water pressure (Benn & Evans, 1998). Thus, in Lp-areas the velocity of the water was low and suspended-load abrasion negligible as indicated by the lack of p-forms. Plucking is facilitated by the existence of cavities, and cavity-formation is facilitated by a high water pressure which lowers the effective normal pressure (Benn & Evans, 1998). The high water pressure helps to lift the blocks off the bed, which makes it easier to loosen them and transport them away. The low ice pressure makes it easier for the ice to freeze onto the bed (Bennett & Glasser, 1996). Abrasion is a subordinate process which is focused to the flat areas above the edges of rock steps where the ice was in contact with the bed.

The areas of low roches moutonnées and faceted roches moutonnées (Tr-areas) are situated on top surfaces and on gently sloping proximal and distal slopes of bedrock hills. Larger abraded surfaces with low roches moutonnées, striae and friction marks show that the effective normal pressure was higher than in Lp-areas and that the ice was coupled to a larger part of the bed (Benn & Evans, 1998; Glasser & Bennett, 2004). However, faceted roches moutonnées indicate that there have been cavities. P-forms also indicate that the water-flow velocity must have been high (Sharp & Shaw, 1989).

The model predicts that a bedrock ridge will end in an Lr-, or Lf-area (63%) (Fig. 14 & 15); Lr-areas end 50% of all ridges in the study area. Lr-, and Lf-areas, together with Tr-areas, have the third largest areal distribution in the study area, after Sr-, and Lp-areas (Fig. 16). Hence, the areas with the largest quantitative distribution are also the areas predicted by the model of the most likely transitions. In Lr-areas abrasion is the dominating process which is evident from the many roches moutonnées, striae and friction marks (Fig. 17). There is plucking at the lee side of roches moutonnées, but this is a subordinate process. P-forms are common around roches moutonnées, showing that water, like in the Sr-areas, has flowed around the rock bumps. The effective normal pressure must have been high, despite the position of the area in a distal slope. Increasing water-flow velocity due to converging flows makes the water pressure drop, helping to increase the effective normal pressure (Benn & Evans, 1998).

Lf-areas with faceted roches moutonnées and whalebacks also appear at the end, or towards the end, of bedrock hills. The dominating processes in the area are melt-water erosion and abrasion, as can be seen from faceted roches moutonnées, whalebacks, striae, friction marks and numerous p-forms (Benn & Evans, 1998; Glasser & Bennett, 2004). As the water flows from an Lp-area to an Lf-area the flow converges and accelerates and thus the basal contact between the ice and the bed increases. However, cavities still cover a relatively large part of the bed, perhaps because the low-relief topography makes the flows shallow. The plucking in the area is negligible.

Almost all potholes in the study area cluster in two places (Fig. 12). The south cluster is situated in an Lf-area which in its turn is located down-ice of an Lp-area and the north cluster is situated approximately at the transition between an Lp-, and an Lf-area with potholes in both areas. This location may be explained by the changes in basal conditions from slowly flowing water in the Lp-cavities to higher velocities in the more concentrated flows of an Lf-area. The high velocity water may erode potholes if the turbulent water stream hits the bedrock at a high angle (Kor *et al.*, 1991).

Ls-areas do not follow on any specific glacial morphological area, but are bound to steep edges. However, this is nothing unique for Ls-areas as several Lr-areas are also situated at steep edges. In contrast to Lr-areas, the effective normal pressure in Ls-areas is low and a cavity existed in the lee of the bedrock hill. The low ice pressure makes it easier for the ice to freeze onto the bed and facilitates transport of blocks away from the hill (Bennett & Glasser, 1996). Both abrasion and melt-water erosion are negligible processes.

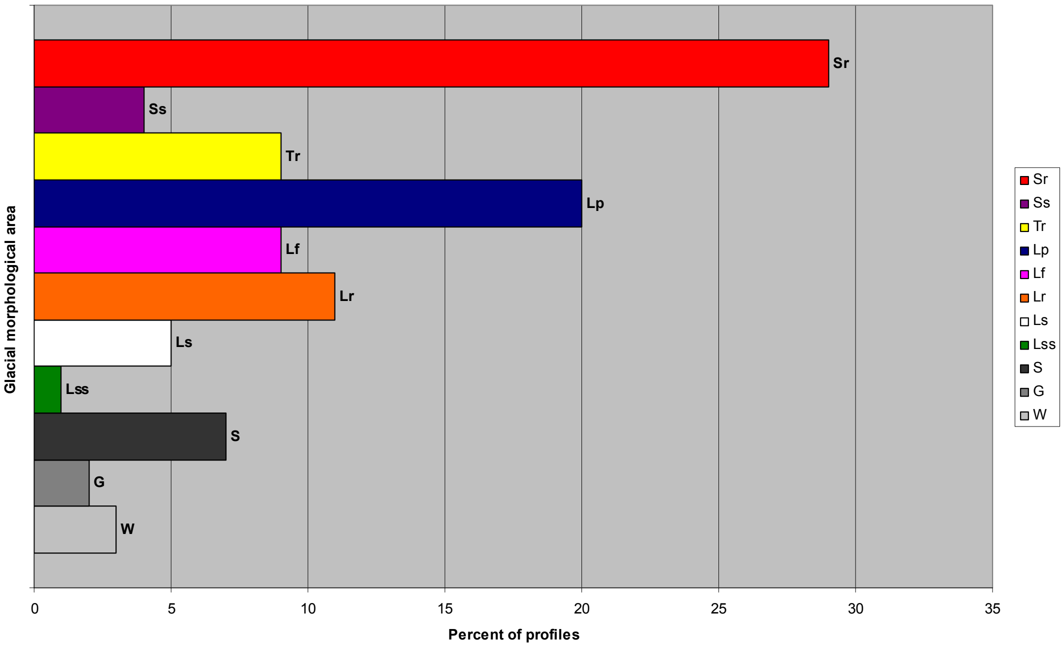

Figure 16. The calculated quantitative distribution in percent of each glacial morphological area . The calculations are based on the profiles. The profiles miss one large Tr-area and only capture a smaller part of the largest Tr-area, as well as only capturing the narrower sides of the two largest Lp-areas. This makes the calculated percentage for these two areas too low and it can therefore only be seen as a minimum.

8.2 Areal distribution of boulders

Lp-, and Ls-areas, the two areas where plucking is the dominating process, produce the majority of the boulders that are later deposited. Several accumulations are deposited in the lee of bedrock ridges or in the joint valleys between two ridges, for example the accumulations west of the Sote Bonde ridge (Figs. 1b & 9). The boulders are deposited as the ice moves over the cavity, which is likely to develop in the lee of a ridge. The boulder either melts out or is pushed out by the downward force created by the large weight of the boulder in comparison to the ice (Bennett & Glasser, 1996). Several accumulations are also located against the proximal slope of ridges, for example east of Sote Huvud (Fig. 1b & 9). For a boulder to be transported from the lee side of a ridge to the stoss side of the next ridge without being deposited, the boulder must have been incorporated into the ice. If not, the boulder would have been deposited when the ice moved over a cavity. In these cases the boulders are deposited first when pressure melting at the proximal slope lowers them to the bed (Bennett & Glasser, 1996). There are two deposits situated on the south side of a hill, striking in an E-W direction, i.e. in the ice-flow direction. It is hard to explain how an ice sheet moving in an E-W direction could have deposited these accumulations. They may have been deposited if the ice flow shifted towards a more northerly direction during a shorter period or during the earlier ice advance from the north.

Most boulders are angular and of local bedrock and have clearly not been transported far. Many of these angular boulders seem to have been dropped in the first joint valley following a plucked edge or distal slope. The subangular to subrounded boulders, which are of more varied lithologies, have been transported a little further and could be the coarse-grained remnants of till.

9 Discussion

9.1 Subglacial physical processes and drainage systems

There is much evidence of the former subglacial erosional processes that have been active in the study area. Both the occurrence of the different erosional forms and their distribution in the small-, and large-scale topography provide many clues. Roches moutonnées, striae and friction marks found over large parts of the area prove that there has been basal contact between the base of the ice and the bed (Benn & Evans, 1998; Glasser & Bennett, 2004). For the abrasion and fracturing to be effective the base of the ice must also have contained debris and there must have been a continuous transfer of new material towards the bed (Glasser & Bennett, 2004). The lowering of material to the bed requires basal melting. The ice must have been sliding over the bed and must also have exerted a high normal pressure at the bed to keep it in contact with the bed (Glasser & Bennett, 2004). However, the pressure must not be high enough for the clasts to lodge. That the base of the ice is at the pressure melting point

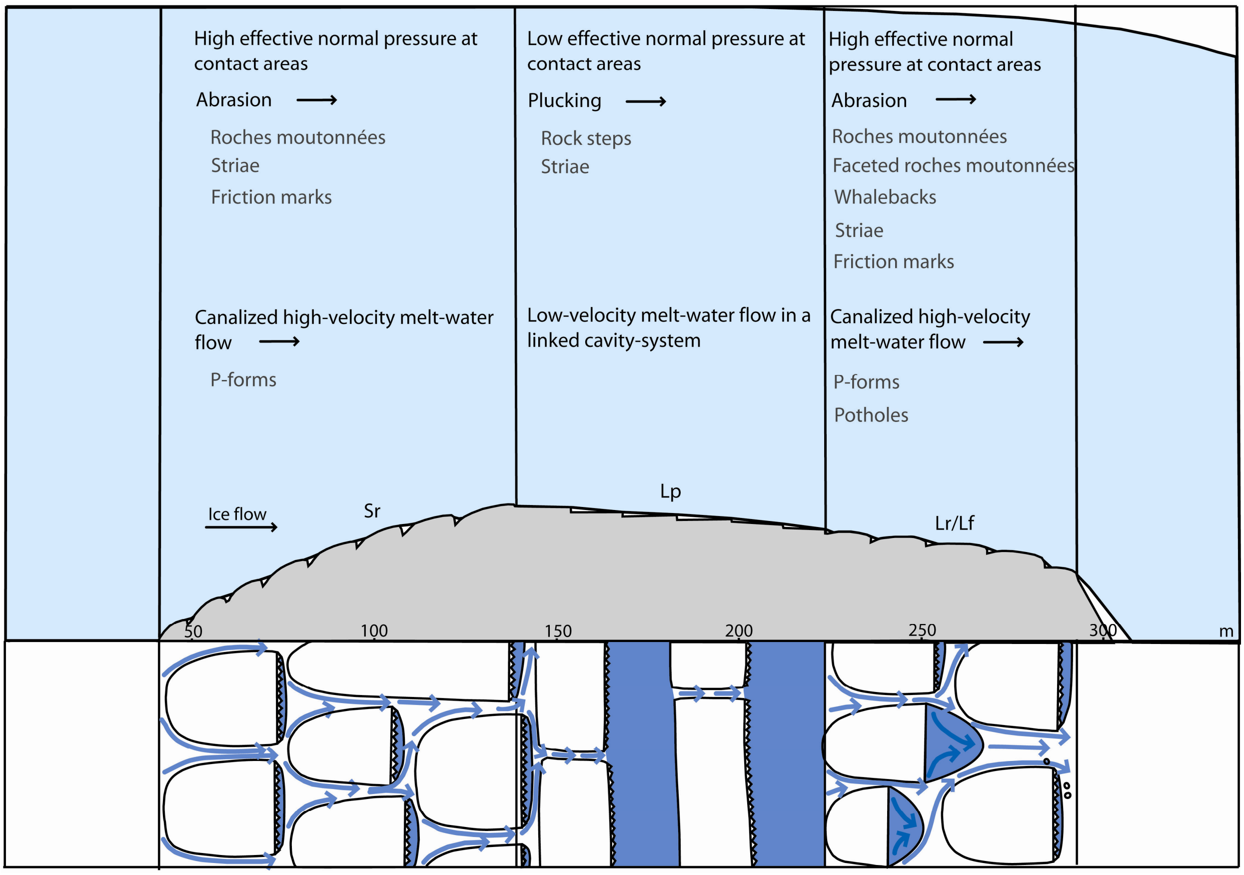

Figure 17. The characteristic processes and erosional forms for each glacial morphological area shown in the model. A sketch of the drainage system for each glacial morphological area is shown underneath each area in the model. Sr-, Lr-, and Lf-areas have channelized flows around rock bumps; in Lf-areas there is also water flowing in cavities over the lee-side facets. In Lp-areas the water flows in a linked-cavity system. The dots symbolize potholes.

is a prerequisite for any erosion to take place (Benn & Evans, 1998).

P-forms are found in the lower parts of the topography. They are most common in connection with rock bumps, occurring on their up-, and down-ice side and also striking alongside or between them. Cavettos can also be found in open joints and on the walls of the large-scale bedrock hills. This proves that there has been water flowing with a high velocity over parts of the bed during at least some point in time (Sharp & Shaw, 1989). There are also many signs of cavities, such as plucking at lee sides, lee-side facets and p-forms. The cavities at the up-, and down-ice side of rock bumps could have been connected by the channels striking alongside the rock bumps, forming a linked-cavity system. However, a classical linked-cavity system has very low through-flow velocities as the connections between the cavities are usually narrow (Benn & Evans, 1998). The narrow connections function as bottle necks and slow down the flow, raising the water pressure. A linked-cavity system would create the cavities needed to promote plucking, but cannot explain the p-forms as these require high through-flow velocities to form. The p-forms reflect concentrated high-velocity flows (Fig. 17). However, a channelized flow quickly evacuates water from the bed which lowers the water pressure and reduces the favourable conditions for cavity formation and maintenance. There is evidence for the existence of both cavities and channelized flows, which implies that there are two main alternatives: (1) a linked-cavity system existed for the majority of the time and changed into a channelized drainage during periods of exceptionally high water flow, and (2) the drainage interchanged between a linked-cavity system and a channelized flow on a seasonal basis. The drainage of a subglacial or supraglacial lake would transfer large amounts of water to the bed and the drainage would then switch to a more effective drainage as linked-cavity systems are unstable at high water discharges (Benn & Evans, 1998). However, the second alternative of a seasonal-based change seems more likely. This seasonal switch in drainage has been observed at glaciers in Scandinavia (Benn & Evans, 1998). Considering the many cavities, which indicate much water at the bed, it is likely that this discharge would have been reached already during more normal flows, and a large drainage would not have been required. In a channelized drainage the water-flow is from smaller towards larger channels, because of the larger channels lower water pressure (Benn & Evans, 1998). A linked-cavity system is stable at low discharges when the water pressure is higher in larger cavities, but becomes unstable at higher discharges when the water pressure relations are reversed (Benn & Evans, 1998). The water will then flow towards the larger cavities which will grow even more and the system will eventually switch to become a channelized flow. The evolution of the drainage from a linked-cavity system to channelized flows can happen on a seasonal basis (Benn & Evans, 1998). In the beginning of the melting season the drainage is in the form of linked cavities, but changes to a channelized flow when the water discharge increases due to increased melting during the summer.

The lack of p-forms in plucked areas (Lp-areas) shows that the through-flow velocity has not been high in all parts of the study area, since p-forms require high transit velocities to form (Sharp & Shaw, 1989). There are thus areas of both high and low through-flow velocities; the areas with roches moutonnées, faceted roches moutonnées, whalebacks and p-forms represent areas of high through-flow velocities whereas areas with rock steps and no p-forms represent areas with low through-flow velocities (Sharp & Shaw, 1989; Benn & Evans, 1998). The fact that there are so few traces of channels in Lp-areas shows that concentrated flows have not existed at all areas of the bed. In Lp-areas there was probably a linked-cavity system (Fig. 17). Alternatively, the p-forms were created some time before the majority of the plucking took place and they may then have been removed along with the sheets of bedrock that were quarried.

Shaw (2002) proposes that the p-forms he and colleagues have investigated have been formed by catastrophic drainages of subglacial lakes which would have lifted the ice sheet off its bed. However, there is no evidence at Ramsvikslandet that the ice would have been lifted completely off the bed by a large sheet flood. There are very few p-forms at higher parts of the detailed topography; these are instead completely dominated by abrasional forms which indicate ice – bed contact. The Canadian locations usually also contain larger p-forms than are found at the study area. These Canadian p-forms can be tens of metres wide and hundred of metres long (Kor *et al*., 1991; Kor & Cowell, 1998). Larger p-forms require larger-diameter vortices to form and thus larger water depth (Shaw, 2002).

9.2 Age relations

The small-scale, intermediate-scale and large-scale forms are of different ages. The small-scale erosional forms are of late Weichselian age. The well-preserved fine striae and sharp edges of p-forms would not have withstood longer periods of weathering, which makes it unlikely that they have been exposed during earlier ice-free interstadials. A later ice advance would also have worn down the sharp rims and edges (Johnsson, 1956). The intermediate-scale erosional forms can be of Weichselian age, but they can also have been preserved from earlier glaciations. In contrast to the small-scale forms, the intermediate-scale forms would withstand longer periods of weathering, because their larger size requires a longer time to wear down. Plucking at distal slopes of bedrock hills would most likely have occurred during earlier glaciations, as well as the last one, and the rock steps created would gradually lower the lee side, increasing the asymmetry of the ridge (Olvmo *et al*., 1999). The large-scale erosional forms, i.e. the bedrock ridges and rises and the joints valleys, are of Pre-Quaternary age (Olvmo *et al*., 1999). They were formed during the deep weathering in the Mesozoic and the Cenozoic.

The end of the glaciation can be divided into two phases: a main intensive phase and a second phase at the very end of the deglaciation. During the main phase there was much water under the ice and a high sliding velocity. The small- and intermediate-scale erosional forms were created during this phase, meaning that all descriptions of subglacial conditions above refer to this main phase. The second phase is at the very end of the glaciation and involves a reduction in ice-flow velocity. There is no large input of water to the bed so there is little water under the ice, reducing the sliding velocity and causing the ice to couple to the bed. The ice is very plastic and has contact to basically the whole bed, creating the striae inside p-forms. A little plucking could have taken place if the ice froze locally to the bed.

10 Regional implications

10.1 The water source

The erosional forms and the many signs of cavities show that there has been much water under the ice. Pressure melting and geothermal heat, i.e. heat from within the Earth emanating from the bed, would have made a small contribution (Drewry, 1986). Frictional heat created from the sliding of the ice sheet over the bed and from flowing water against ice also produces water through melting (Benn & Evans, 1998). The two latter processes have probably been of some importance as there is evidence of much water at the bed; the water would have melted ice directly and would also have increased the sliding velocity, creating more frictional heat and thus more water (Benn & Evans, 1998).

Melt-water from the ice surface can make its way to the bed by moulins and crevasses. This can be both in the form of surface melting and the drainage of supraglacial lakes (Benn & Evans, 1998). When a lake drains, large quantities of water reach the bed and water also backs up the system (i.e. all the moulins and ice tunnels are filled) raising the water pressure. Drainage of supraglacial lakes on Greenland caused raised water pressures for hours to days (Box & Ski, 2007).

Subglacial lakes form in depressions on the bed and can store large amounts of water (Benn & Evans, 1998). The drainage of a subglacial lake, similar to the drainage of a supraglacial lake, release large quantities of water and thus raises the water pressure for the duration of the drainage.

10.2 The cause of the missing sediments

As has been described, p-forms and forms created by abrasion (striae, roches moutonnées etc.) are ubiquitous in the study area. Melt-water erosion requires suspended minerogenic material and abrasion requires particles frozen into the base of the ice (Benn & Evans, 1998). However, the scattered or accumulated boulders and the accumulations of glaciomarine silt and clay are the only sediments in the study area (Johansson *et al.*, 2001b). The erosional forms are thus evidence that minerogenic material must once have existed or been transported through the area, but today only the boulders are left. The landscape of exposed bedrock and glaciomarine sediments cover a large area in SW Sweden, of which the study area is only a small part (Johansson, 1982; Fredén, 2002). The area has the shape of a wedge, beginning in the Vänern basin and widening towards the coast. Lines can be drawn approximately from Mariestad to Gothenburg and from Karlstad to Strömstad (Fig. 1a). SE of the Gothenburg-Mariestad line the sediments are dominated by till and glaciofluvial sediments, with wave-washed sediments along the coast (Fredén, 2002).

The sediment in the area of exposed bedrock might have been removed by the reworking of waves or swept away by flowing water, but it is also possible that no sediments were deposited. The deposits of till are usually found in the lee of bedrock hills or along the sides of valleys, which may indicate that their sheltered position has protected them from erosion and thus speaks against a non-depositional model (Johansson, 1982). The fact that boulders, but no other sediments, would have been deposited is also strange. It is also unlikely that the material have been reworked by waves as there are no wave-washed sediments in the area. The striated bedrock close to several stone or boulder accumulations are also undisturbed, indicating that the clasts have not been moved around. It is concluded that the material has probably been swept away by flowing water, either in a catastrophic outburst flood or in a prolonged high-velocity flow. The remaining boulders show that the water velocity must have been high. The fact that the sediment-poor area starts at the Vänern basin and widens towards the coast leads to the speculation that the basin may have provided the water for the removal of the sediments, and when the sediments had been removed, also for the formation of the p-forms. Lake Vänern is Sweden's largest lake and the basin may have constituted a subglacial lake during the last glaciation.

The boulder lag in the study area, together with the wedge-shaped sediment-poor area originating in the Vänern basin and the tendency for the occasional till deposits in the area to be located in sheltered positions, could all be signs of a large drainage of the basin similar to those described by John Shaw and his colleagues from Canada (Kor *et al.*, 1991; Shaw, 2002). They propose huge sheet floods with a water depth of about 10 m and a velocity of approximately 5 to 10 m/s and a width of many tens of kilometres (Sharpe & Shaw, 1989; Kor *et al.*, 1991, Shaw, 2002). They base their arguments mainly on studies of p-forms (often of intermediate-, or large-scale) and drumlin fields. Just as in Bohuslän, the p-forms cover large areas, at Georgian Bay, Ontario, for example, the area is 70 km wide (Kor *et al.*, 1991). A difference is that the intermediate-, and large-scale p-forms (such as channels several metres wide and hundreds to thousands metres long) are not found in SW Sweden. This difference could indicate that a large drainage which is proposed to have occurred at several locations in Canada has not taken place here. As regards the similarities, another example is the lack of sediments except for a boulder lag. However, the boulders described from Canada are rounded and originate many tens of kilometres in the up-stream direction (Kor *et al.*, 1991; Kor & Cowell, 1998), whereas the boulders at Ramsvikslandet are mainly angular and of local bedrock.

A very rough calculation of a possible drainage of Lake Vänern gives the following result. A sheet flow 1 m high with a water velocity of 5 m/s and a width of 100 km lasting for 24 hours would produce a discharge of 4.32×10^{10} m^3, i.e. 28% of Lake Vänern's current water volume. If the water velocity is increased to 10 m/s, the discharge is doubled to 8.64×10^{10} m^3, i.e. 56% of Vänern's water volume. Unless the subglacial water source was considerably larger than that of today, these calculations do not support a catastrophic drainage. If the basin would lose such enormous quantities of water, i.e. approximately 30-60% of the current water-volume of the Vänern basin, the hydraulic pressure driving the drainage would fall and the drainage would stop (Benn & Evans, 1998). The calculations together with the differences described above make a large-scale drainage according to Shaw's model seem unlikely.

The second possibility is that a continuous ice stream removed the till and created the p-forms. A continuous out-flow of water from the Vänern basin, enough to maintain a high water pressure and a high hydraulic gradient, would create a high water-velocity and could also have maintained cavities. Large amounts of water at the bed reduces friction and would have increased the sliding velocity of the ice and could have created an ice stream from the Vänern basin towards the coast. The ice-stream would have been maintained by calving. This continuous high-velocity water-flow could have been enough to remove the sediments and create the p-forms, especially since the ice-stream could have been active for a much longer period of time than a catastrophic drainage, with a balance between in-, and out-flow of the basin. An additional possibility is that the ice did not have contact with the bed as it passed over the large Vänern basin. This could have caused sediments to melt out of the ice and new material would not have been picked up by the ice either, thus reducing the amount of sediments held by the ice and resulting in little sediment deposition. There would then also be less sediment to remove. An ice stream seems a more reasonable explanation for the sediment-poor area than the large-scale drainage.

The change in geology, from mostly exposed bedrock NW of the Gothenburg-Mariestad line to till and glaciofluvial deposits SE of it, implies a change in the subglacial hydrological conditions. Glaciofluvial deposits such as eskers and deltas are formed outside the mouths of large ice tunnels and their absence in Bohuslän indicates that large tunnels were absent or at least rare in this area. The glaciofluvial deposits were formed during the deglaciation and would thus not have been removed even if there had been a large subglacial drainage. Around the Gothenburg-Mariestad-line there has thus been a change in drainage system, from a discrete system of large ice tunnels in the south to a more distributed system where the water was spread over a larger part of the bed in both linked-cavity systems and concentrated flows in the north.

The increased amount of water at the bed could also be due to climate amelioration and drainages of supra-glacial lakes (Benn & Evans, 1998). This, however, cannot explain the shape of the area with little till.

Whether the p-forms were created by a catastrophic drainage or a continuous ice-stream it was a phase that lasted for a limited period of time and ended before the final deglaciation of the study area. The striae inside p-forms are evidence that the ice must have coupled to the entire bed following the formation of the p-forms. The reason for the recoupling may have been that the high sliding velocity of the ice reduced the surface gradient of the ice sheet to such an extent that sliding velocity was reduced. If the ice could no longer be driven forward with the same velocity the ice would have coupled to the bed.

11 Conclusions

- The erosional forms found in the study area are: striae, crescentic fractures, crescentic gouges, pits, triangular pits, concoidal fractures, troughs, sickle troughs, comma forms, bowls, potholes, channels, roches moutonnées, faceted roches moutonnées, whalebacks and rock steps.
- Most proximal slopes of bedrock hills were dominated by roches moutonnées, striae, crescentic fractures, crescentic gouges, pits and p-forms (Sr-areas). Top surfaces and distal slopes are mostly plucked with rock steps and striae as the only erosional forms (Lp-areas). Towards the end of the bedrock hills the roches moutonnées normally reappear, these can be either classic roches moutonnées (Lr-areas), but also faceted roches moutonnées and whalebacks (Lf-areas). Crescentic fractures, crescentic gouges and p-forms also reappear again along with the roches moutonnées.
- Abrasion was the dominating process on proximal slopes (Sr-areas); the effective normal pressure was high and the ice-bed contact area was large. The water was channelized and had a high trough-flow velocity, eroding p-forms in the lower parts of the topography. Plucking dominated the distal slopes and cavities in front of every rock step made the ice-bed contact area considerably smaller than on the proximal slope. Water flowed in a linked-cavity system with low through-flow velocities and the meltwater erosion was therefore negligible. Towards the end of the bedrock hills abrasion again becomes the dominating process with high contact forces and large contact areas. The water-flow becomes channelized again.
- The end of the glaciation can be divided into a main intensive phase with much water at the bed and a second phase of reduced ice-flow velocity with little water and ice-bed coupling. The erosional forms were created during the first phase.
- Ramsvikslandet is part of a larger area that lacks sediments except for glaciomarine fine sediments filling out the basins between bedrock hills. The area begins at the Vänern basin and widens towards the coast, which leads to the speculation that the Vänern basin may have constituted a subglacial lake during the last glaciation and a continuous output of water could have created a fast-flowing ice-stream towards the coast, washing away the till as well as supplying the water for the formation of the p-forms.

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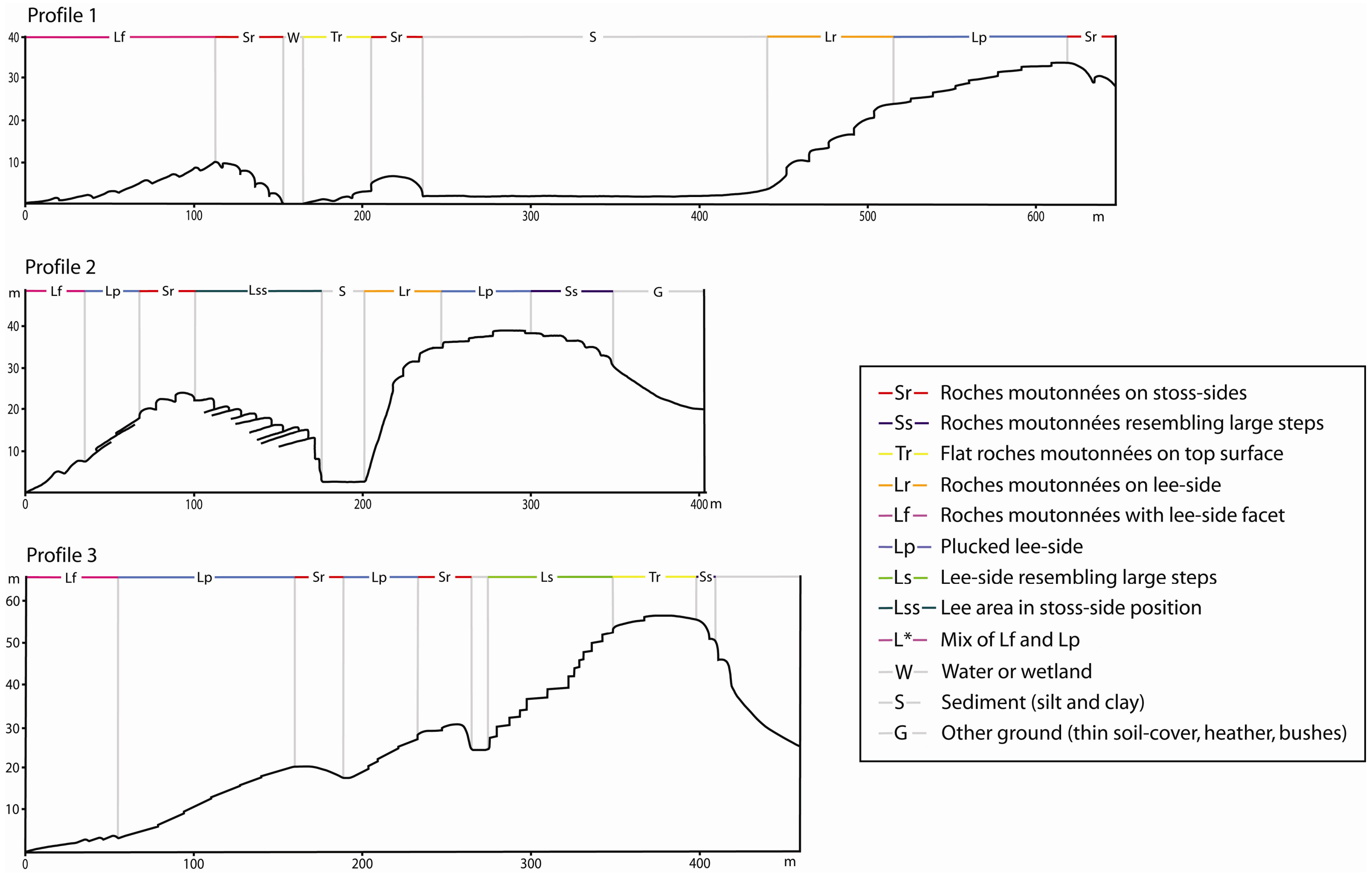
Appendix A

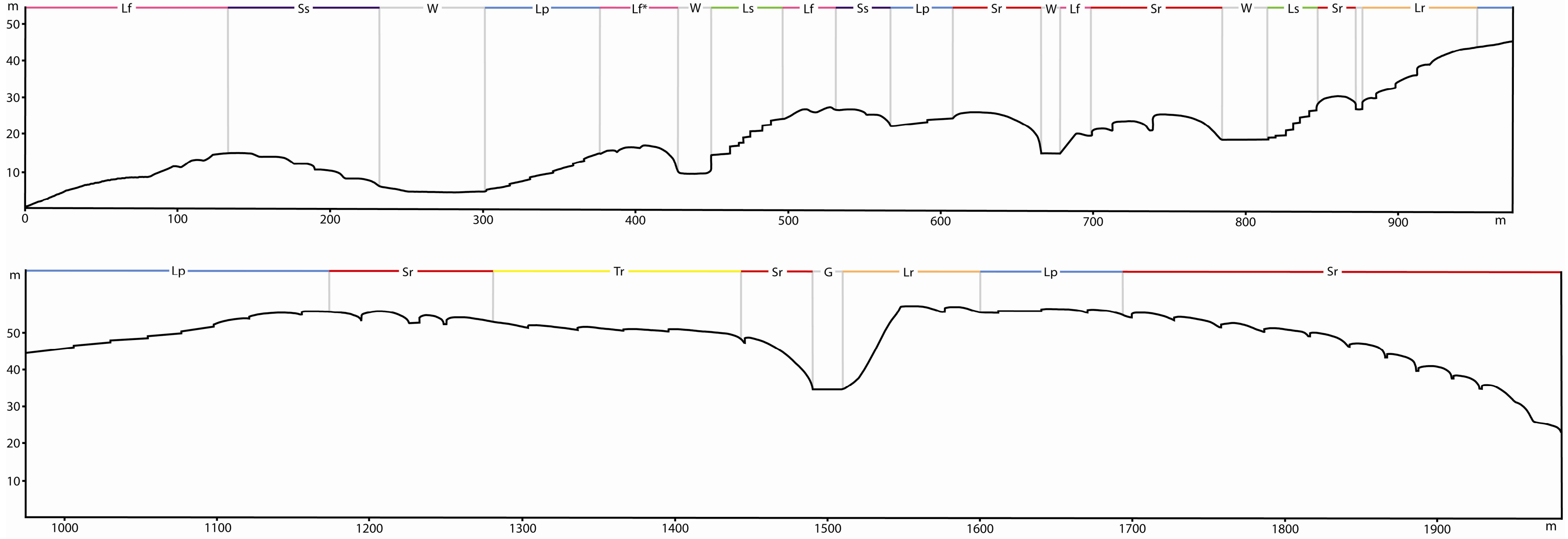

Profile 1

Profile 2

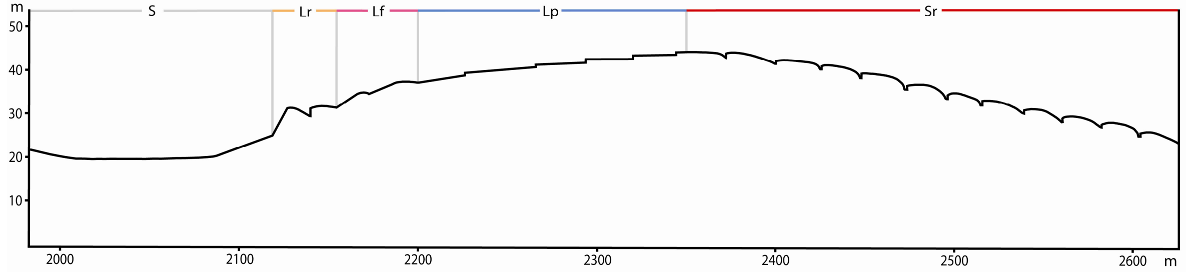
Profile 3

Appendix B

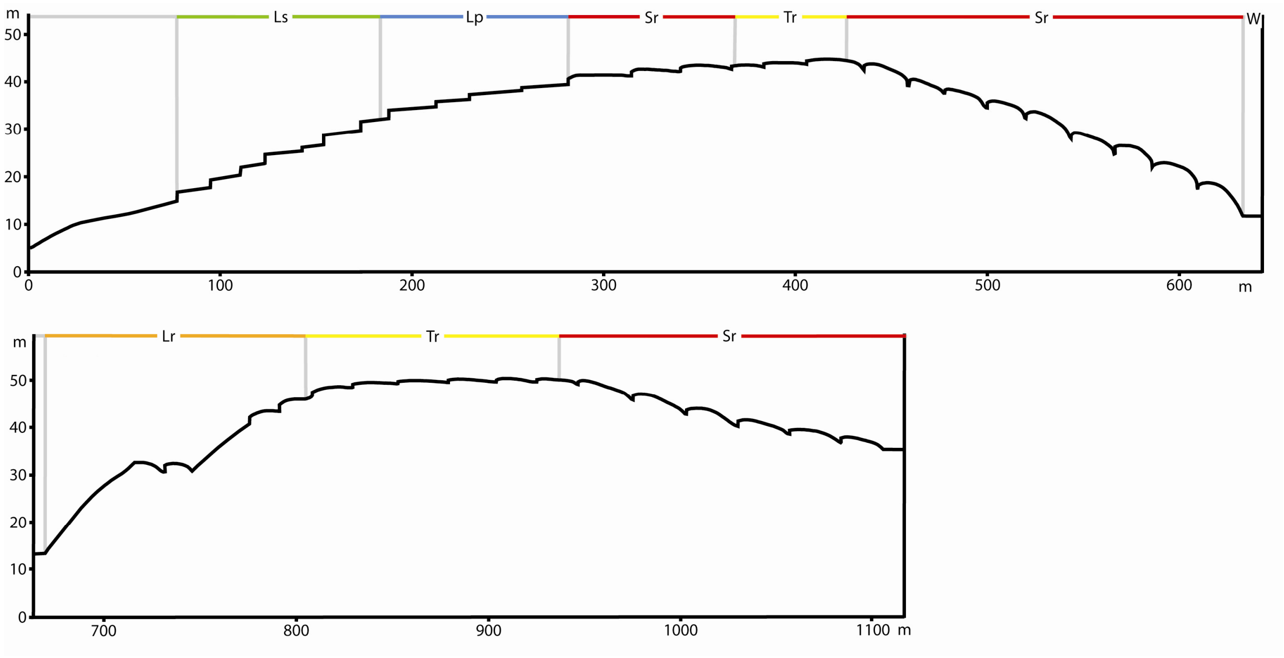
Profile 4b



Profile 4a



Appendix C



m
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Lr
Tr
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700
800
900
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1100
m

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