Research Paper C 838

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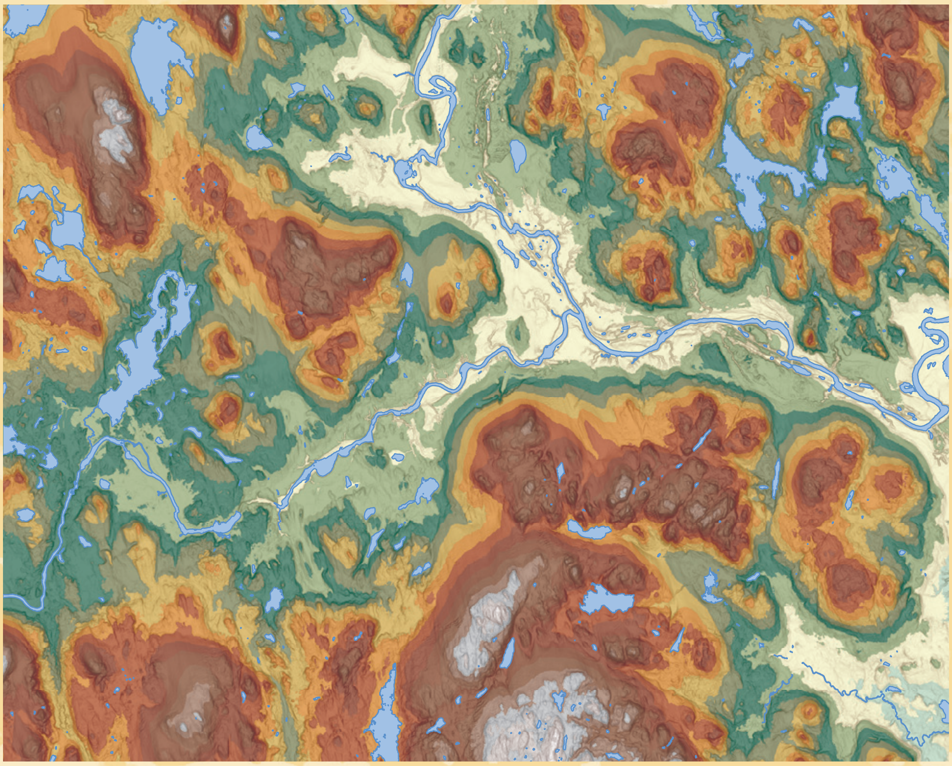

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2015

ISSN 1103-3371
ISBN 978-91-7403-308-3

Cover: Hilly relief, west of Borlänge, surrounding the confluence of Västerdalälven and Österdalälven. Map construction: Mats Olvmo. Data sources: GSD-Elevation data, Grid 2+ and GSD-Terrängkartan from Lantmäteriet.



Layout: Jeanette Bergman Weihed, SGU
Tryck: Elanders Sverige AB, 2015

# Innehåll

## Abstract

The historical development of observations, ideas and concepts in the field of large-scale geomorphology in northern Sweden is reviewed. Interpretations of the origin of landforms by different authors are discussed. The relief differentiation of basement rocks was recognised early on and flat areas in many settings were identified as a sub-Cambrian peneplain. Undulating hilly relief extends over large areas of central and northern Sweden, but no explanation was given in the early papers. Plains with residual hills in stepped sequences were also identified, particularly in the far north, and could find explanations in the international literature.

Lately the relief differentiation has been used to suggest temporary covers by relating developments to conditions in south Sweden, where the South Swedish Dome has been found to be a key area. This gives arguments for differential uplift of three Scandinavian domes: the Northern Scandes, the Southern Scandes and the South Swedish Dome.

We also summarise arguments for the view that glacial erosion has generally had little effect on the large-scale landscape. The relief of re-exposed surfaces in southern Sweden and plateaux in Norway and Greenland supports the reliability in reconstruction of stepped peneplains in the Swedish mountains as well. On the other hand, the form and depth of valleys in relation to mapped peneplains have given some hints on the locally pronounced impact of deep glacial erosion. We also note that some watergaps have been used for tectonic conclusions.

The Swedish approach with relief descriptions and studies of the relation of basement relief to covers has been found to be a good method for drawing conclusions on Phanerozoic tectonics in basement terrain.

# Introduction

This paper deals with the northern two-thirds of Sweden, including Norrland and northern Svealand (Fig. 1), with description and interpretation of major relief types of the bedrock and incised valleys. While description of relief types in basement rocks has a long tradition in Sweden (e.g. Rudberg 1960), it has not been a main theme in international geomorphology, which has mainly focused on granite landforms (Migoń 2006).

Early international literature focused on describing and interpreting stepped surfaces (Penck 1924), but in Sweden geologists and geographers have a long tradition of relating basement forms to cover rocks. A flat sub-Cambrian peneplain was identified early on (e.g. Högbom 1910). The importance of deep weathering in the shaping of landforms in bedrock was established by international studies in the 1960s and conveyed to Swedish scientists by Mattsson (1962). The relationships between hilly relief and deep kaolinitic weathering of fracture zones in relation to Jurassic and Cretaceous covers were discovered in southern Sweden (Lidmar-Bergström 1989). This later led to suggestions that some areas with hilly relief further north also could be related to former Jurassic or Cretaceous covers (Lidmar-Bergström 1995). The difference between the two major relief groups within the Precambrian terrain was thereby given an explanation for the first time. Finally, cross-cutting relationships between the main types of peneplains (sub-Cambrian flat peneplain, sub-Cretaceous hilly peneplain, epigene plains with residual hills) were used for conclusions on Phanerozoic tectonics (Stratigraphic landscape analysis, Lidmar-Bergström et al. 2013, Green et al. 2013).

The current focus in Swedish geomorphology is on glacial morphology and what it can tell us about the dynamics of former ice sheets (e.g. Kleman & Stroeven 1997, Kleman et al. 2008). Here, we instead summarise some literature on the depth of glacial erosion of importance for peneplain studies. As knowledge about relief types, peneplains, valleys and their interpretation over time is starting to vanish, there is a need to summarise our knowledge and how it can be used to draw conclusions about Phanerozoic tectonics.

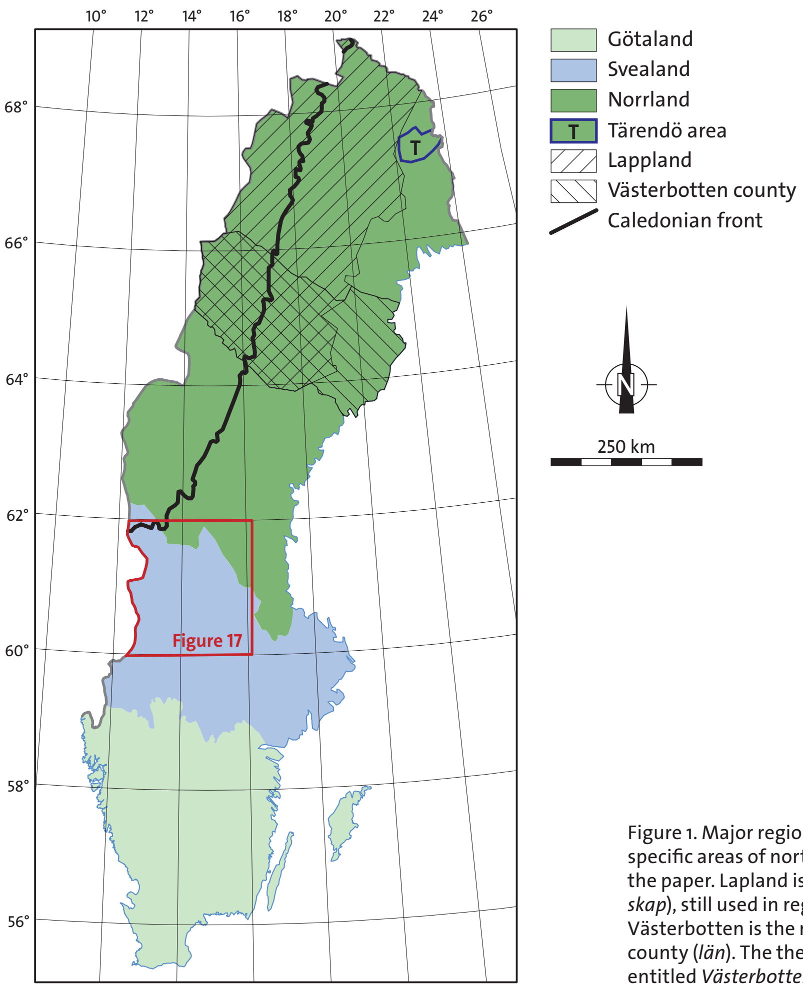


Figure 1. Major regions of Sweden and some specific areas of northern Sweden discussed in the paper. Lapland is an old county name (*landskap*), still used in regional descriptions, while Västerbotten is the notion of a present-day county (*län*). The thesis by Rudberg (1954) was entitled *Västerbottens berggrundsmorfologi*.

## Bedrock and glaciation

The forms of the bedrock have evolved in Precambrian basement rocks except for the area along the Norwegian border, where Caledonian basement rocks occur. The Scandes are areas above 700–800 m a.s.l. (e.g. Lidmar-Bergström 1996). The mountains extend over basement rocks of both the Caledonian and the Precambrian (mainly Svecokarelian) orogens (Stephens et al. 1994, Fig. 2).

The surface of the Northern Scandes reaches 2 097 m at the Kebnekaise bedrock summit. The Southern Scandes are highest in Norway (Galdhøpiggen 2 469 m) but reach 1 796 m at Helagsfjället in Sweden. In the saddle between the Southern and Northern Scandes the highest points are below 1 000 m. The highest areas of the Scandes occur within the Caledonian rocks, but these rocks reach only about 300 m in the Östersund area, which does not belong to the Scandes. Areas with Precambrian rocks reach over 1 000 m within both the Northern and Southern Scandes.

The whole study area has been covered by often cold-based ice sheets during 40–50 glacial cycles since 2.6 Ma, with long interglacials and interstadials (Kleman & Stroeven 1997, Helmens et al. 2000, Kleman et al. 2008, Helmens 2014).

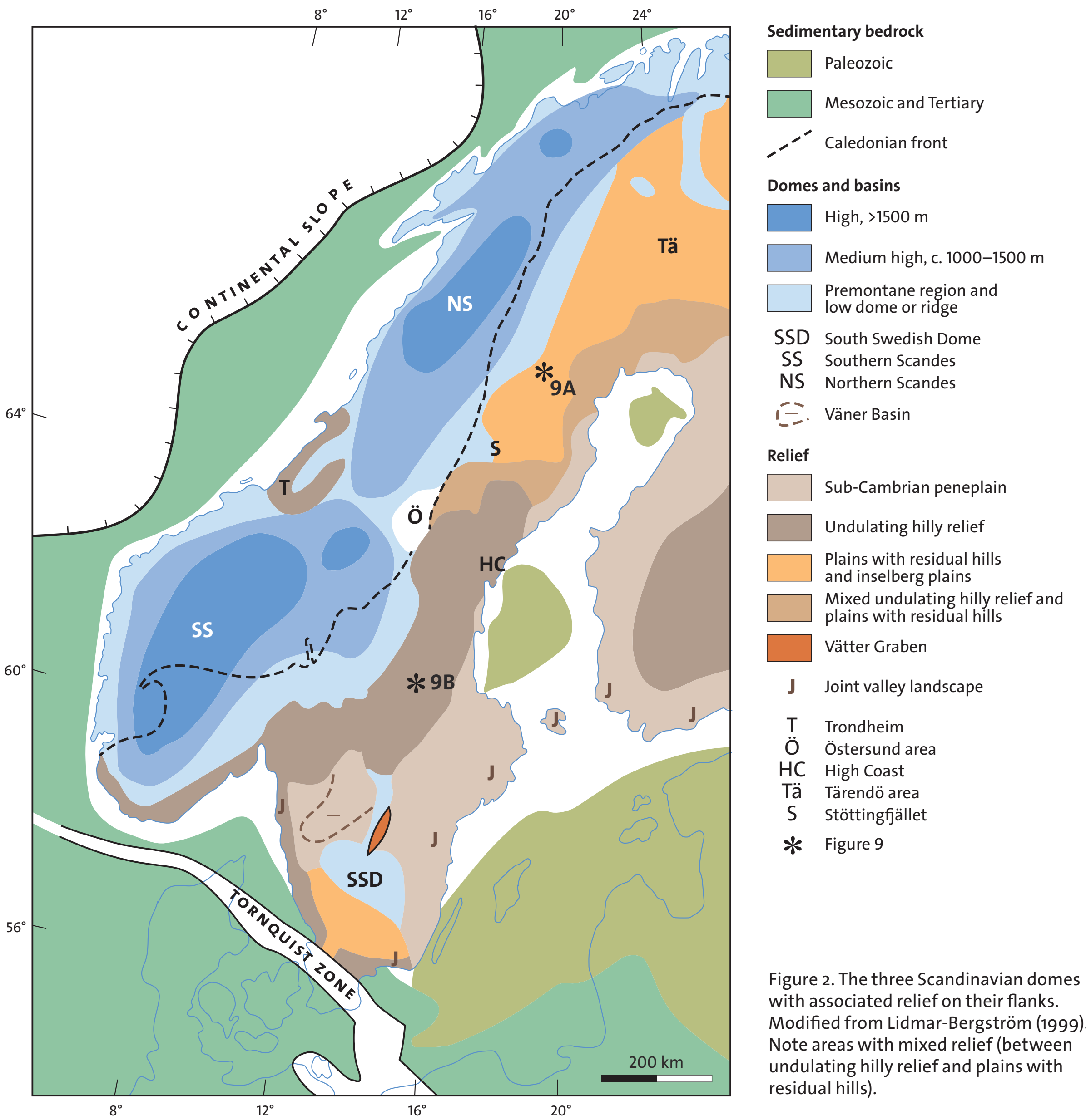


Figure 2. The three Scandinavian domes with associated relief on their flanks. Modified from Lidmar-Bergström (1999). Note areas with mixed relief (between undulating hilly relief and plains with residual hills).

## Overview of relief types

*Stepped sequences of low relief surfaces (peneplains)* were identified early on in northern Norrland (Fig. 1). Remnants of these peneplains or low relief surfaces cut across the contact between Precambrian and Caledonian basement rocks within the Scandes (Wråk 1908, Rudberg 1954). East of the mountains in northern Norrland there are stepped surfaces consisting of extensive plains across Precambrian rocks (Fig. 2). Isolated hills rise above the smooth plains, which are often covered with mires (Högbom 1906). These plains have been given different names, such as monadnock plains (Rudberg 1960, 1970, Elvhage & Lidmar-Bergström 1987), inselberg plains (Rudberg 1988, Ebert et al. 2011) and *plains with residual hills* (Lidmar-Bergström 1995, 1996). In southern Norrland and western Svealand (Figs. 1–2), the relief is instead characterised by closely spaced hills separated by valleys, and is termed undulating hilly land (Rudberg 1960, 1970) or *undulating hilly relief* (Lidmar-Bergström 1999). Both relief types – plains with residual hills and undulating hilly relief – are formed across Precambrian basement rocks. There are only few descriptions in the international literature of undulating hilly relief on Precambrian shields, whereas inselberg plains are often mentioned (Migoń 2006). As early as 1906 Högbom pointed out the marked difference in appearance between these two landscape types in the Precambrian rocks of Sweden. It was a long time before this major relief difference was interpreted.

Swedish geologists also noted in the early twentieth century that extremely flat surfaces across Precambrian basement rocks extend a long way from below Cambrian cover rocks in central and southern Sweden (see summary in Rudberg 1954). These surfaces constitute *the sub-Cambrian peneplain* (Högbom 1910, Fig. 2). This peneplain was also identified along parts of the Norrland coast bordering the Gulf of Bothnia (De Geer 1918). Such re-exposed (exhumed) surfaces have only occasionally been discussed in international geomorphological literature (e.g. Baulig 1928, Ambrose 1964, Twidale 1994), but have not been used for conclusions on Phanerozoic tectonics. In addition, valleys have been studied in terms of river profiles (Norlindh 1924) and valley patterns (Rudberg 1988, Lidmar-Bergström 1996), and used for discussions on relief origin.

The review is organised as follows. First, the discovery, mapping and interpretation of relief types are presented. Thereafter the discovery and interpretation of stepped peneplains as well as their mixing with other relief types are presented. The literature on fluvial valleys, their form and distribution, is elucidated in a following section and interpretations are given. Thereafter, the glacial effect on the landscape is reported, followed by a section with a comprehensive discussion of the origin of the various landscapes and how they are used to draw conclusions on the formation of relief and tectonics.

## Discovery, mapping and interpretation of relief types

### STEN DE GEER 1926

Geographers took over the description and interpretation of landforms at an early stage. Sten De Geer worked at Stockholms högskola 1912–1929 before becoming Professor of Geography and Ethnography at Göteborgs högskola 1929–1933. De Geer (1926) provided the first general description of the topography of northern Sweden. He mapped a zone with premontane massifs in the north and premontane plateaux further south (the premontane region). East of the broad mountain region he noted an area of *plains with rocky hills (bergkullsland*) north of the mountain Stöttingfjället (Fig. 2). Further south the topography changed drastically. Here he noted a landscape with narrow, structurally controlled valleys incised below large plateaux. He named this landscape *square plateaux landscape (rutplatålandskap*).

These two completely different landscape types within the Precambrian basement rocks of northern Sweden had already been recognised by one of the early geologists (Högbom 1906), and were now mapped for the first time. "The square plateaux landscape" (approximately "undulating hilly relief" in Fig. 2) has its most well-developed plateaux east of a low area in easily erodible Caledonian rocks around Östersund. "The square plateaux landscape" coincides here with a zone of water gaps, which had been noted by Högbom (1906). De Geer regarded the rocky hills of the plains in the north to be glacially formed rock drumlins and the structurally controlled valleys further south to be glacially eroded fracture zones, but he did not comment on the origin of the major relief difference between the two areas. Along the coast in the north he noted plains with distinct faults in some parts; a landscape he paral-

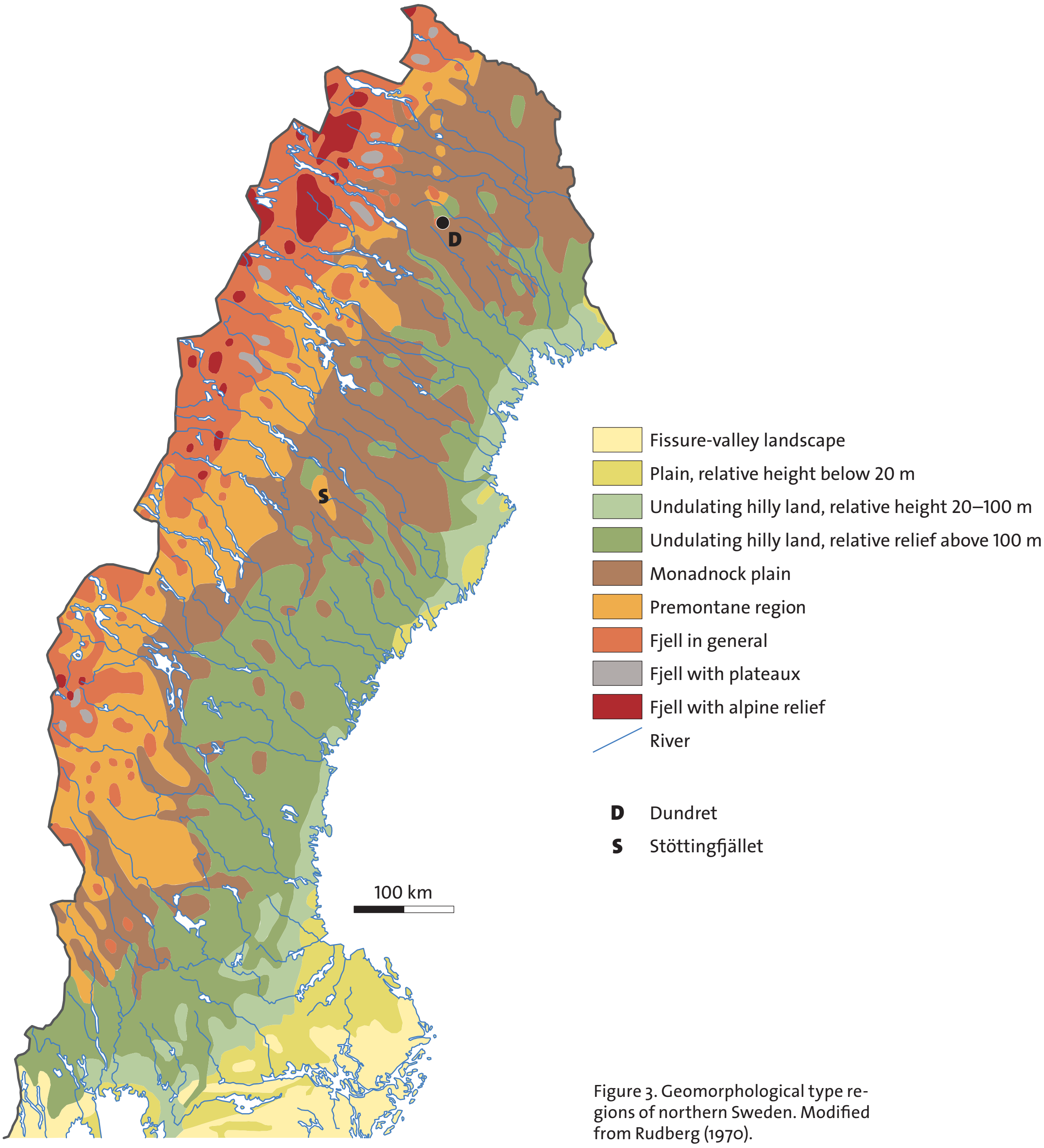


Figure 3. Geomorphological type regions of northern Sweden. Modified from Rudberg (1970).

leled with the faulted sub-Cambrian peneplain of central Sweden (De Geer 1918). He described a similar area around Tärendö, along the border with Finland (Figs. 1–2).

## STEN RUDBERG 1960 AND 1970

Sten Rudberg was Professor of Geography at the University of Gothenburg 1958–1984 (from 1961 Physical Geography, in particular). As a professor of geography in the 1960s and 1970s, Rudberg was obliged to write in geography text books. For this purpose he not only summarised the old literature, but made a new classification of the relief of the Nordic countries by examining all topographic maps (Rudberg 1960, the Swedish area also in Rudberg 1970: Geomorphological type regions, Fig. 3). He also made a map of relative relief to support his classification (Rudberg 1960, in Sømme 1960, colour map 4). For the area under discussion he discerned the following units: "*fjell* (mountains) with alpine relief" (high and steep with lofty peaks and cirques), "*fjell* with plateaux", "*fjell* in general" (with rounded forms and slopes of medium height), "premontane region" (at altitudes of 500 m to over 1 000 m with well-developed valleys), and outside the mountains:

"monadnock plain", "undulating hilly land" with relative relief between 20 and over 100 m (three categories, shown as two in Fig. 3), and "plain" with relative heights below 20 m. The latter mainly coincides with identified facets of the sub-Cambrian peneplain along parts of the Bothnian coast (Rudberg 1970). Southwards in central Sweden he also noted a small-scale structurally controlled landscape, which he named fissure-valley landscape (approximately the "joint valley landscape" of Fig. 2). It is noticeable that he identified "monadnock plains" over large parts of Lapland, while "undulating hilly land" (Norrland Terrain) was identified only as a border inside the coast in the north, but covering most of the areas east of the mountains in the south. He thus confirmed the observation by De Geer (1926) and Högbom (1906) of two strikingly different landscapes to the south and the north of Stöttingfjället within the area of Precambrian rocks in northern Sweden. Unlike De Geer (1926), Rudberg always claimed (in lectures) that there are neither squares nor plateaux, but simply "undulating hilly land" in southern Norrland and western Svealand. This is discussed further in section *S. Rudberg 1988* below.

## CHRISTIAN ELVHAGE & KARNA LIDMAR-BERGSTRÖM 1987

Christian Elvhage was the first person to make a digital relief map of Sweden, one of the first digital relief maps in the world. This digital relief map was first published by the National Land Survey of Sweden as a separate map with interpretation by Lidmar-Bergström (Sveriges relief 1986). A pattern of lineaments (topographically expressed fracture zones) was later extracted (Fig. 4, Elvhage & Lidmar-Bergström 1987). The relief and lineament pattern of Sweden was analysed in relation to a map of dolerite dyke swarms and Precambrian domains, a map of remnant cover rocks on land and offshore (Elvhage & Lidmar-Bergström 1987 with new information on surrounding cover rocks summarised by Flodén 1984, cf. Fig. 2), and a map of weathering residues.

Analysis of the digital relief maps revealed that the orientation of fractures differed between different Precambrian domains, but that there was also a considerable difference in the expression of fractures in the morphology from area to area, which was explained by weathering and subsequent erosion. The lineament pattern of Sweden clearly showed the difference between areas of Lapland with only few lineaments (approximately the area of "plains with residual hills") and the southern area of northern Sweden with well-expressed lineaments (corresponding to "undulating hilly relief", cf. section *De Geer 1926*). As regards lineaments, it was concluded that the southern area of northern Sweden resembles areas of southern Sweden with re-exposed sub-Cretaceous hilly relief on an inclined surface, while the former area can be associated with the South Småland Peneplain (a plain with residual hills) in the south, cutting off the hilly relief and formed in post-Cretaceous time (Fig. 5, Lidmar-Bergström 1982). For the first time it was possible to give an explanation of the origin of "undulating hilly relief."

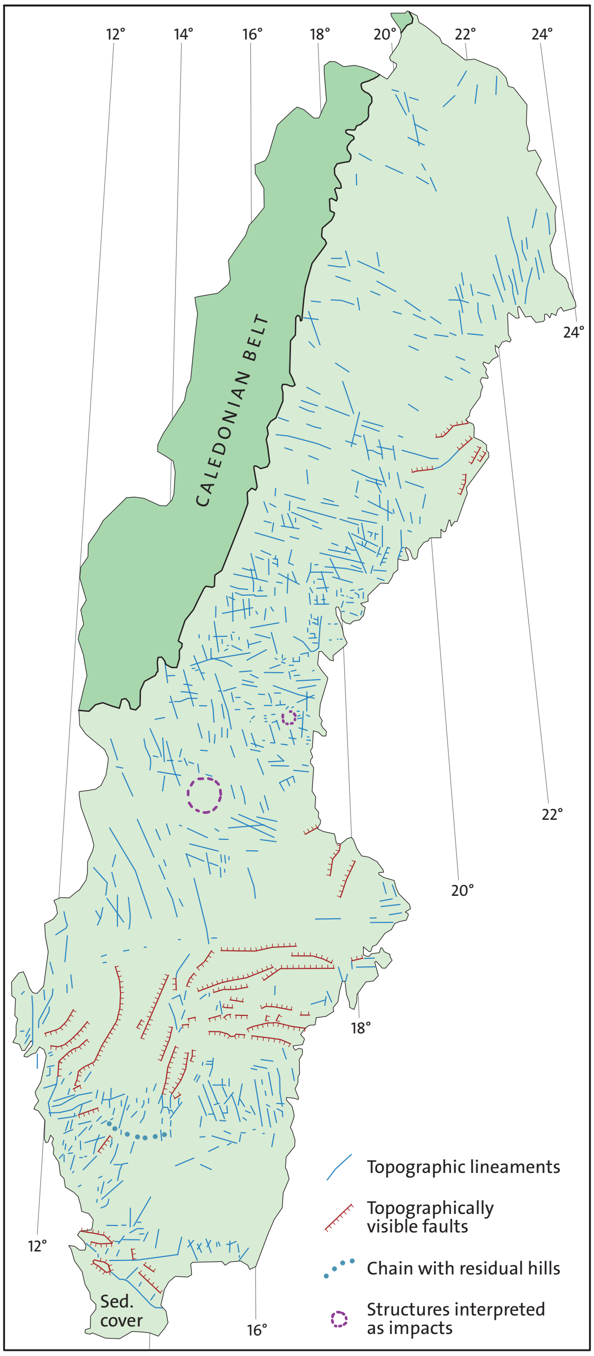


Figure 4. Topographical lineaments. Modified from Elvhage & Lidmar-Bergström (1987).

Weathering remnants had been encountered in the iron-ore zone within the undulating hilly relief (Geijer & Magnusson 1926). Weathering has resulted in "soft ores" (a kind of saprolite), which consist of products from two separate processes. Reducing solutions have first formed secondary siderite and kaolinisation (real saprolite), while martite and limonite are the work of oxidising waters during a later stage (Geijer & Magnusson 1926).

The structural control of "the undulating hilly relief" (the Norrland Terrain) was obvious when Figures 3 and 4 were compared. The different forms, the pattern of weathering residues, and the clear border between the Norrland Terrain and the flat sub-Cambrian peneplain to the east and south, with its remnant Cambrian covers (Fig. 2), provided arguments for the geological and geomorphological development of the area: the well-preserved sub-Cambrian peneplain must still have had a protective Lower Paleozoic cover when the fracture zones of the present Norrland Terrain were exploited by deep weathering, which eventually led to the formation of the structurally controlled "undulating hilly relief". Information from the geological literature gave some further indications of the processes involved. Any re-exposure and re-shaping of a flat Precambrian basement area from below a former Lower Paleozoic cover could not have occurred until after the Carboniferous (Elvhage & Lidmar-Bergström 1987, pp. 353–354), and any deep weathering of fractures in a warm and humid climate could not have occurred until the latest Triassic (Lidmar-Bergström 1982). Thus, deep weathering of the fracture zones of a re-exposed Precambrian basement most likely did not occur until the Jurassic or Cretaceous, with formation of the "hilly relief". It was also concluded that the preservation of this "undulating hilly relief" in southern Norrland and western Svealand until the present day was due to a subsequent cover and late re-exposure. The hilly relief must have been protected below Upper Cretaceous cover rocks in line with the conditions in southern Sweden (Fig. 5) and remained covered during formation of "the plains with residual hills" in northern Norrland during the

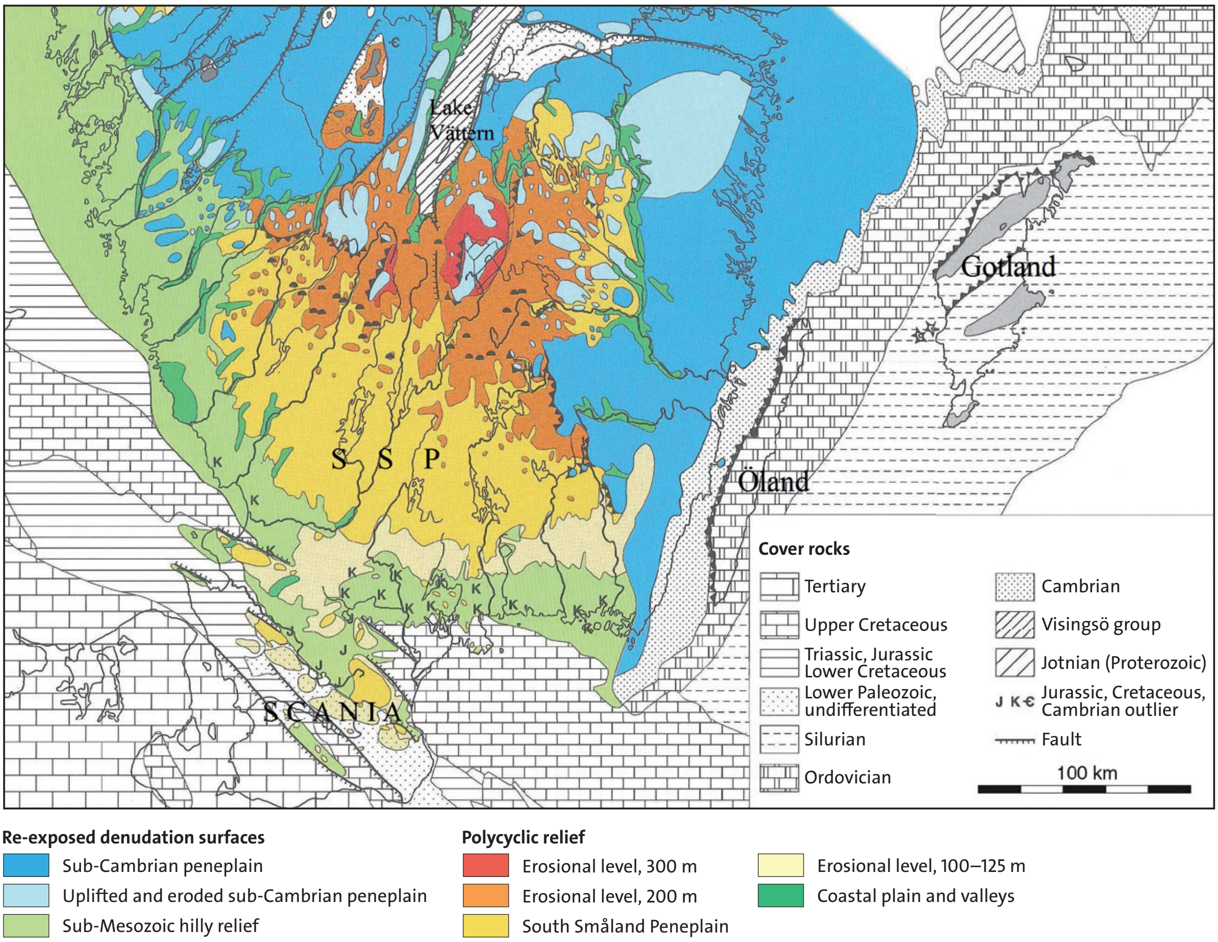


Figure 5. Major peneplains of the South Swedish Dome (SSD). Fault scarps, erosional slopes and residual hills are marked. Modified from Lidmar-Bergström (1994).

Tertiary. Elvhage & Lidmar-Bergström (1987) also suggested that the final stripping of saprolites and renewed weathering and erosion across the "undulating hilly relief" occurred in conjunction with Late Tertiary tectonic uplift.

## S. RUDBERG 1988

Rudberg (1988) summarised the knowledge he had gained about the gross morphology of Fennoscandia. He discussed its explanation under six headings, of which five will be presented here, and one, the river network (number 3 of Rudberg), in a later section.

### The relation landform – rock type (1)

In summary it is concluded that within the Precambrian rocks, differences in rock type do not have much impact on relief, with some exceptions, such as quartzites and some basic rocks, which give rise to high hills. In the Caledonian basement the situation is different, since the rocks are more differentiated. Under this heading he also discussed the importance of lost rock sequences and in particular of sedimentary rocks. He noted that the surface of the Precambrian basement below the easternmost Caledonian nappes slopes down westwards and that an easterly continuation of the nappes should be sought at higher levels than the present topography (cf. Fig. 11).

### Rock structure and landscape (2)

Joint aligned valleys (the fissure-valleys of Rudberg, Fig. 3, *sprickdalar*) are an important feature of the landscape in central and southern Sweden. The old literature mainly concerned geology and discussed the origin and age of the joints and fracture zones, whereas Rudberg focused on the evacuation of debris and discussed the fluvial and glacial alternatives for their expression in the relief as valleys.

Rudberg never explained any landscapes in the northern two-thirds of Sweden as structurally controlled. Instead, he expressed the view in personal communications that De Geer (1926) was wrong in his interpretation of the relief in southern Norrland and western Svealand as being structurally controlled. Rudberg (1954) had interpreted the landscape in Västerbotten as fluvial, and it appears that he believed fluvial processes to be responsible for the present appearance of the undulating hilly land (relief) in southern Norrland and western Svealand. He did not accept the clear structural pattern of the digital relief map, particularly well expressed in southern Norrland (Sveriges Relief 1986, Elvhage & Lidmar-Bergström 1987, Fig. 4). Knowledge of the impact of deep weathering on relief was new and he did not discuss its importance for expressing structures in the morphology as Elvhage & Lidmar-Bergström (1987) had done.

### Erosion surfaces (4)

The re-exposed sub-Cambrian peneplain is a major feature in the relief of Sweden. Rudberg thought that younger, re-exposed surfaces might only occur in southern Sweden. He suggested lost Lower Paleozoic rocks along parts of the Bothnian coast and in the Tärendö area (Figs. 1–2) as an explanation for the flat surfaces there (cf. De Geer 1918, De Geer 1926). Rudberg (1954) had made a thorough study of fluvial landscape generations (stepped peneplains) in the Västerbotten County (see section *S. Rudberg 1954*). It is here of interest to note that Rudberg (1988, p. 154) expressed the following view: "For the old regenerated surfaces like the sub-Cambrian peneplain a main suggestion for studies would be the interference with younger erosion surfaces, truncating the old one at low angles." This had already been performed for a limited area of southern Sweden concerning an inclined, regenerated sub-Cretaceous surface, cut off upwards by a horizontal plain (Lidmar-Bergström 1982, Fig. 5). Rudberg had accepted the dating of the horizontal plain as being younger, i.e. of Tertiary age (Rudberg 1982), and changed the dating from Mesozoic in his map "Peneplains and cyclical denudation surfaces" (Rudberg 1970) to Younger peneplain, probably Tertiary, when he reprinted this map in the 1988 paper.

### Climatic geomorphology (5)

Rudberg here discussed "the inselberg plains", which in his early dissertation (Rudberg 1954) had been related to a warm climate. He noticed in the present paper that the inselbergs are surrounded by pediment-like low angle slopes(surfaces) and he favoured an explanation including slope retreat of the inselberg side exemplified by Dundret (Fig. 3), where the boundary of the gabbro extends outside the boundary of the inselberg. Rudberg (personal communication in the early 1980s) saw the inselberg plains as having a higher genetic position (i.e. higher position during formation) than the "undulating hilly relief", although these relief types now partly occupy the same height intervals, but he gave no explanation for this idea.

### Glacial erosion (6)

In short, Rudberg discussed new advances in glaciological research, Scandinavian glaciations, cold-based glaciers, glacial striae and roche moutonnées, as well as some erosional features in the mountains, such as trough valleys, closed basins and cirques. He expressed general uncertainty about the effect of glacial erosion and noticed without any references that it seems popular to regard glacial erosion as weak. From his own experience he remarked that "archipelago forms like those in Scandinavia and thought to be typical of the glacial landscape, are found also in never glaciated areas without stoss- and lee-side of course." He particularly noted the reshaping of inselbergs to *flyggberg*, a kind of giant roche moutonnées. Some of his comments on the glacial effect on valleys are discussed in the section *Fluvial valleys and their implications*. In another paper (Rudberg 1992), he noted that glacial erosion has generally been faint across plains, but more pronounced along mountain valleys.

### K. LIDMAR-BERGSTRÖM 1994, 1995 AND 1996 The sub-Cambrian peneplain and further relief classification

Improved topographical maps had appeared in the mid 1990s. They were based on aerial photographs and fixed points in the terrain from which detailed contours (5 or 10 m interval) were constructed, which were then used by the National Land Survey of Sweden to construct a digital database. Mapping of stepped peneplains (Lidmar-Bergström 1994, 1996) as well as the re-exposed sub-Cambrian peneplain and other relief classes (shown approximately in Fig. 2) was carried out by Lidmar-Bergström (1994, 1995). It was based on the combined analysis of contour maps with 25 m contour intervals and closely spaced digital profiles. Both horizontal and inclined peneplains could thus be identified.

The *sub-Cambrian peneplain* predominated in south-east Sweden, both as an extremely flat surface close to its cover rocks and as a continuation in plateaux and summits further away. This peneplain was shown to continue along parts of the east coast also in the north (Figs. 2, 6). Lidmar-Bergström had continued Rudberg's identification of a landscape with joint aligned valleys in southern Sweden (fissure valley landscapes of Rudberg 1960, 1970). In parts of south and west Sweden, it is clearly a part of the sub-Cretaceous relief (Figs. 2, 5). In eastern central Sweden (the Stockholm region), the landscape is rough, with steep slopes along shallow valleys but with summit plateaux as a continuation of the coherent sub-Cambrian peneplain, and it is therefore included in the area of the sub-Cambrian peneplain (marked J in Fig. 2).

Similar observations of summit plateaux without residual hills were made in parts of Norrland in the "large-scale joint valley landscape" (the north-eastern part of the undulating hilly relief, Fig. 2). The high coastal plateaux here were identified as the sub-Cambrian peneplain (Fig. 7) and explained by late uplift along coastal faults, east of which Cambrian cover rocks occur (Axberg 1980). These observations and interpretations were in accordance with those by Ahlmann et al. (1942). The mapping of the sub-Cambrian peneplain confirmed many of the earlier observations in the north, including faulting of the sub-Cambrian peneplain along the coast (Fig. 8A). Tilted triangular blocks were identified along the Norrland coast with the aid of their identified sub-Cambrian summit plains. One such triangular block has its highest point at Hornberget, 561 m a.s.l. (Figs. 6–7).

Lidmar-Bergström (1994, 1995) mapped four major relief classes besides the re-exposed sub-Cambrian peneplain of northern Sweden. The *highlands* extend above 600 m a.s.l., including both the mountain region and the premontane region of previous authors (cf. Fig. 2). East of the mountains, *plains with residual hills* were identified mainly in Lapland, northern Norrland. The landscape further south, "the square plateaux landscape" of De Geer (1926) and "the undulating hilly land" of Rudberg (1960, 1970), was divided into two groups: *large-scale joint valley landscapes* with plateaux close to the coast in the northern part (cf. above), and *undulating hilly land* in the southern part. The idea of the "large-scale joint valley landscape" and the "undulating hilly land" (together: undulating hilly relief in Fig. 2) having resulted from Mesozoic deep weathering, subsequent covering and late re-exposure had first been put forward by Elvhage & Lidmar-Bergström (1987).

A zone south of Stöttingfjället was mapped as belonging to stepped plains with residual hills (Lidmar-Bergström 1996, Fig. 6), but this interpretation can be questioned (section *Undulating hilly relief* in the *Discussion*). The area belongs to a type of relief that is shown as transitional between the two relief types "undulating hilly relief" and "plains with residual hills" in Fig. 2). Along the coast, this type of relief was described as "mixed relief" by Lidmar-Bergström (1996).

### The importance of former covers in preserving relief

A literature review on the occurrence of all remnants of cover rocks on the Precambrian basement of Sweden clearly showed that the Precambrian bedrock was denuded to low relief even before sedimentation of the Middle Late Riphean (Jotnian) cover rocks within areas underlain by older orogens (Lidmar-Bergström 1996). These cover remnants are partly preserved in a few minor basins (Lidmar-Bergström 1996, 1–5 in Fig. 14), which are thereby explained as old fault basins. However, profiles elucidating the relationships between basement and cover rocks showed that it is only the younger sub-Cambrian peneplain that is of major importance for the shape of the present land surface

(Lidmar-Bergström 1996). The sub-Cambrian peneplain constitutes a primary peneplain, from which all relief in the Precambrian basement evolved later during different periods of exposure.

There is a sharp boundary between the flat sub-Cambrian peneplain and undulating hilly relief in central Sweden but no corresponding lithological boundary (Fig. 2). The two relief types have the same

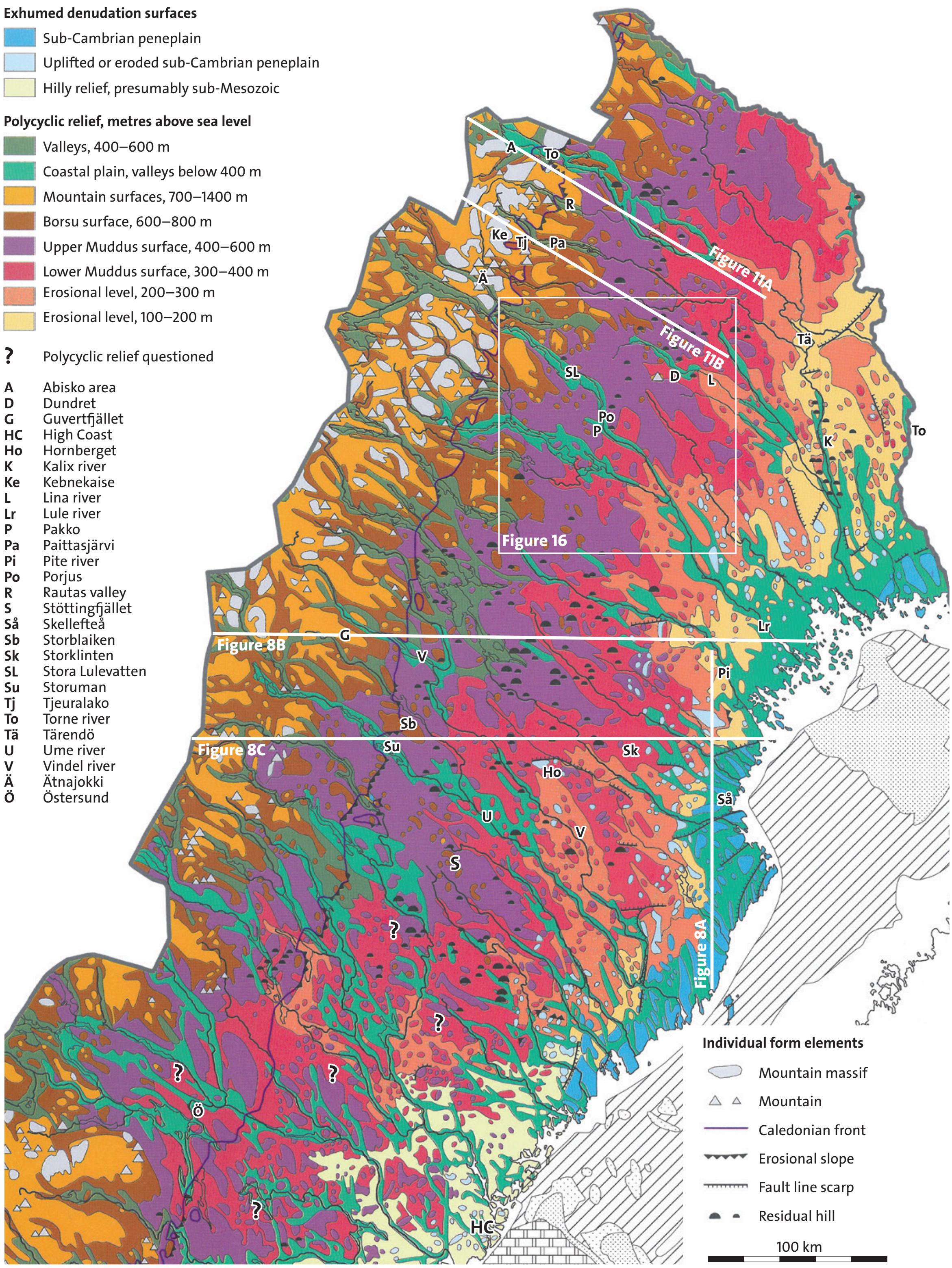


Figure 6. Landforms of the bedrock in northern Sweden. Locations of Figs. 8, 11 and 16 are shown. The Scandes formed in both Caledonian and Precambrian basement rocks. Legend for cover rocks in the sea, see Fig. 5. Modified from Lidmar-Bergström (1994).

appearance as the re-exposed sub-Cambrian flat peneplain and the sub-Cretaceous hilly peneplain around the South Swedish Dome (Lidmar-Bergström 1988, Fig. 5). The latter is associated with remnants of deep kaolinisation and remnants of the Cretaceous cover. Within the hilly relief of central Sweden there is partial alteration of the iron ores to soft ores and of their surrounding basement to kaolin clays (Geijer & Magnusson 1926). This supports the view that the hilly relief was caused by uplift and re-exposure of the basement surface, with subsequent formation of deep saprolites along fracture zones, most likely in the Mesozoic, while the sub-Cambrian peneplain to the east still had a Lower Paleozoic cover.

## Origin of "plains with residual hills"

Rudberg (1988) had made a few observations about inselbergs in northern Norrland. He noted that they are surrounded by a low angle basal slope, which he considered to constitute a pediment. This was confirmed by Lidmar-Bergström (1995 ) from studies of contour maps. The inselbergs are of a limited extent in plan and rise from larger bedrock compartments that are of similar size in plan to the larger hills of the

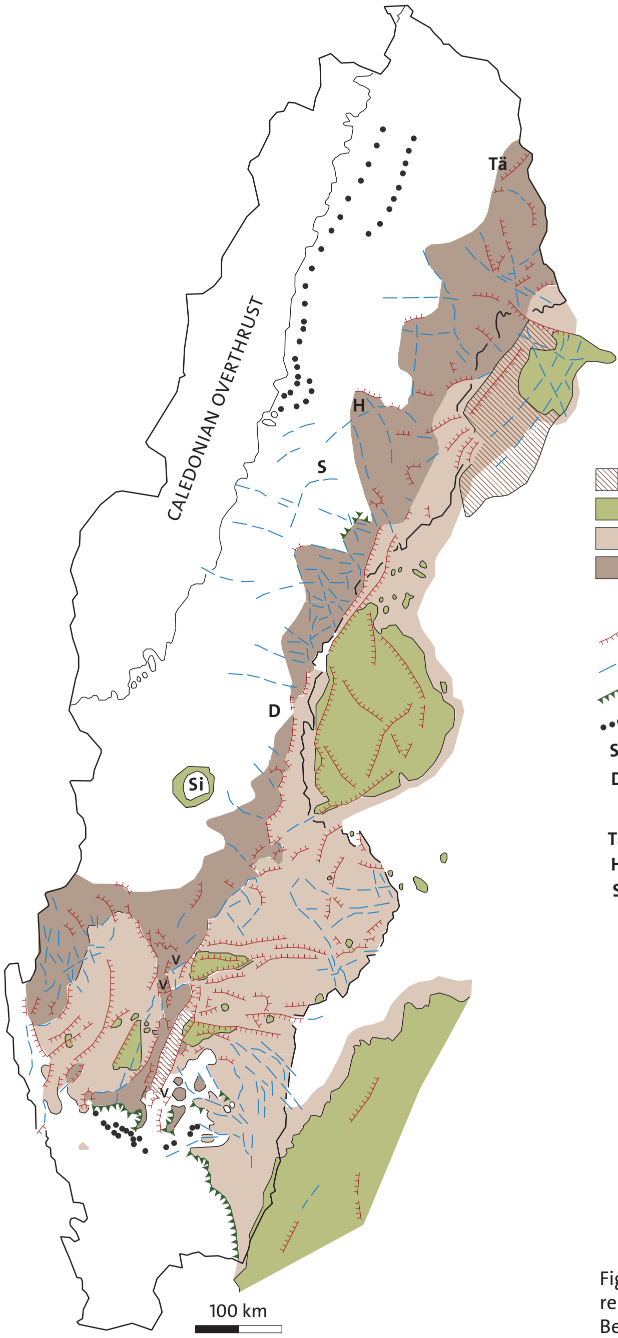


Figure 7. The sub-Cambrian peneplain with related tectonics. Modified from Lidmar-Bergström (1996).

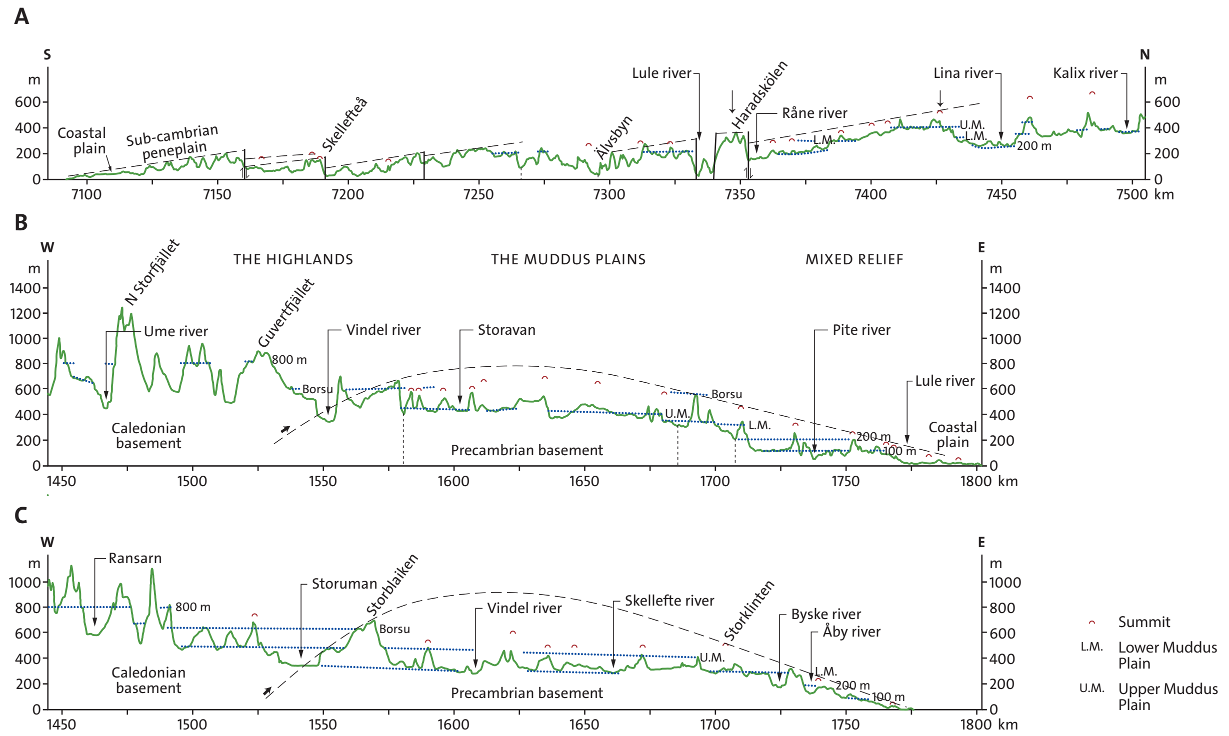


Figure 8. **A.** The faulted sub-Cambrian peneplain in a north–south profile along the Bothnian coast with hilly relief around Älvsbyn and the stepped peneplains above 200 m a.s.l. North–south grid 1740. **B.** East–west grid 7300. **C.** East–west grid 7240. East–west profiles across the highlands, the Muddus Plains and the mixed relief inland from the coast. Note that the sub-Cambrian peneplain can be followed in the summits for some distance. Modified from Lidmar-Bergström (1996). For location, see Fig. 6.

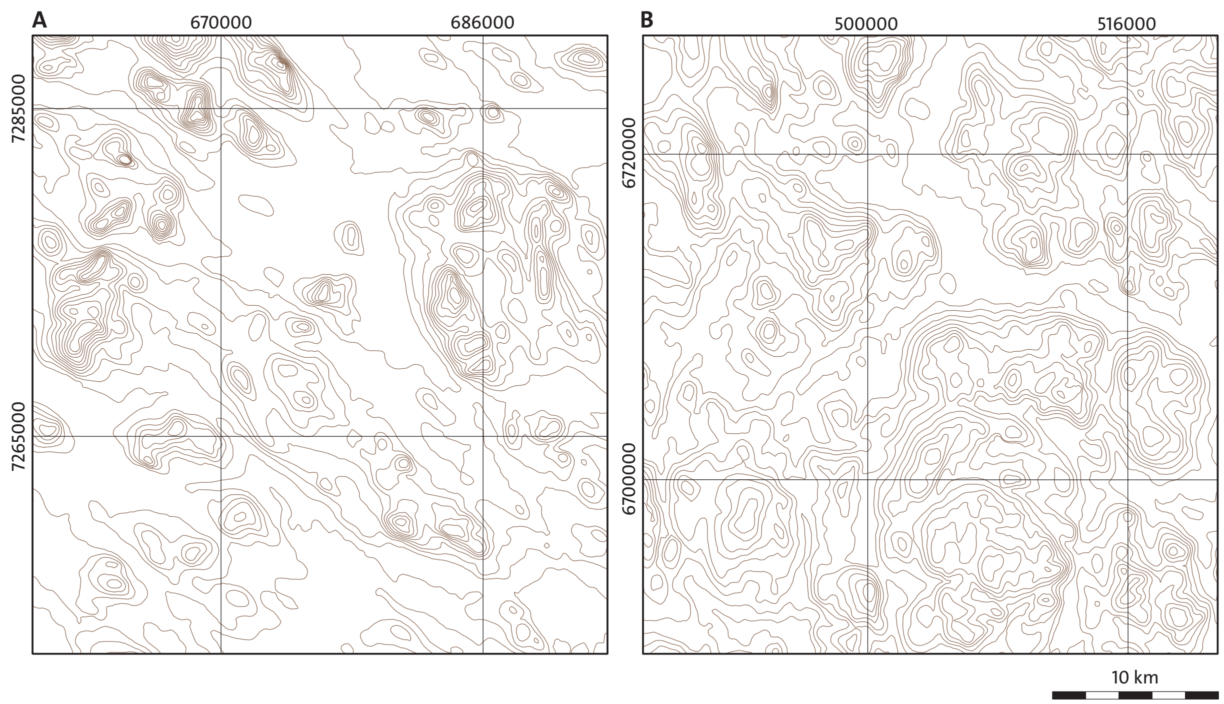


Figure 9. **A.** Plains with residual hills (inselberg plains) south-west of Arvidsjaur. The basal plain is at 400–500 m (Upper Muddus) and the highest inselbergs rise to just above 725 m. **B.** Undulating hilly relief west of Borlänge with a relative relief of about 300 m. The Dalälven River crosses the area below 200 m and the highest point is above 500 m. Contour intervals 25 m. Co-ordinate system Sweref99. For location, see Figure 2.

"undulating hilly land (relief)" further south (Fig. 9, Lidmar-Bergström 1995). The configuration of the hills within the "undulating hilly relief" is guided by major fractures (Elvhage & Lidmar-Bergström 1987). The difference in shape between the hills in the north and those in the south supported the conclusion that the landscape in the north, with small isolated inselbergs rising from a distinct base, must be the result of further development of a sub-Cretaceous hilly etch surface after its re-exposure (Lidmar-Bergström 1995). The occurrence of less clayey weathering (Hirvas et al. 1988) supports the suggestion that slope retreat occurred after erosion of kaolinitic saprolites by loosening of bedrock compartments along weathered fractures. The analysis of forms and saprolites in relation to climate changes suggested a Tertiary age for "the inselberg plains" in the north, when the hilly relief types in southern Norrland and central Svealand are likely to still have had a protective Upper Mesozoic cover (Lidmar-Bergström 1995).

### K. LIDMAR-BERGSTRÖM 1999
### Relief differentiation, causes and implications

The transition of the basement surface during times of exposure from the sub-Cambrian peneplain to undulating hilly relief during the Mesozoic and eventually to plains with residual hills during the Tertiary was summarised by Lidmar-Bergström (1995) and later simplified (Lidmar-Bergström 1999, Fig. 10A). The

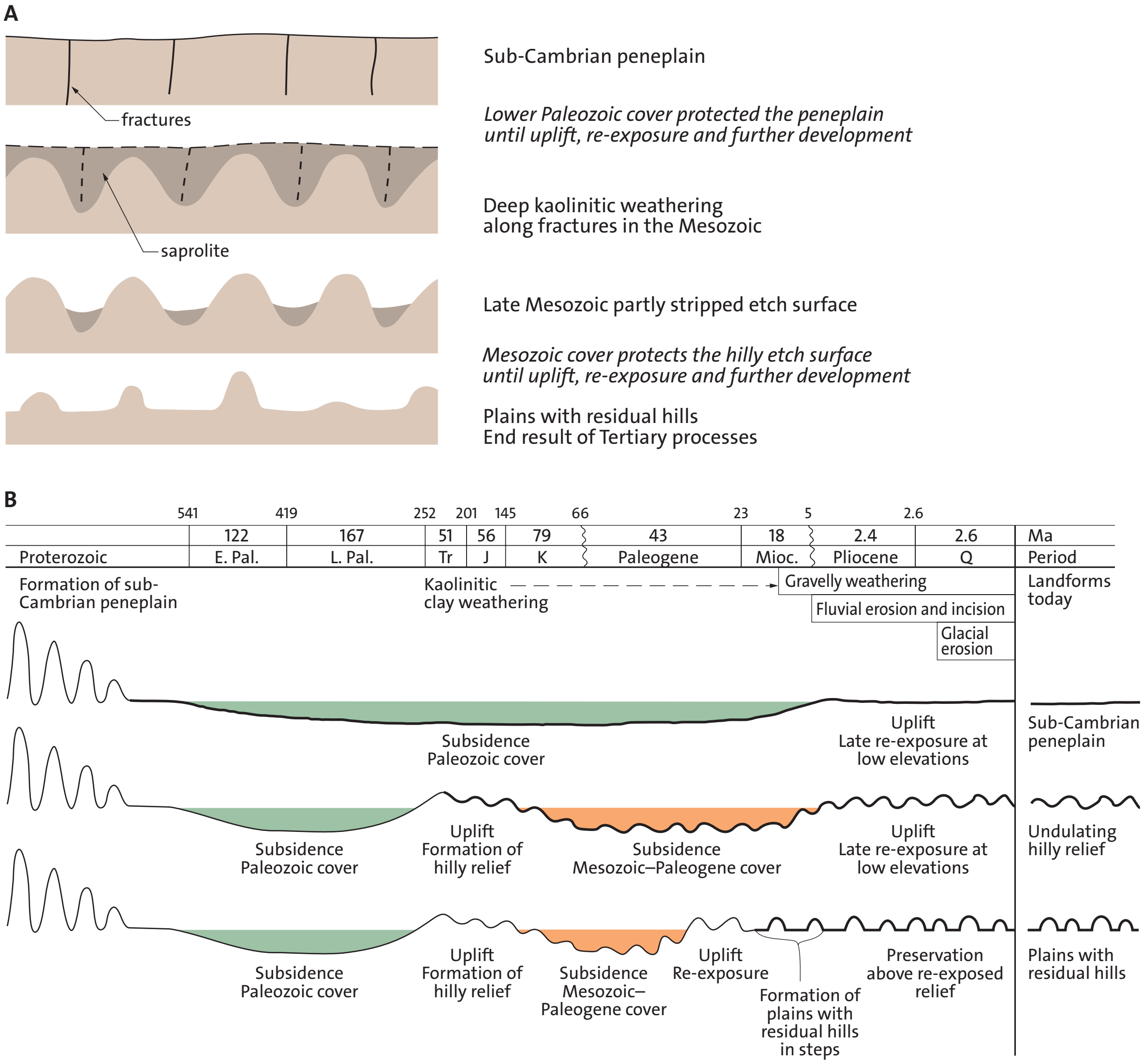


Figure 10. **A.** The transition of the basement surface from a primary peneplain (generally a sub-Cambrian surface) to undulating hilly relief during a Mesozoic period of exposure and eventually to plains with residual hills, where exposed during the Tertiary as summarised in Lidmar-Bergström (1999). **B.** Summary diagram illustrating the formation of the three main relief types in Precambrian basement rocks by uplift with subsequent relief formation and subsidence-with subsequent covering over time: the sub-Cambrian peneplain, undulating hilly relief and plains with residual hills.

present mosaic of landforms was explained by protection by cover rocks of different age lying directly on basement, which had been uplifted and exposed to weathering at different times with different climates (Fig. 10B). This implies differential uplift and subsidence of the Precambrian basement over time. Where the old relief is preserved today as the sub-Cambrian peneplain or as undulating sub-Mesozoic relief, there have been long-lasting protective covers of Lower Paleozoic rocks and Mesozoic rocks, respectively, resting directly on basement.

### The differential uplift of the Scandinavian mountains

The South Swedish Dome had been identified by Lidmar-Bergström (1988, Fig. 5). A simplified map of Scandinavia was constructed (Fig. 2) based on experience of her mapping of south Sweden (Lidmar-Bergström 1988) and relief classification by Rudberg (1960). It was noted that the undulating hilly land occurred south-east of the Southern Scandes, whereas the plains with residual hills occurred east of the Northern Scandes. Closer examination revealed that the plains with residual hills do not continue to the south of Stöttingfjället. Here, a zone with "mixed relief" was instead identified. Structures are well expressed in the landscape here (Fig. 4) but at the same time there is a distinct base level for the structural relief (cf. Fig. 6). The differences in relief east of the Northern and Southern Scandes respectively could indicate long-lasting covers over the hilly relief as in southern Sweden and thus different uplift histories of the two mountain areas.

### KARIN EBERT, ADRIAN M. HALL & CLAS HÄTTESTRAND 2012A: SHAPING OF INSELBERGS

Ebert et al. (2012a) studied the size, shape and height range of 794 inselbergs in northern Norrland using digital elevation models (DEMS) and examined the controls on inselberg formation by integrating field mapping, geological map data and fracture patterns within a GIS framework. They noted the location of inselbergs in relation to stepped palaeosurfaces and, at some locations, documented their situation as isolated inselbergs on a lower step. They found structure (particularly sheet structure) and gruss weathering to be important factors in inselberg formation during the Neogene. Some inselbergs are very high in the north-west and they argued that this suggested they had taken longer to form, which the authors related to kaolinised weathering along some fractures (Frietsch 1960). They also noted that granite inselbergs have dome forms determined by joint patterns. They could not identify any "soft ore" in connection with the Kiruna iron ore, which supports the observation by Geijer & Magnusson (1926) that only a younger oxidising weathering of the ore body has occurred here, not the reducing older weathering that has caused saprolite formation in central Sweden.

## Stepped peneplains

### OBSERVATIONS AND IDEAS ON STEPPED PENEPLAINS IN THE CLASSICAL INTERNATIONAL DISCUSSION

In contrast to the Swedish focus on different relief types and re-exposed relief, much of international research in geomorphology in the first half of the twentieth century focused on stepped peneplains. Rudberg (1954 pp. 84–86) gave the following summary, translated and abridged by the present authors:

"The primary observations were made early on. Ramsay (1846) describes from Wales a smooth, slightly inclined plain with higher residuals above incised valleys. This was a primary observation met with in many subsequent studies. The ideas on the development of fluvial relief derive mainly from the American school, represented by Gilbert, Powell, Dutton and Davis. Powell described subaerial denudation as working towards a flat, levelled plain and elucidated the notion of base level (Powell 1875, 1876). Davis seldom mentioned polycyclic relief. However, stepped plains and successive generations of valleys were identified in Europe. The most influential work was written by W. Penck (1924). He introduced the term "piedmonttreppe" and explained it with continuous accelerated uplift and not intermittent uplift as usual."

Base level, often the sea, was the guide for peneplain formation in the past, and intermittent uplift was mainly thought to have caused the present, often high, positions of peneplains. The present time was thus considered a time with high position of continents. Rudberg (1954) made a study of stepped peneplains in Västerbotten (Fig. 1), the interpretation of which he based on the valley-in-valley development as described by Baulig (1928). During the 1950s, 1960s and 1970s, King (e.g. 1951, 1976) described major steps along the coasts of the southern continents and related their initiation to

Tertiary intermittent uplift after Mesozoic continental break-up and formation of a new coast. Brown (1960) mapped several steps in Wales, and Sissons (1976) and Hall (1991) in Scotland. The origin of these steps has remained obscure and their relation to former general base levels has been questioned. However, studies of the formation of peneplains in southern Sweden clearly indicated they had formed in relation to specific base levels (Lidmar-Bergström 1988). Recently, several authors have accepted the relationship between major peneplains and former base levels (Schoenbohm et al. 2004, Bonow et al. 2006, Japsen et al. 2006, Clark et al. 2006, Hetzel et al. 2011, Japsen et al. 2012, Green et al. 2013, Bonow et al. 2014).

## STEPPED PENEPLAINS AND VALLEYS IN NORTHERN SWEDEN – A REVIEW

Stepped peneplains comprise mountain areas with plateaux and areas classified as "plains with residual hills" outside the mountains.

### Walter Wråk 1908

Wråk (1908) worked in three Scandinavian areas: 1) Rejsen, Kvaenangen and Finnmark (Tromsö, northern Norway), 2) The rest of Tromsö County in addition to the northern half of Norrbotten County (the provinces of northern Lapland and Norrbotten in Sweden (Fig. 1), and 3) Gudbrandsdalen, Romsdalen and Eikisdalen (southern Norway). The maps he used were poor and he therefore based his work on material obtained in the field such as photographs, drawings and elevation records (obtained using an aneroid barometer). His study of northern Sweden has been used as a reference by many later researchers. Despite the poor quality of the maps, he identified four erosional peneplain steps with an easterly inclination along major valleys in the mountains (Table 1). He correlated the lowest of the mountain steps with the major plains just east of the mountains: the Muddus Plains (Fig. 6). He also identified two valley generations eastwards along the Lule River below the Muddus Plains. Wråk (1908, pp. 150–151) provided a summary, which is in turn summarised and commented on here:

1*) Likka* was a name he gave to flat summit areas in the mountains at different elevations above his highest major mountain surface, the Tuipal surface.

2) The *Tuipal surface* was identified in the central parts of the Northern Scandes at about 1 000 m. From there he followed it as a surface inclined towards the south-east. The Tuipal Mountain, with the type locality for the Tuipal surface, is located at the border between Sweden, Finland and Norway in the far north. Here the Caledonian front is cut across by both this surface and a lower surface (Borsu, Wråk 1908, p. 294). The Tuipal surface is here at about 900 m a.s.l.

Table 1. Correlation of surface and valley steps between five studies of northern Lapland. Wråk's names have been widely used, but difficulties have arisen when his inclined surfaces are used for correlation and naming of horizontal surfaces and when his naming of valley generations is used for surface generations. Note that the Caledonian front is not a morphological divide and that peneplain steps cut across it. * Figures compiled from the few values given by Wråk (1908). **Both sides of Caledonian front.

| **Wråk 1908**<br>Surfaces inclined to the SE in the mountains | **Frödin 1914**<br>Surfaces along the Lule River | **Rudberg 1954**<br>Horizontal surfaces/ generations | **Lidmar-Bergström 1994 & 1996**<br>Near horizontal surfaces with bottom steps | **Lidmar-Bergström et al. 2007**<br>Surfaces inclined to the SE in the mountains | **Ebert et al. 2011**<br>Areas limited by distinct steps |
|---|---|---|---|---|---|
| **Likka** | | | | **0** 1850–1500 m | *Ätnajokki/Tjeuralako*<br>**I** 2066–1521 m |
| **Likka** | | *High mountain*<br>**13** 1200–1150 m | | **1** 1750–1100 m | **II** 1520–1321 m |
| **Tuipal** 1100–900 m* | Tuipal 1100–950 m | *Low mountain*<br>**12** 1000–950 m<br>**11** 900–800 m | | **2** 1500–800 m** | **III** 1320–861 m |
| **Borsu** 850–650 m* | Borsu 860–625 m<br>Minor step 575 m | **10** 800–750 m<br>*Premontane*<br>**9** 725–625 m<br>**8** 650–550m | 800–600 m | **3** 1200–650 m** | **IV** 860–721 m<br>Caledonian front as boundary<br>**D** 1100–401 m |
| **Muddus**<br>575–400 m*<br>—————<br>*Downstream Porjus*<br>400–300 m* | Muddus 525–300 | **7** 550–475 m<br>*Inland generations*<br>**6** 450–400 m<br>———————<br>**5** 400–300 m | Upper Muddus<br>600–400 m<br>———————<br>Lower Muddus<br>400–300 m | **4** mountain valleys**<br>800–400 m successive confluence of steps 3 and 4 down to 400 m<br>Muddus Plains 550–300 m | **C** 400–251 m |
| **Pakko**, valley incision 300–250 m* | | **4** 300–200 m | Erosional level<br>300–200 m | Outside study area | **B** 250–191 m |
| **Lule**, valley incision <200 m* | | *Coastal generations*<br>**3** 200–100 m<br>**2** 100–25 m<br>**1** <25 m | Erosional level<br>200–100 m<br>Coastal plain | Outside study area<br>Outside study area | **A** 190–65 m |

3) The lower and younger *Borsu* generation, incised in the Tuipal surface, is also inclined to the south-east and formed by water running in this direction. During its formation the water divide was much further to the west than today. Wråk does not give any elevation figures for the Borsu surface in his general summary. However, on p. 175 he mentions 650–750 m a.s.l. in the Abisko area in the Torneträsk valley and 700–780 m a.s.l. in the parallel Rautas valley (p. 182, Fig. 6).

4) Below the Borsu generation, Wråk identified the *Muddus* generation. In the Torneträsk valley he estimated its level at 450–480 m in the west (p. 180), while in the areas of the Muddus Plains, east of the mountains, the valley bottoms were recorded at 300–400 m a.s.l. He put the bottom level for the Muddus generation at 400 m at Porjus (p. 187) along the Lule River. Hampered by the lack of good maps and travelling along the valleys, Wråk could not produce maps showing the distribution of his levels.

5) Along the Lule River, Wråk identified two younger valley generations in the east, the *Pakko* generation between 300 m and 250 m, having a limited extent, and the *Lule* generation below 200 m. He never studied their connection to plains at corresponding elevations, but noticed that they were incised below the Muddus Plains.

Wråk (1908) considered that the surface and valley steps had been formed by fluvial processes during uplift in the north-west, which caused the high surfaces to incline towards the south-east. He correlated surfaces at about the same elevation between the Northern and Southern Scandes and interpreted a common evolution for the whole mountain chain. Since Wråk identified west dipping surfaces west of the mountains only at low levels (not described in this review), he thought that land had been lost there during uplift.

### John Frödin 1914

Frödin (1914) studied the upper reaches of the Lule River and followed Wråk closely with Tuipal at 1 100–950 m, Borsu at 850–625 m and Muddus at 525–350 m, and an additional minor step at 575 m (Table 1). However, concerning the lower valley generations of Wråk, he was critical of the explanation for the valley steps along the river as part of cyclical landscape development caused by stepped uplift. At the eastern end of Lake Stora Lulevatten, the Stora Lule River suddenly turns south in a narrow and deeply incised valley (Fig. 6, cf. Fig. 15). Based on the topographic conditions, Frödin suggested that the Stora Lule River had continued its flow in a general south-easterly direction in pre-glacial times. He interpreted the present incision of the Lule River down to the Pakko level as secondary, i.e. younger than both the river valley above and below (Frödin 1924, p. 29), and caused by young river capture along fracture zones. He believed this large rearrangement had caused increased water discharge in the present Stora Lule River. He thought that this rearrangement should thus explain the high waterfalls Porjus and Harsprånget (Figs. 6 and 16), and the deep incision of this part of the river, unique among rivers crossing the "plains with residual hills" with their gentle steps (cf. section *Sven Norlindh 1924*).

### Gustav Braun 1935

Braun made several studies of the morphology of Norrland and adjacent parts of Norway. He summarised his studies of the Scandinavian mountains, essentially confirming the results of Wråk (1908). He introduced the term "piedmondttreppe" for stepped relief in Sweden.

### Hans W. Ahlmann, Erik Laurell & Carl Mannerfeldt 1942

Ahlmann et al. (1942) focused on all of Norrland. They identified mountains, woodland and younger valleys in the coastal area. In the woodland they described two peneplain generations, namely "the inland peneplain" (*inlandspeneplanet*) and "the hill peneplain" (*lidpeneplanet*). Like Wråk (1908), they regarded the surfaces as being inclined towards the east. "The hill peneplain" was correlated with higher surfaces in the mountains. They also noted that "the inland peneplain" was dislocated and now occurs at different levels in the present landscape. Along some parts of Norrland comprising the "square plateaux landscape" (De Geer 1926), they found no hills above "the inland peneplain" (Ahlmann et al. 1942: table II, p. 6), and they therefore suggested that it is close to the sub-Cambrian peneplain in these parts (cf. Lidmar-Bergström 1996). This is also an area of spectacular water gaps. The authors suggested a Late Tertiary rise of "the inland peneplain" and faulting along the coast as the cause of the water gaps (Ahlmann et al. 1942, pp. 20–21). The basic study was never finished because the main contributor (E. Laurell) died before the work had been completed. The paper was published after his death.

### S. Rudberg 1954

A comprehensive study was made of Västerbotten County (the provinces of southern Lapland and Västerbotten, Fig. 1) by Rudberg (1954). He based his work on the idea of fluvial development of peneplains and especially the idea of valley-in-valley to cause steps as presented by Baulig (1928). A major question he considered was whether there were just a few (two?) surfaces as claimed by Ahlmann et al. (1942), or many surfaces.

Rudberg (1954) used hachure maps supplemented with some new measurements. Aided by students, he constructed a contour map of the whole study area from these data. On this basis he inferred 13 erosional generations, almost horizontal in the mountains, but slightly inclined close to the Gulf of Bothnia (Table 1). Rudberg also noted several sub-Cambrian facets resulting from the erosion of cover rocks and discussed more locations than he actually mapped (Rudberg 1954: pp. 35, 241, 405). However, his main result was the 13 horizontal steps. This led him to conclude that the rise of the land had been "en bloc" and not a tilt, as the inclined surfaces of Wråk (1908) had suggested. It should be noted that while Rudberg only worked on the eastern side of the mountains, Wråk worked across the mountain chain, which gave him a broader perspective. Moreover, Wråk worked in northern Lapland, whereas Rudberg worked in southern Lapland (Västerbotten County); they thus worked in different areas.

**S. Rudberg 1970**

Rudberg (1970) constructed a map of interpretation for the Atlas of Sweden together with the map of geomorphological regions (Fig. 3), commented on in section *Sten Rudberg 1960 and 1970*. Rudberg noted the presence of polycyclic relief (peneplain steps) all the way from the Norwegian border to the coast in his own study area, Västerbotten (Rudberg 1954), including areas characterised by monadnock plains (plains with residual hills or inselberg plains). He also noted polycyclic relief in the immediately adjacent area to the north, and again in the mountains in the northernmost corner of Sweden with the type area of the Tuipal surface of Wråk (1908). The large area with monadnock plains (Fig. 3) in the far north was largely excluded from the multicycle topography. However, in mutual discussions during the 1980s, Rudberg mentioned that he had noticed the existence of steps here as well, and suggested further studies.

**K. Lidmar-Bergström 1994, 1996**

Lidmar-Bergström (1994, 1996) mapped all of Sweden based on a method developed for south Sweden (Lidmar-Bergström 1988a). She based her mapping on contour maps from the Land Survey. These were combined with profiles from the digital database of the Land Survey. Northernmost Sweden was divided from west to east into the Highlands, the Muddus Plains between 550 and 300 m, and "mixed relief" inside the coast, where hilly relief as well as re-exposed sub-Cambrian peneplain interfere with stepped plains (Figs. 8B–C).

The Scandes, which constitute the Highlands, extend across both Caledonian and Precambrian rocks (Figs. 2, 6). Rudberg (1988) had noted that there is a larger variation in rock type in the Caledonian basement than in the Precambrian basement, which explains several peaks in the Scandes. A Caledonian front scarp, a glint, has been formed along certain parts of the Caledonian front and was interpreted as having been caused by specific rock resistance (Lidmar-Bergström 1996, Fig. 6), but in general the mountain surfaces cut across the Caledonian front.

The profiles (examples in Fig. 8) showed large "plains with residual hills" graded to steps at 200 m, 300 m (Lower Muddus Plains) and 400 m (Upper Muddus Plains) east of the Northern Scandes (Fig. 6). The Muddus generation of Wråk (1908) was thus separated into two plains with a step in between. The data used for this overview of all of Sweden (25 m contours and 500 m digital database) did not allow detailed mapping in the mountains, and it was difficult to see whether the mountain surfaces were horizontal as Rudberg claimed for southern Lapland or inclined as Wråk had claimed for northern Lapland. The interpretations of the profiles (Lidmar-Bergström 1994, 1996) used the common assumption of horizontality, since at that time no data used indicated otherwise (Figs. 8B–C).

In southern Norrland and western Svealand the stepped "plains with residual hills" are replaced by "large-scale joint valley landscape" and "undulating hilly land" ("undulating hilly relief" in Fig. 2), which were interpreted as belonging to a re-exposed sub-Mesozoic etch-surface. Yet Lidmar-Bergström, following Rudberg (1970), continued the mapping of steps south of Stöttingfjället, which might be incorrect (question marks in Fig. 6).

The approximate vertical location of the primary sub-Cambrian peneplain was outlined in profiles (Fig. 8). It may be noted how Caledonian covers have long protected Precambrian rocks close to the present Caledonian front from destruction and how late erosion has locally re-exposed facets up to 8 km long (Rudberg 1954) of the sub-Cambrian peneplain.

**K. Lidmar-Bergström, Jens-Ove Näslund, K. Ebert, Truls Neubeck & Johan M. Bonow 2007**

The contribution from Lidmar-Bergström et al. (2007) focuses on the levels of remnant peneplain steps in the mountains of northern Lapland and their connection to the inselberg plains (the Muddus Plains) to the east. Since it had been demonstrated that glacial modification of high plains had not changed their large-scale geometry (Lidmar-Bergström et al. 2000, Bonow et al. 2003, 2006), the following method was used. Slope maps depicting flat areas at certain levels and closely spaced profiles were constructed from a DEM (Digital

Elevation Model) with a 50 m horizontal resolution, and these two data sets were interpreted in combination (Lidmar-Bergström et al. 2007). The close profile method made it possible to correlate fairly small flat areas and detect the inclination of originally coherent surfaces and valley benches. Wråk's field observations of inclined surfaces in the mountains were confirmed. Stepped low relief surfaces occur below each other in the mountains and are at most 300–400 m apart vertically. The five identified surfaces slope gently to the southeast thus: 0) 1 850–1 500 m (equivalent to highest Likka remnants according to Wråk), 1) 1 750–1 100 m (lower Likka remnants), 2) 1 500–800 m (Tuipal), 3) 1 200–650 m (Borsu) and 4) 800–400 m (Muddus, Fig. 11). The last-mentioned is a valley generation in the mountains and continues in the inselberg plains of the Upper Muddus Plains (Lidmar-Bergström 1996) outside the mountains (Table 1). The four major surfaces span a height interval of 1 150 m in the mountains but approach each other outside the mountains of northern Lapland to span a height interval of only 250 m. Here, the two lower surfaces merge to form a continuous plain, the Upper Muddus Plain (550–400 m) with residual hills, the summit surfaces of which represent the dissected higher surfaces. Hence, the uplift did not cause a simple tilt as Wråk (1908) thought, but rather a warp, with the Muddus surfaces maintaining near horizontality east of the mountains. Based on the identified preglacial levels, the amount of glacial erosion in the main trunk valleys was estimated to at least 250 m.

### K. Ebert, C. Hättestrand, A. Hall & Göran Alm 2011

A GIS study was performed in two small areas of Caledonian rocks in the mountains of Lapland (Ätnajokki and Tjeuralako areas, Fig. 6) and a larger area of Precambrian rocks to the east termed "lowland", but also including some low mountains up to 1 100 m. This was a methodological study to find out whether it is possible to identify stepped surfaces by using a hypsographic curve based on digital elevation data. The results show distinct steps. Four levels with intervening steps were seen in the Precambrian "lowland" (A 65–190 m, B 191–250 m, C 251–400 m and D 401–1 100 m) and four levels in the mountains (IV 721–860 m, III 861–1 320 m, II 1 321–1 520 m and I 1 521–2 066 m, Table 1). They conclude that the surfaces are true erosion surfaces, since they have been formed across units of diverse bedrock geology and that the results confirm earlier studies. However, this is not obvious, since the authors have misunderstood the surfaces of Wråk (particularly the extent of his Muddus generation), and they do not refer to the only study of the whole area (Lidmar-Bergström 1996).

## Fluvial valleys and their implications

### SVEN NORLINDH 1924

In a comprehensive study of the relationship between Swedish hydropower and morphology, Norlindh (1924) related waterfalls of major rivers throughout Sweden to a general landscape staircase. He was preoccupied by the view of a common staircase that should be the same for the whole country and largely followed Wråk's (1908) work from northernmost Sweden. The study was printed but rejected as an academic thesis. His detailed descriptions and the collected river profiles are nonetheless of great value and have been used by other scientists. A plate with river profiles for six major rivers (Fig. 12) confirms some general morphological observations of the river valleys of northern Norrland. The major rivers (Figs. 12, 13A), Torneälven (1), Luleälven (3), Piteälven (4) and Skellefteälven (5), all flow through major lakes outside the mountains at about 300 m a.s.l. in the far north (Torneälven with Torneträsk) but at 350–450 m a.s.l. further south (Luleälven with St. Lulevatten, Piteälven with Tjeggevals and Skellefteälven with Hornavan). Below these levels they descend with steeper gradients. Norlindh (1924) wrote: "The boundary between the Norrland plateau area (the Muddus Plains, *translator's comment*) and the coastal plain is very sharp. It constitutes a zone of rejuvenated erosion, where narrow valleys are incised at the edge of the highland (the Muddus Plains). This zone of narrow valleys is particularly rich in waterfalls. Ahlenius (1903) therefore calls it the dejectal region." (Translation and comment by the authors.) The two northernmost rivers, Torneälven (1) and Kalixälven (2), as well as the southern Ume River, have gentler gradients across the dejectal region than the rest.

### S. RUDBERG 1988

A short review follows of some views of Rudberg (1988) from his third way of explaining the topography. He started by ascertaining the old age of the *river network* (Fig. 13A). There are 12 *main rivers* starting in the mountains but he noted that the total number

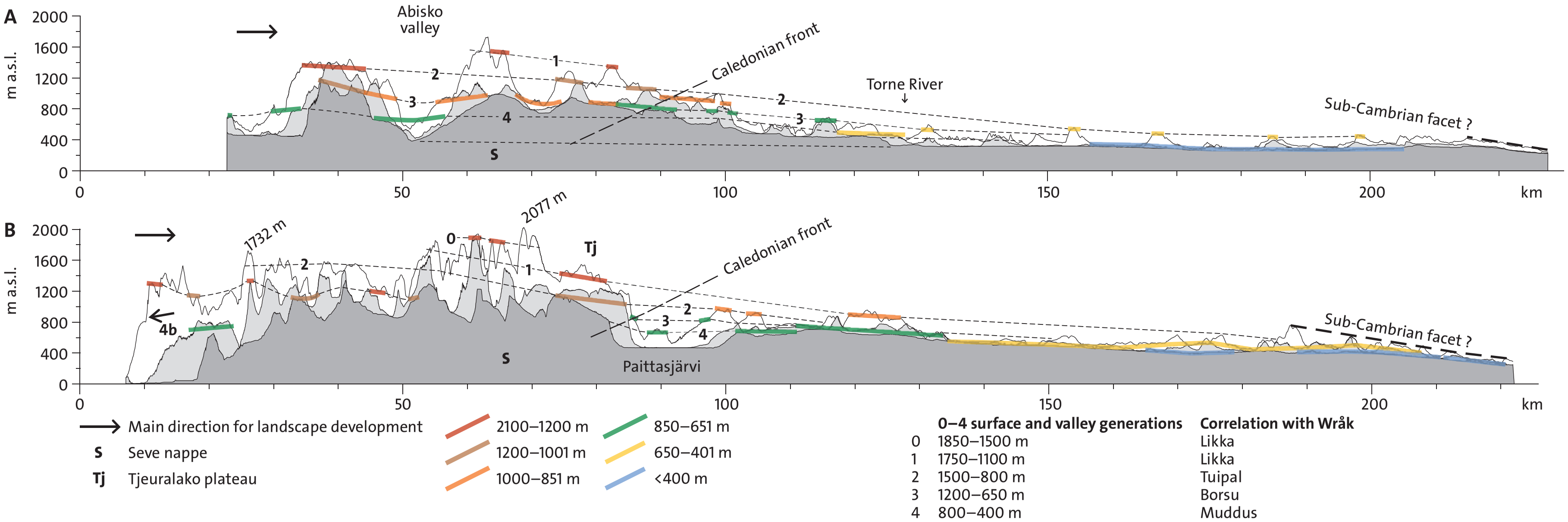


Figure 11. Two profiles across the Northern Scandes. Modified from Lidmar-Bergström et al. (2007). The profiles show maximum and minimum values from a 5 km wide zone along the profiles. Mapped surface remnants within the zones are inferred (0–4) and coloured according to elevation. Note the lowering by glacial erosion along Lake Paittasjärvi (lake bottom not marked). Lowering by glacial erosion in the Torneträsk and Torne River valley causes the low position of the valley bottom at the end of the Abisko valley and where the profile crosses the Torne River. For location, see Figure 6.

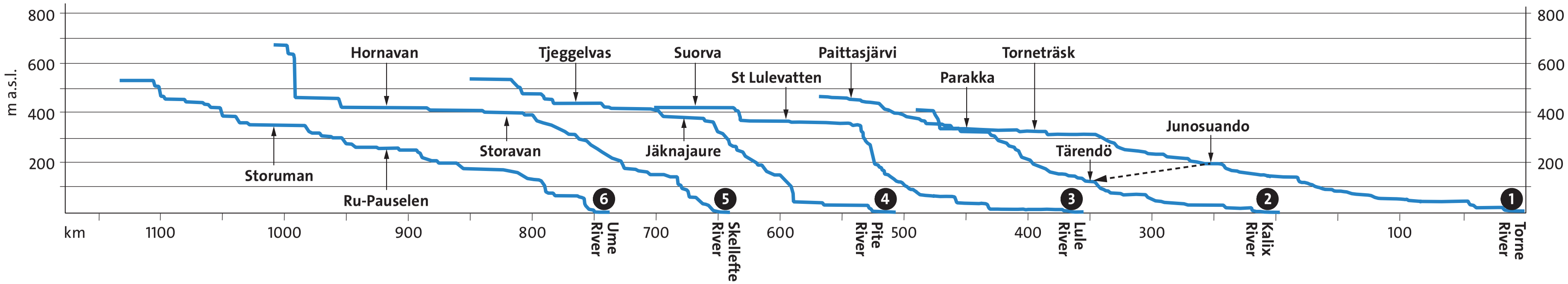


Figure 12. River profiles from Norlindh (1926). The Tärendö bifurcation between Torne and Kalix Rivers (from Junosuando to Tärendö) is indicated by a dashed arrow.

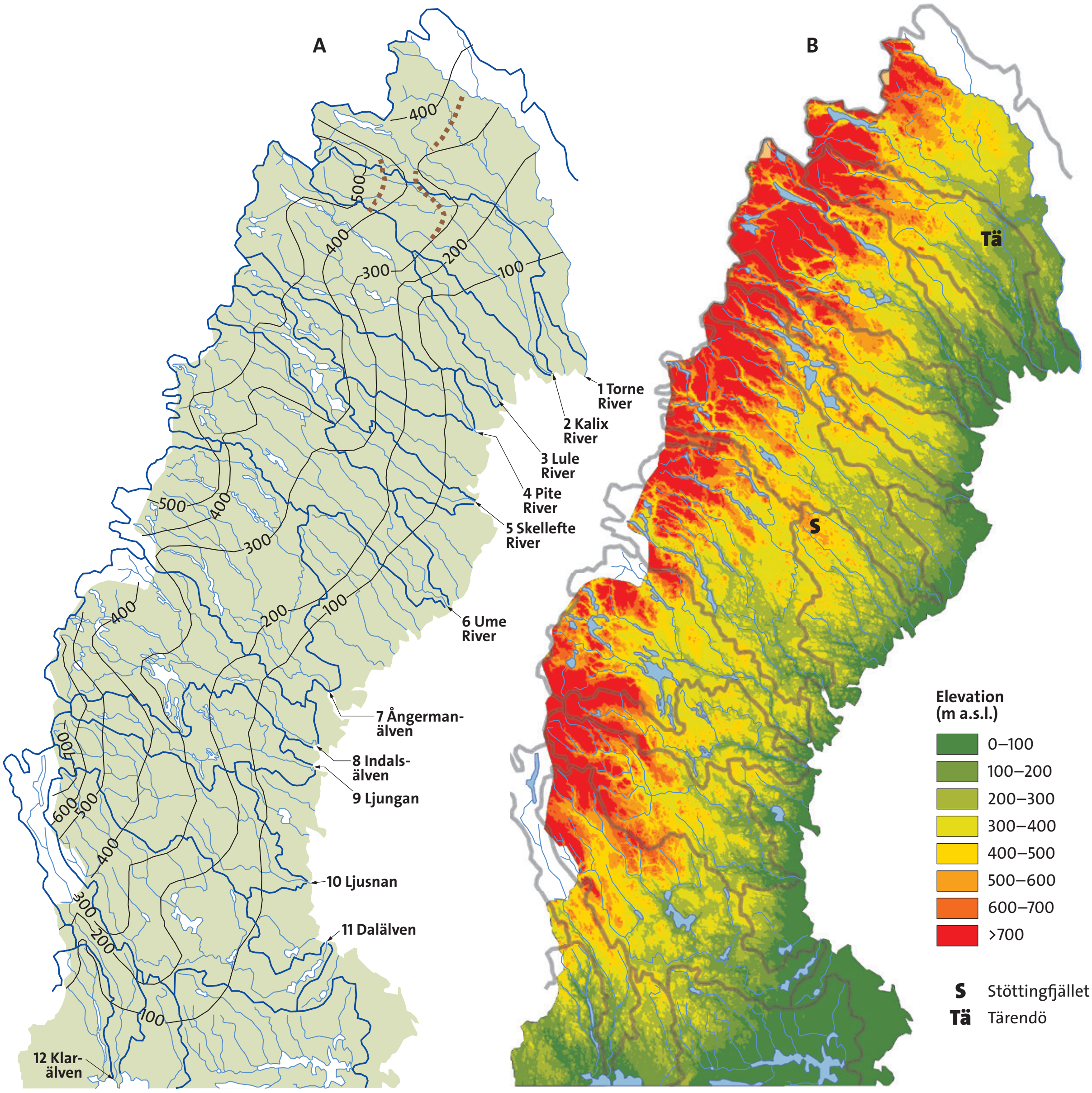


Figure 13. **A.** Map of the drainage basins and rivers of northern Sweden according to Rudberg (1988). Contour lines for the elevation of the rivers with some modifications (the dashed lines are Rudberg's original lines). **B.** The drainage basins of northern Sweden combined with layers for elevation, based on a digital elevation raster with 1 x 1 km cell size.

of *mountain rivers* is about three times that figure. This means that the main rivers have several tributaries with only four exceptions: Klarälven (12), Ljungan (9), Skellefteälven (5) and Piteälven (4). The main rivers often diverge from parallel drainage inland from the coast. In the triangle between two such diverging rivers there are minor rivers, called *forest rivers*. Two, Ångermanälven and Luleälven, have most tributaries and diverge southwards from the general south-east directions (Fig.13A).

Rudberg noted the very low gradient in the river profiles of the Kalix and Torne Rivers in the far north (Figs. 6, 12, 13A). However, his contour lines for their higher levels were not quite correct (Fig. 13A). He noted that the forest rivers have steeper gradients than the main rivers. He remarked that the three southernmost rivers, Ljungan, Ljusnan and Dalälven (Österdalälven and Västerdalälven) rising in the Southern Scandes, comprise the highest points of all river profiles.

Rudberg described several *water gaps*, which he generally explained as proof of lost, easily erodible rocks (often Paleozoic cover rocks) upstream of harder rocks. First he gave examples of water gaps in the Skellefteå area (Fig. 6), where the rivers cross tilted blocks of the sub-Cambrian peneplain close to the coast (cf. Fig. 8A). This suggests that Paleozoic cover rocks have been eroded. He gave the same explanation for two water gaps in the Kalix and Torne Rivers below the "inselberg plains" (Fig. 6). He suggested that the plain at the bifurcation of the Torne and Kalix Rivers, the Tärendö area (Figs. 6, 13B), once had a cover of Lower Paleozoic rocks. He explained another water gap in the Lina River (Fig. 6), where it crosses a row of hills, in a similar way.

Rudberg further suggested lost cover rocks in the present downstream directions as the cause of some *river deflections,* although he also thought the deflections might have been caused by blocking Quaternary deposits in the original south-east directions of the rivers. He thought that deep glacial erosion before the latest glaciation might have played a part in the deflection. He made a map (Rudberg 1988) of fluvially and glacially influenced valleys across Scandinavia from southern Norway to the Bothnian Sea and concluded that the Swedish valleys have a combined influence from fluvial and glacial processes.

Rudberg argued that water gaps in the mountain rivers indicate long stability of river positions. He believed that the rivers of northern Sweden started on a very flat surface emerging from the sea. The arguments were: tendencies to parallelism (although he gave many examples of the opposite), water gaps in resistant rocks, and lack of strong influence from Caledonian folding. He therefore concluded that the Caledonides must have been denuded to very low relief and that sediments, not older than Late Paleozoic, covered the whole area. He considered subsequent actions to be fluvial with no influence of structure.

## K. LIDMAR-BERGSTRÖM 1996

### Valley patterns

Lidmar-Bergström (1996) constructed a map of valley patterns (Fig.14) from the map of landforms of the bedrock. The map shows distinct valley forms, not rivers, and distinguishes between valleys below and above 400 m. She noted that the Muddus Plains (Fig. 6) lack broad incised valleys, except for the rivers Stora Luleälv and Umeälv. Marked valleys generally start to appear at the eastern border of the Muddus Plains (cf. Ahlenius 1903: the dejectal zone, Norlindh 1924). There is a threefold division in northern Norrland (cf. Ahlmann et al. 1942) with: 1) mountains with distinct valleys in the west, 2) the large Muddus Plains without incised valleys in the middle and 3) a coastal zone with mixed relief, steeper gradient and incised valleys.

In the area of "undulating hilly relief" (Fig. 2), south of the "plains with residual hills", distinct valleys occur

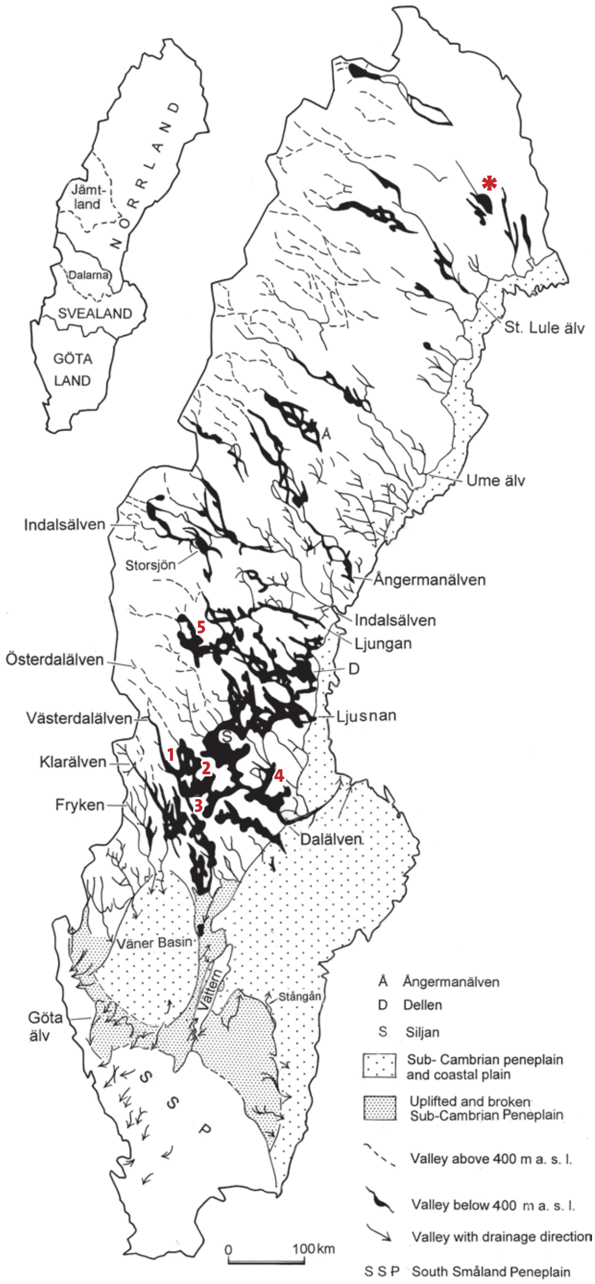


Figure 14. Valley patterns, extracted from the map: Landforms in the bedrock (Lidmar-Bergström 1994, 1996). Valleys above 600 m, mountain valleys, are glacially reshaped. Broad incised valleys below 400 m, marked black, suggest areas of heavy glacial erosion. Asterisk marks one of the areas with marked incision identical to an area interpreted to have been affected by glacial erosion (Hall et al. 2013a). Figure depicts also downfaulted basins made visible by glacial erosion of Jotnian sedimentary rocks in downfaulted basins: 1) Malung–Öjen area, 2) Vansbro area, 3) Svartälven–Lisjön area, 4) Lake Runn area, 5) Sveg area. Map slightly revised from Lidmar-Bergström 1996.

everywhere (Fig. 14). Their shape differs in the north and south. They are narrow in the "large-scale joint valley landscape" (Lidmar-Bergström 1994, 1995), which is part of the undulating hilly relief along the High Coast in Figure 2, whereas they are broad and

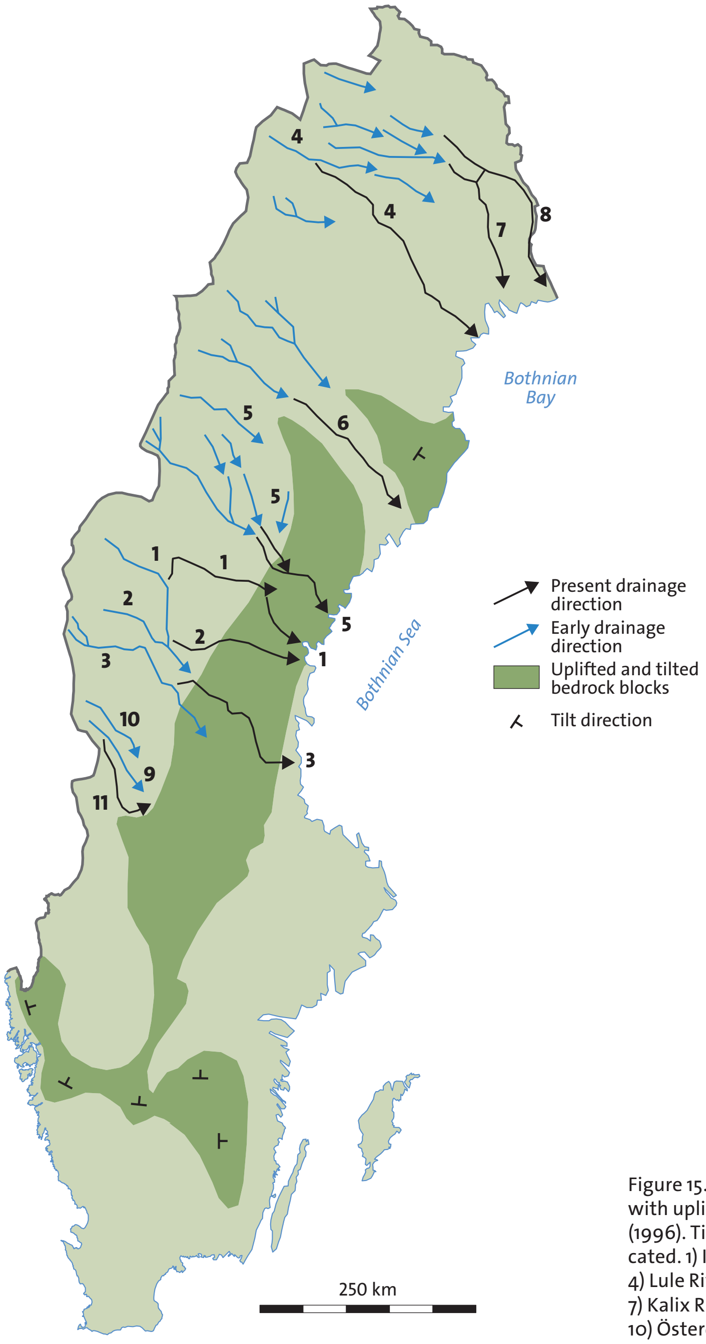


Figure 15. River deflections in conjunction with uplifted blocks from Lidmar-Bergström (1996). Tilt direction of some blocks is indicated. 1) Indalsälven, 2) Ljungan, 3) Ljusnan, 4) Lule River, 5) Ångermanälven, 6) Ume River, 7) Kalix River, 8) Torne River, 9) Vanån, 10) Österdalälven, 11) Västerdalälven.

irregular further south in the "undulating hilly land". It was argued that the rivers here occupy differentially weathered fracture zones (Lidmar-Bergström 1995). In addition to exposure to prolonged deep weathering and subsequent stripping, the irregularity of the valleys in southern Norrland and western Svealand was interpreted in some cases to be the result of evacuation of easily eroded sedimentary cover rocks, mainly of middle Late Riphean (Jotnian) age, from small downfaulted basins (Lidmar-Bergström 1996, Fig. 14).

## Suggested river deflections

The analysis of the river and valley pattern also resulted in a map showing suggested river deflections (Fig. 15). The map of the landforms of the bedrock (Fig. 6, Lidmar-Bergström 1994, 1996) indicated that the northernmost valleys (in one case a valley having another direction than the present river) have an almost easterly direction from the mountains and over the Muddus Plains, before the valleys with their present rivers turn south-eastwards into the coastal zone with mixed relief. This change of direction was considered to reflect a lowered base level as well as a changed coastline caused by downfaulting of the Bothnian Bay in the Late Tertiary (Neogene).

Along the coast of the Bothnian Sea, all the main rivers from Ångermanälven to Dalälven (Figs. 14–15) have to pass a high area in major water gaps. It is suggested that the high area has caused several river deflections. The river Ångermanälven was thought to have been the major river, to which the present middle Indalsälven might also have belonged as a tributary, while the lower river Indalsälven was thought to have been deflected at a late stage to its present fracture zone in a narrow valley. Neogene uplift along the coast may have contributed to the present situation. The rivers Ljungan and Ljusnan, rising in the Southern Scandes, were considered to have been deflected to more easterly courses from originally south-easterly courses. They pass the high area in wide valleys, interpreted to belong to the area exposed to prolonged Mesozoic deep weathering, subsequent covering and late re-exposure.

## Relief and the effect of glacial erosion

### PENEPLAINS AND GLACIAL EROSION

The different peneplains of the South Swedish Dome and plateau relief in Norway and Greenland had revealed that areas of glacial scour cannot be excluded in the geometrical reconstruction of preglacial landscapes (Lidmar-Bergström 1997, Bonow et al. 2003, Bonow et al. 2006). Kleman & Stroeven (1997) described a "preglacial surface", referring to a landscape surface (including shallow valleys) whose details were not affected by glacial erosion. They distinguished between areas unaffected by glacial erosion, those with signs of minor glacial erosion, and glacially scoured terrain. They used it for a model on ice sheet behaviour. However, they also declared that "if a reconstruction of older planation surfaces were the objective, the glacially scoured surfaces must be excluded". That is true only with reference to the details of the preglacial landscape. However, areas without signs of glacial erosion ("preglacial surfaces" in the sense alluded to by Kleman & Stroeven 1997) are not the only areas that can be used in reconstructions of Phanerozoic tectonics based on bedrock landforms.

Lidmar-Bergström et al. (2000) made a study of palaeic surfaces in south-western Norway to draw conclusions on uplift, but also evaluated the effect of glacial erosion. They concluded "Even if the Palaeic surface, with its broad valleys, has clear signs of glacial reshaping, it is still distinct from the deeply incised valleys."

In a study of stepped surfaces in the Southern Scandes in Norway (the Kjølen Mountains), it was found that stepped peneplains are still geometrically well identifiable in areas affected by glacial erosion (Bonow et al. 2003). They used an area displaying only weak effects of glacial erosion. It was thereby possible to measure the effect of glacial erosion in different settings in relation to peneplains that preserved "preglacial surfaces" (as defined by Kleman & Stroeven 1997). It was concluded that glacial erosion mainly affected the lowest of the four identified peneplains. In general, glacial erosion was here estimated to have been a few tens of metres. Peneplain steps were clearly identifiable over the whole area. Bonow et al. (2006) mapped planation surfaces at high elevations in western Greenland. It was found that the type of basement rock determined whether a surface was preserved or not, while glacial scour did not destroy the geometric surface.

Detailed studies of the South Swedish Dome had revealed that the three palaeosurfaces (the inclined sub-Cretaceous hilly peneplain, the inclined sub-Cambrian flat peneplain and the horizontal South Småland Peneplain, a plain with residual hills) were preserved and their major shape unaffected by glacial erosion (Lidmar-Bergström 1997), although the sub-Cretaceous surface of e.g. Blekinge has been affected by glacial scour (Kleman et al. 2008). It seems that glacial scour mainly evacuates loose material and only affects the fresh bedrock to a minor extent. Studies of Precambrian basement rocks in southern Sweden show that generally hilly relief becomes sharpened, while flat relief is preserved (Johansson et al. 2001), even in areas below wet-based scouring ice (Kleman et al. 2008). This all accords with the general view of Rudberg (1992), i.e. that there has been little glacial erosion of plains.

### VALLEYS AND GLACIAL EROSION

The river profiles of Norlindh (1924, Fig. 12) strikingly reveal the Upper Muddus level (3 Lule River, 4 Pite River, 5 Skellefte River) and the Lower Muddus level (1 Torne River, 2 Kalix River), but a closer examination explains the straight lines as the surface of glacial lakes dammed naturally or artificially at these levels at the mountain front. Glacially formed lakes at these levels occur outside the mountains, particularly along the Skellefte River (5) but also along the Pite River (4). The

Kalix River (2) is the least affected by glacial erosion. It shows a clear step at Parakka at the Lower Muddus level. Not until Lake Paittasjärvi does this valley reach the mountains and is glacially reshaped.

To estimate the glacial reshaping of valleys, Lidmar-Bergström et al. (2000) compared incised valleys along the Australian eastern margin with incised valleys in western Norway. They used valleys with the same upper width in Norway and Australia. The glacial character of the Norwegian valleys could be seen from the broadening and deepening of the valley floors. The incision of the valley was not dependent on glacial erosion, but on the height difference between a plateau and the base level.

Wråk (1908) had identified the Muddus generation in the inner part of the Torneträsk valley as well (at 450–480 m a.s.l.), but it was clear from the studies made by Lidmar-Bergström et al. (2007) that the Muddus level here is at about 800 m (the entrance to the Abisko valley, Fig. 11). Lake Torneträsk is at 341 m a.s.l. and the lake bottom still lower. The incision below the Muddus level was interpreted as being due to glacial erosion and it was thus not possible to discern any lower preglacial generations along the valley. It was clear that Wråk had underestimated the effect of glacial erosion, particularly in the valleys in the mountains.

How much has glacial erosion lowered local base levels, causing renewed fluvial incision in mountain regions (Rudberg 1992, Kleman & Stroeven 1997)? Reconstructed preglacial fluvial landscape generations can be used to measure the depth of glacial erosion below such reconstructed generations (Bonow et al. 2003, Lidmar-Bergström et al. 2007). Bonow et al. (2003) estimated different glacial overdeepening in different settings, with 120–150 m in Gudbrandsdalen and 320 m in the Vågå-Otta valley. Similarly, deep glacial erosion of some trunk valleys in the Northern Scandes was estimated at about 250 m, perhaps up to 450 m (Lidmar-Bergström et al. 2007). The lake basins along the mountains have long been assigned a glacial origin (Ljungner 1949), with a maximum depth of 228 m (Hornavan). The map of the valley pattern by Lidmar-Bergström (1996, Fig. 14) shows several incised and widened valleys east of the Northern Scandes. Here we suggest that they all show the effect of glacial erosion. This is supported by some observations.

A study of the effect of glacial erosion of the inselberg plains (Hall et al. 2013a) stated that the erosion varied from negligible in some areas to being concentrated to valleys in others. This had caused dissection and loss of palaeosurface area, with a mean depth of erosion of 27 m. The area they describe as displaying maximum glacial erosion is identical to one area of marked incision in Figure 14 (marked with an asterisk). Similarly, the wide valleys of the Lule Rivers and upper Ångermanälven River and tributaries suggest glacial erosion (Fig. 14). Glacial impact along parts of the Stora and Lilla Lule Rivers is clearly seen in Figure 16. Glacial erosion has also affected the Storsjön area, Jämtland, between the Northern and Southern Scandes, to a large degree. Rudberg (1988) pointed to erosion of cover rocks here and the anomalous outlet of Indalsälven from Lake Storsjön. The wide valleys on the map of valley patterns of incised valleys (Fig. 14) support the view of pronounced glacial erosion in these areas.

A comparison between the map of contour lines for the major rivers by Rudberg (Fig. 13A) and an elevation map combined with the drainage basins (Fig. 13B) provides some interesting information on the effect of glacial erosion on the present river valleys. Glacial erosion seems to have been particularly deep along the upper reaches of the Torne River, with formation of Lake Torneträsk. The effect on both Stora and Lilla Lule River outside the mountains has been great, as has the effect on the upper reaches of the Ume River.

Glacial erosion has also affected the central area of the Jotnian sandstone in Dalarna. It was assumed that the central river here, Vanån, hosted preglacial drainage (Fig. 15, Lidmar-Bergström 1996), since the present rivers (Västerdalälven and Österdalälven) have curious courses. Glacial meltwater might have caused these valleys (Fig. 17). Fluvial erosion might have further incised Österdalälven at Trängslet (Rudberg 1988, Olvmo 1989) due to a lowered local base caused by glacial erosion of sedimentary rocks downstream. As glacial erosion has a greater impact on sedimentary rocks than on crystalline rocks (Ottesen et al. 2009) the central area of the Jotnian sandstone (around the River Vanån) might have been glacially reshaped and glacial erosion might also have aided in evacuating sedimentary rocks in the basins, with remnants of Jotnian covers in the area of undulating hilly relief (Figs. 2, 15).

## GLACIAL EROSION IN GENERAL

Lidmar-Bergström (1997) made a rough estimate of glacial erosion of the Precambrian basement in relation to the total denudation of bedrock since its formation in the Proterozoic. The analysis led to the conclusion that glacial erosion is responsible for merely polishing the northern shields and that most denudation occurred during the Proterozoic, when it totalled tens of kilometres. The Precambrian basement was then protected for a long time by Paleozoic cover rocks, before large parts of it were gradually re-exposed during the Mesozoic. Mesozoic and preglacial Cenozoic denudation of basement rocks is estimated to have been 600 m at most

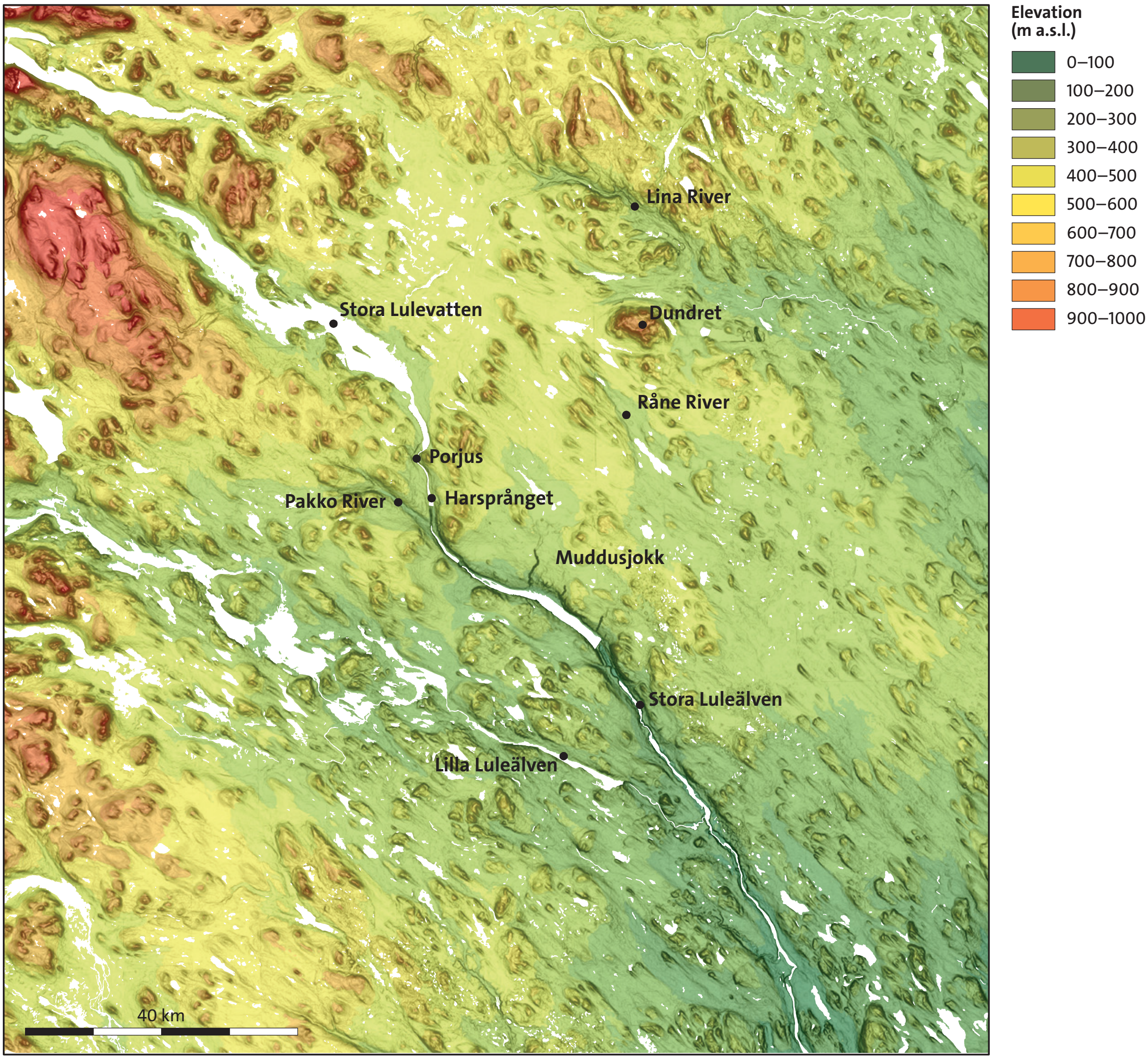


Figure 16. The rivers Stora Luleälven and Lilla Luleälven with surrounding areas. For location, see Figure 6. Interpretation according to Frödin (1914): The original Stora Lule River continued south-eastwards towards the Råne River. Later the Pakko River captured the Stora Lule River, which was directed southwards. Increased water discharge caused deep incision, and the two waterfalls Porjus and Harsprånget were created. Incision of the main river caused incision of the small rivulets from the north, e.g. Muddusjokk. Stora Lulevatten is a glacially formed lake. The image shows heavy glacial erosion along Lilla Lule River and to the south of it, which has affected the present Lule River valley downstream.

(interrupted by temporary covers), while glacial erosion was estimated to generally be in the tens of meters, albeit with great variations. In an area of southern Sweden with re-exposed sub-Cretaceous hilly relief, the occurrence of weathered flints without accompanying limestone showed that preglacial denudation of cover rocks had occurred (Lidmar-Bergström 1982).

It is generally difficult to estimate the amount of glacial erosion. One way practised for mid-Norway has been to identify glacial deposits offshore and to estimate the amount of glacial erosion in the supposed catchment area (Dowdeswell et al. 2010). This method suggests that the bedrock here has been lowered by 520 m over the last 2.7 million years, but does not say anything about the differential distribution of this erosion. However, although this offshore formation is regarded to be glacial it is not sure that all of its material emanates from direct glacial erosion. Nesje & Whillans (1994) showed that the Sognefjord valley in southern Norway was affected by interglacial and interstadial slope processes, which created loose material that was incorporated in the tills of the following glacial and stadial. Thus, the figure for glacial erosion might be too high. The extent to which easily eroded sedimentary covers (Hall et al. 2013b), off and along the coast, have contributed to offshore sediments is also uncertain.

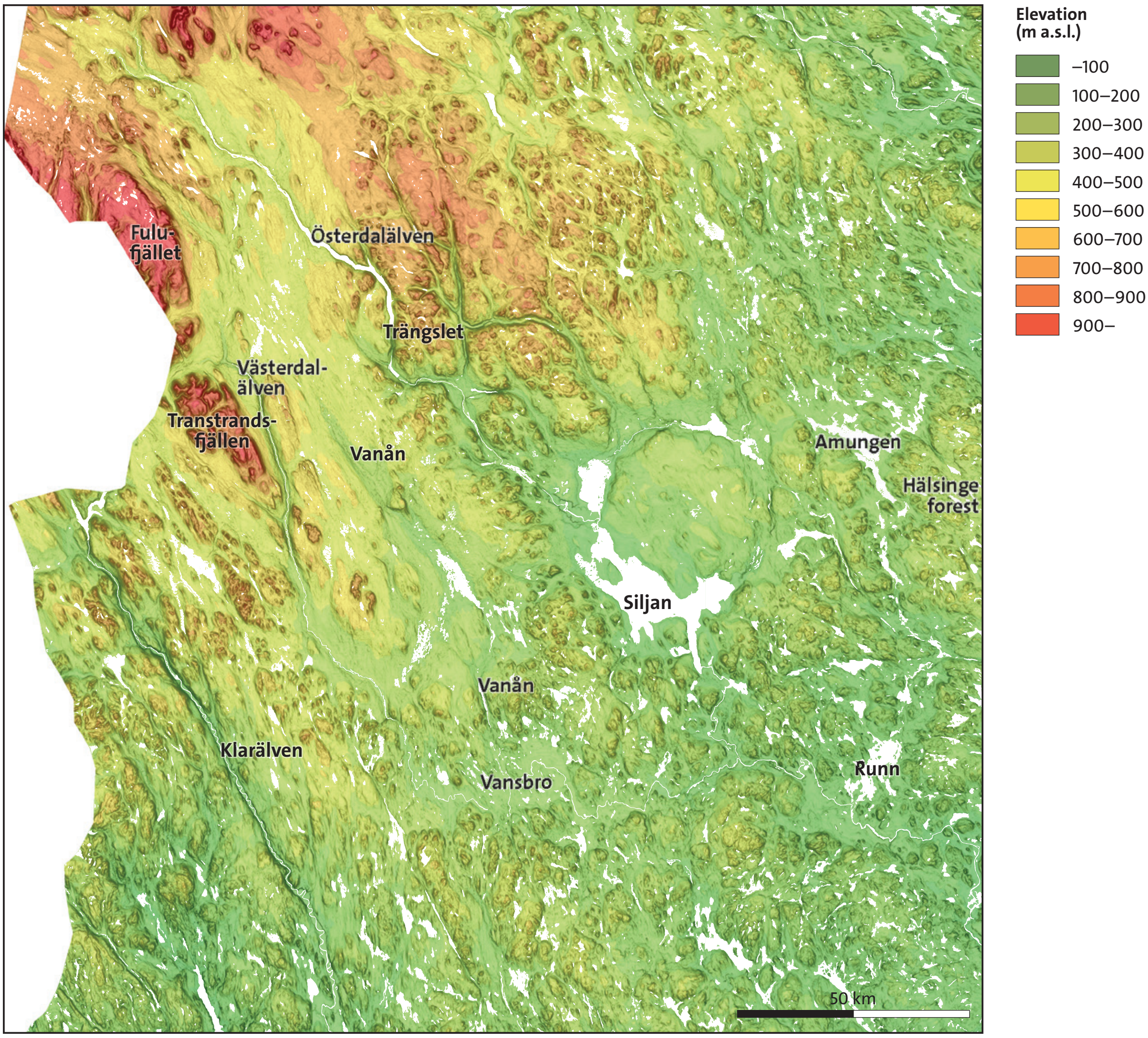


Figure 17. Part of Svealand (for location, see Figure 1) characterised by undulating hilly relief in Precambrian basement, with a smooth area formed in sedimentary Proterozoic rocks (Dala sandstone) in the north-west. The Dala Sandstone includes the mountains of Fulufjället and Transtrandsfjällen and areas to the east and south of the mountains. The Dala sandstone is slightly folded and constitutes a late Proterozoic syncline (Lundqvist et al. 2011). The Vansbro area seems to be a tectonic basin from where the Proterozoic sediments have been eroded and perhaps also Lake Runn (Lidmar-Bergström 1996), The Siljan ring with Lake Siljan is an impact structure from the Devonian/Carboniferous boundary (Wickman 1988). The summits of the Hälsinge Forest east of Lake Amungen reach the sub-Cambrian peneplain (Lidmar-Bergström 1996). The present drainage of the area by Österdalälven and Västerdalälven is curious. It is here suggested that the drainage of the area was totally reorganised during the Quaternary glaciations. Many of the incised valleys in these areas are the result of erosion by glaciofluvial meltwater (Olvmo 1989).

## Discussion

The following discussion is focussed on five themes: 1) Relief development in relation to weathering in different climates and structure, 2) Relief preservation below covers and its tectonic implications, 3) Significance and correlation of peneplains (stepped and re-exposed), 4) Implications of valleys for conclusions on tectonics and glacial erosion and 5) Relief types and glacial erosion.

### RELIEF DEVELOPMENT IN RELATION TO WEATHERING IN DIFFERENT CLIMATES AND STRUCTURE

Besides the importance of deep weathering for relief formation the origin of two major relief types are discussed, namely undulating hilly relief and plains with residual hills.

#### Deep weathering – an important factor in relief formation even in a formerly glaciated area

Swedish awareness of the importance of deep weathering in shaping landforms began in the late nineteenth century. Nathorst (1879) presented to Swedish researchers Pumpelly's theory on the importance of secular weathering of the bedrock surface in the origin of lakes. However, it was not until the work of Mattsson (1962) that international discussion of the impact of deep weathering on the shape of landforms was introduced among Nordic geomorphologists. Mattsson (1962) noted weathering characteristics and forms of the Precambrian surface. Lidmar-Bergström (1982) started to study the relationships between the forms of the basement and cover rocks of different ages lying directly on basement. Besides confirming "landscapes with joint aligned valleys" and "undulating hilly relief" as sub-Mesozoic etched relief in south-western Sweden (Lidmar-Bergström 1995, Fig. 2), younger types of weathering were also acknowledged as factors in landscape development (Lidmar-Bergström et al. 1997, Olvmo et al. 2005, Ebert et al. 2012a,b).

Clay weathering with the formation of kaolinite occurred during the late Precambrian, but since no vegetation cover existed, saprolites were shallow and the denuded basement became extremely flat (Elvhage & Lidmar-Bergström 1987). In contrast, remnant Mesozoic saprolites in southern Sweden are up to 60 m thick. They are clayey (mainly >50% silt and clay), include no gravel, and may have 30–70% sand, whereas young saprolites are gravelly (mainly >50% gravel), may have a little clay (up to 10%) and 25–50% sand (Lidmar-Bergström et al. 1997). Clayey Mesozoic saprolites consist mainly of kaolinite, whereas young gravelly saprolites are characterised by vermiculite, illite and other clay minerals such as kaolinite, chlorite, etc. Thus, a high clay content of a saprolite, created at the expense of basement rocks, testifies to ancient origin, whereas the existence alone of kaolinite in a gravelly saprolite does not. Gravelly saprolites (gruss) are found to be of Neogene age in Europe (Migoń & Lidmar-Bergström 2001). These conditions are thought also to apply to weathering residues of northern Sweden. Studies of meteoric $^{10}$Be concentrations from saprolites here seem to confirm a late Neogene age of about 2–5 Ma (Ebert et al. 2012b) for a gruss saprolite.

In conclusion and in contrast to early opinions, preglacial deep weathering has been shown to be of greater importance than glacial erosion for present relief differentiation in Scandinavia. Major structures, exploited by deep, probably Mesozoic clay weathering, have a profound influence on "undulating hilly relief" (including both "large scale joint valley landscapes" and "undulating hilly land") of northern Sweden, whereas minor structures, slope retreat (in one way or another) and gruss weathering influenced the formation of individual hills on "the inselberg plains" during the Neogene.

#### Undulating hilly relief

De Geer (1926), Elvhage & Lidmar-Bergström (1987) and Lidmar-Bergström (1995) noted structural influence in areas of "undulating hilly relief". Rudberg (1988) disputed the importance of structures in the formation of "undulating hilly relief", suggesting purely fluvial action on the landscape of northern Sweden. In contrast to De Geer's (1913, 1926) idea that glacial erosion was responsible for the appearance of fractures and joints as valleys in the landscape, Elvhage & Lidmar-Bergström (1987) and Lidmar-Bergström (1995) focused on deep weathering along fracture zones as a prerequisite for formation of hilly relief. Lidmar-Bergström (1995) was influenced by the mapping by Rudberg (1970) and tried to go southwards from Stöttingfjället to map plains in stepped sequences. However, it was clear from the relief maps (Elvhage & Lidmar-Bergström 1987) that this area was highly influenced by structures. Moreover, the profiles did not show any plains inland as are found further north, but only showed a common base level for the structural relief (Lidmar-Bergström 1996).

#### Plains with residual hills (inselberg plains)

De Geer (1926) looked upon the inselbergs of the "plains with residual hills" in northern Sweden as glacially overprinted structures. Both Rudberg (1954, 1988) and Lidmar-Bergström (1995) regarded them as mainly non-glacial forms. The latter authors regarded slope retreat in pre-glacial time as an important process in their formation. Lidmar-Bergström (1995) noted that their formation seemed to originate from hilly relief caused by Mesozoic deep weathering, supported by the scattered occurrence of kaolinised fracture zones (e.g. Frietsch 1960).

The origin of inselbergs was further investigated by Ebert et al. (2012a), who noted the importance of both structure and weathering for their shape. Structural control and the existence of a basal platform around them (Rudberg 1988, Lidmar-Bergström 1995, Fig. 9) suggest that pre-glacial denudation in comparatively dry climates has contributed to inselberg formation. The absence of soft ores (Geijer & Magnusson 1926, Ebert et al. 2012a), which occur in central Sweden, attests to different processes for their formation than for formation of hilly relief. Evacuation of rock compartments along weathered joints and sheeting planes must have been part of the ordinary slope process.

Ebert et al. (2012a) argued for inselberg formation in relation to gruss-type saprolites, assumed to be 10–20 m thick. However, they also drew conclusions about the isolation of the inselbergs by extension of the palaeosurfaces they rest on. The existence of a basal platform is seen in the contours (Fig. 9A). Thus, a basal platform with immature weathering and the absence of soft ores and clayey kaolinitc saprolites suggest that these inselbergs were not formed below deep Mesozoic clayey saprolites, whereas younger and thinner gravelly saprolites, penetrating the sheeted bedrock, may instead have contributed to their present shape by loosening bedrock sheets (cf. Ebert et al. 2012a).

The contour maps in Figure 9 support the view that inselbergs on the plains with residual hills have developed from larger rock compartments making up the hilly relief. They may have been formed in a dry climate, where weathering and stripping go hand in hand (Migoń & Goudie 2003). Glacial plucking has locally caused a steep scarp, known as a *flygg* (Rudberg 1954, 1988). Otherwise, there is little glacial reshaping (Ebert et al. 2010).

## RELIEF PRESERVATION BELOW REMNANT COVERS AND ITS TECTONIC IMPLICATIONS

The extremely flat sub-Cambrian peneplain was identified long ago along the Bothnian coast (De Geer 1918). It was not until the 1980s that Lower Paleozoic strata were recognised in the Gulf of Bothnia (Axberg 1980, Wannäs 1989), supporting the old interpretation. Until recently, Lower Paleozoic cover rocks must have protected the sub-Cambrian peneplain in those parts, where it is still well preserved. Erosion of cover rocks has exposed characteristic landscapes with long ridges (*mårdar*) or rows of residual hills marking former fault scarps. These features can thus be used to identify faults cutting the sub-Cambrian peneplain (Fig. 6).

Glacial erosion must have removed the Paleozoic cover close to remnant covers, but further away the time of removal is often uncertain. However, where the cover had gone in the Mesozoic, "undulating hilly relief" and "joint valley landscapes" might have formed as a result of the combined action of deep weathering and evacuation of debris along fracture zones at the expense of the flat sub-Cambrian peneplain. Such a situation has been confirmed in southern Sweden, where cover rocks of Cambrian, Jurassic and Cretaceous age rest directly on differently weathered and shaped Precambrian basement (Lidmar-Bergström 1988, Fig. 5).

Further north along the west coast, the relief is labelled "landscape with joint aligned valleys" (fissure valley landscapes, Rudberg 1960), and the basement here disappears below Mesozoic cover (Figs. 2, 5). The irregular relief continues north-eastwards as undulating hilly relief. Kaolinisation is found both at the coast (Lidmar-Bergström et al. 1999) and in areas of undulating hilly relief (references in Elvhage & Lidmar-Bergström 1987). In the latter area, soft ores are also described (Geijer & Magnusson 1926, Vivallo & Broman 1993) and regarded as Mesozoic (Lidmar-Bergström 1995).

All these circumstances suggest that a protective Mesozoic cover might also have existed over large areas of the north with hilly relief ("undulating hilly land" and "large-scale joint valley landscapes", Lidmar-Bergström 1995). Where not preserved below a protective cover, "undulating hilly relief" in southern Sweden was transformed into "plains with residual hills" (Lidmar-Bergström 1988), supporting the conclusion that a similar process occurred in the north for the "inselberg plains". Thus, areas of undulating hilly relief could have first been uplifted and exposed during the Mesozoic and subsequently preserved by late Mesozoic and younger covers.

It is difficult to judge from preserved deposits how far the Jurassic, Cretaceous and Paleogene transgressions reached. From the distribution of "undulating hilly relief" and remnants of deep weathering, it is argued that the Mesozoic transgressions reached far into the present day landmass of Scandinavia (Lidmar-Bergström 1995, Lidmar-Bergström et al. 2013). No covers are left but Cretaceous pollen grains are encountered both in Bohuslän and Västergötland (Fries & Ross 1950, Fries 1953). Moreover, apatite fission track thermochronology of central Sweden can be interpreted to mean there was a kilometre-thick cover during the Mesozoic and

Cenozoic, which finally disappeared during the late Neogene (Cederbom 2000).

Modelling of the thermal history of central Sweden from analysis of apatite fission track data suggests a Paleozoic cover about 2.5–3.5 km thick (Larson et al. 1999, Huigen & Andriessen 2004). This was questioned by Hendriks & Redfield (2005), but was supported by a large amount of geological data (Larsson et al. 2006). Erosion of this cover during Late Permian to early Mesozoic times, as suggested by Nikishin et al. (1996), accords well with the proposed model of Mesozoic deep weathering in basement areas with undulating hilly relief (Fig. 2), which must thus have been uplifted and re-exposed during that period.

Relief differentiation on the Canadian shield is similar to Swedish conditions, with flat surfaces extending from below Lower Paleozoic (in this case Ordovician) cover rocks (Wilson 1903, Cooke 1929, Ambrose 1964, Lidmar-Bergström & Jansson 2005) and irregular kaolinised basement extending from below Cretaceous covers (e.g. in Minnesota: Grout 1919, Bergquist 1944, Sloan 1964, Austin 1972, Patterson & Boerboom 1999). Re-exposed relief on shields seems to be a general phenomenon. The possibility of the existence of former covers might provide a clue for understanding relief differentiation on a shield, and relief differentiation might thus help in revealing the Phanerozoic tectonic history of shields.

## SIGNIFICANCE AND CORRELATION OF PENEPLAINS (STEPPED AND RE-EXPOSED)

This section first summarises identified peneplains. Thereafter the following topics are discussed: the faulted sub-Cambrian peneplain, correlations of stepped peneplains in northern Lapland, inclined or horizontal peneplain steps, differential tectonic uplift and correlation of stepped peneplains, and crosscutting relationships.

### Major peneplains: summary

The Scandes, extending across both Precambrian and Caledonian rocks, are characterised by remnants of stepped surfaces (peneplains) below each other, in addition to their glacial and periglacial features. Two separate relief types, "undulating hilly relief" in southern Norrland and western Svealand, and "inselberg plains" in northern Norrland, have been identified east of the mountains in all classifications. Inselberg plains occur in stepped sequences, while undulating hilly relief might be regarded as a re-exposed peneplain, formed as a Mesozoic etch surface, but with later glacially enhanced hills (Lidmar-Bergström et al. 2013, Green et al. 2013). Below the almost horizontal Muddus Plains (at 550–300 m a.s.l.) there is a gentle, stepped slope towards the coast in the far north and a steeper stepped slope further south. The summit highs here form a continuation of a tilted and dislocated re-exposed sub-Cambrian peneplain.

In his thesis, Rudberg (1954) mapped steps in Västerbotten County (Fig. 1) all the way from the Northern Scandes to the Bothnian Sea. His map of relief types (Rudberg 1960, 1970, Fig. 3) showed a zone of "undulating hilly land" not only to the south of these stepped monadnock plains ("plains with residual hills") in Västerbotten but also to the east, which thus means that "the undulating hilly land" interferes with his lower steps. A zone with "mixed relief" (Lidmar-Bergström 1996, Fig. 2) occurs to the east and south of "the inselberg plains". Mixed relief may include hilly relief (interpreted as a re-exposed sub-Mesozoic often tilted peneplain), horizontal steps and a faulted sub-Cambrian summit peneplain. Further south, the remnants of the sub-Cambrian peneplain are elevated, forming the plateaux of the High Coast (Fig. 2). Rivers cross this high area in major water gaps.

### The faulted sub-Cambrian peneplain

A faulted, re-exposed, sub-Cambrian peneplain plays a major role in the general landforms along the Norrland coast (Fig. 7). In the north, there are tectonic blocks tilted to the south-east. The Tärendö area is interpreted by several of the authors to be a downfaulted part of the sub-Cambrian peneplain. Hornberget is at the upper end of a major tectonic block tilted to the south-west. To the south, the south-eastern tip of Stöttingfjället is instead upthrown (Fig. 6). Southwards from here there are faults, first inland and then just offshore, creating the High Coast. Still further south the faults are again onshore with remnants of the sub-Cambrian peneplain as plateaux on the upthrown side (the "square plateaux landscape" of De Geer 1926). It is an open question whether the tilting of the tectonic blocks along the coast is related to Caledonian tectonics or to later tectonics (cf. Lidmar-Bergström 1996).

### Correlations of stepped peneplains in northern Lapland

In northern Lapland, four studies have been made using different methods to identify stepped peneplains. In the days of Wråk (1908) no maps were available, so his work is a real achievement. By following some major valleys he managed to identify the remnants of a major high surface (the Tuipal surface) and a lower Borsu surface. He noted that they were inclined to the south-east and called them landscape generations. He argued that he could follow the Muddus generation to the water divide at the north-western end of Lake Torneträsk, where he measured its elevation at 450–480 m. He identified at least one lower step along the lake. Outside the mountains he identified the Muddus generation down to 300 m. Below the Muddus surface he identified only two valley steps: Pakko and Lule.

Lidmar-Bergström (1994, 1996) identified horizontal surfaces and used the names given by Wråk (1908) for the higher surfaces. The Muddus generation was divided into two, Upper and Lower Muddus, with a clear step at 400 m. The study by Lidmar-Bergström et al. (2007) aimed to see whether the surfaces in the mountains were inclined as Wråk had suggested. They only studied the mountain area and the area down to the Upper Muddus Plains outside the mountains. They noted a clear inclination, particularly pronounced at the mountain front (Fig. 11). They followed the Muddus generation in the Torneträsk valley to just above 700 m a.s.l. at the Abisko valley (Fig. 11) and noted that Wråk had underestimated the glacial erosion. Moreover, in Wråk's day researchers were not aware of the renewed fluvial valley incision that may exist down to glacial valley bottoms, which has subsequently been documented (Kleman & Stroeven 1997).

The methodological study by Ebert et al. (2011) does not refer to or discuss the methods of earlier mappings of the same area (Lidmar-Bergström 1994, 1996) and the area to the south (Rudberg 1954). They nonetheless confirm the clear step at 400 m. Their correlation with the surfaces identified by Wråk is incorrect (Table 1), which might be due in part to the delimitation of their study areas into two areas with Caledonian and Precambrian bedrock respectively. In addition, Pakko and Lule are names that Wråk (1908) had used for local steps in the Lule River, but not connected to any surface. Unfortunately, Ebert et al. (2011) used these names for their B and A levels, below and east of the Muddus Plains. On the other hand, those two low plains are real features and almost identical to those of Lidmar-Bergström (1994, 1996). Perhaps the young steps in the Lule River are governed by old cyclical steps.

## Inclined or horizontal peneplain steps

Wråk (1908) described surfaces and valley benches inclined to the south-east in the mountains, with the Tuipal surface making up major *fjell* plateaux. He noted the inclination of the surfaces at a time when surfaces elsewhere in the world were generally mapped as horizontal. Similarly, Ahlmann et al. (1942) regarded "the inselberg plains" as consisting of two inclined levels (the inland peneplain and the hill peneplain) that could be correlated with mountain surfaces in the west. In contrast, Rudberg (1954) gained the impression from the contour maps that the surfaces in Västerbotten County were horizontal and separated by steps into 13 surfaces. Lidmar-Bergström (1994, 1996) had problems in identifying and correlating surfaces having a limited extent in the mountains on the basis of the material she used, and stuck to the idea of horizontality. Later, the observations by Wråk (1908) were tested along a section across the Northern Scandes from the Norwegian coast to the Muddus Plains in northern Lapland using a combination of digital slope maps and digital profiles (Lidmar-Bergström et al. 2007). It was confirmed that the surfaces slope eastwards, and also shown that the higher surfaces have the steepest inclination and that the surfaces slope in a slightly curved form, all with a higher inclination along the eastern border of the mountains. Thus, it is not a simple tilt as Wråk (1908) had suggested, but rather a warp.

The surfaces in the mountains occur below each other along major valleys (Lidmar-Bergström et al. 2007), whereas the surfaces outside the mountains are nearly horizontal and extend eastwards side by side below each other (Lidmar-Bergström 1994, 1996, Ebert et al. 2011). The mountain surfaces merge eastwards, the two lowest to form the Muddus Plains, while the higher surfaces constitute the summit plateaux of several inselbergs (Lidmar-Bergström et al. 2007). Important questions arise concerning the horizontal surfaces of the *fjell* areas of southern Lapland as mapped by Rudberg (1954). Are they really horizontal or did the contour map mislead Rudberg (1954) in the mountains, with their dissected surfaces and strong glacial impact on the valleys?

## Differential tectonic uplift and correlation of stepped peneplains

This review has revealed the existence of stepped peneplains in northern Norrland, as in many other areas of the world, whereas the notion of "undulating hilly land", used for southern Norrland and western Svealand, is seldom met with outside the Nordic countries. An almost total evacuation of a former saprolite by erosion might be the cause for the final shaping of the "undulating hilly land".

In southernmost Sweden, the "undulating hilly land" as well as "landscapes with joint aligned valleys" are re-exposed from below Late Cretaceous cover rocks (Lidmar-Bergström 1989). These relief types continue along the Swedish west coast and then continue northwards (a little more pronounced) along the eastern flank of the Southern Scandes (Fig. 2). It is therefore argued that the area with "undulating hilly relief" was uplifted at a late stage together with the Southern Scandes, probably in the Neogene. This caused erosion of the protecting cover rocks (Lidmar-Bergström 1999, Lidmar-Bergström et al. 2013).

Lidmar-Bergström (1999) and Lidmar-Bergström et al. (2013) correlated the major "inselberg plain" of northern Norrland with the lower "palaeic surface" of the Southern Scandes (Reusch 1901, Lidmar-Bergström et al. 2000). A differential uplift of the Scandes with a first common Paleogene uplift for the whole area and a second Neogene uplift, which mainly affected the Southern Scandes, was advocated by Riis (1996) based on conditions off the coast of Norway. Such a differential late uplift satisfies the interpretation of a late re-exposure of the "undulating hilly relief" from a Mesozoic cover and an original lower position of this relief in relation to the inselberg plains in the north.

An initial period with several Cenozoic uplift events should explain the major steps down to 300 m (the map in Figure 2 includes plains down to 200 m in the north under the heading 'plains with residual hills', and may include areas with a re-exposed sub-Cambrian peneplain) in northern Sweden, while a second period caused uplift to the present elevations (Lidmar-Bergström et al. 2013). The late uplift might have been as late as 4 Ma (Japsen et al. 2007).

A renewed study of southern Lapland is needed to achieve better knowledge. An area of particular interest is Stöttingfjället (Figs. 2, 5, 6) and how its surfaces should be correlated northwards, southwards and westwards into the mountains. To the south, Stöttingfjället borders the zone with mixed relief (Fig. 2), and it seems to constitute a major parting between the inselberg plains in the north and the undulating hilly relief in the south, interpreted to be a re-exposed sub-Mesozoic surface (Lidmar-Bergström 1999).

Are the inselberg plains rising southwards due to late uplift? This could explain a genetically low position of hilly relief protected by a cover during formation of the plains with residual hills. It could also explain the correlation of the inselberg plains with the palaeic surfaces of the Southern Scandes (Lidmar-Bergström et al. 2013). A late Neogene uplift (4 Ma according to Japsen et al. 2007) could also explain minimal lowering of the plains since formation.

### Crosscutting relationships

Rudberg (1988) suggested a study of the interference between the inclined sub-Cambrian peneplain and horizontal surfaces. Lidmar-Bergström (1982) had examined the relationships between the inclined sub-Cretaceous hilly relief on the southern and western slopes of the South Swedish Dome and its crosscutting relationships to the horizontal South Småland Peneplain, which resulted in it being dated to the Cenozoic. A method known as Stratigraphic Landscape Analysis (SLA), which uses the crosscutting relationships between re-exposed tilted peneplains of different shape and younger horizontal peneplains, was developed and used for all of Scandinavia (Lidmar-Bergström et al. 2013, Green et al. 2013). Refined SLA is needed for further studies of Fennoscandian preglacial tectonic development.

## IMPLICATIONS OF VALLEYS FOR CONCLUSIONS ON TECTONICS AND GLACIAL EROSION

Four topics are discussed in this section: 1) Valleys and water gaps in relation to the sub-Cambrian peneplain, 2) Influence of the glaciations on some water gaps, 3) Incision of the Lule River and its implications, and 4) Correlations of knick-points and stepped peneplains.

### Valleys and water gaps along the Bothnian coast in relation to tectonics constrained by the sub-Cambrian peneplain

A comparison between the map of drainage basins by Rudberg (1988, Fig.13A), the map of the sub-Cambrian peneplain by Lidmar-Bergström (1996, Fig. 7), and the valley map by Lidmar-Bergström (1996, Fig. 14) indicates that Rudberg's forest rivers are often located in tilted coastal blocks, with the sub-Cambrian peneplain as the original summit surface. This indicates a relatively late uplift and re-exposure of the sub-Cambrian peneplain in these areas. The low position and low gradients of the lower parts of the Torne and Kalix Rivers as well as the Ume River are due to their positions in relation to tilted blocks defined in relation to the sub-Cambrian peneplain (Figs. 6–7).

The Ångermanälven and Indalsälven Rivers make up major water gaps along fracture zones within the "large-scale joint valley landscape" inside the High Coast (Figs. 2, 4, 15, Ahlmann et al. 1942, Lidmar-Bergström 1996). Ahlmann et al. (1942) suggested that a Late Tertiary coastal rise had caused the water gaps. Högbom (1906) noted a tectonic throw of 400 m between the coastal hills averaging 250 m a.s.l. and the sea bottom at an average depth of 150 m, which at that time was not known to be underlain by Lower Paleozoic sedimentary rocks. Faulting was later confirmed by seismic studies of the sedimentary Proterozoic and Lower Paleozoic rocks offshore (Axberg 1980), which shows a total dislocation of the sub-Cambrian peneplain of 650 m (from plateau summits on land to Precambrian surface below Cambrian cover offshore). The water gaps inside the High Coast (Fig. 15) are prominent features and hint at tectonic uplift events.

### Influence of the glaciations on some water gaps

The upper reaches of both the Ångermanälven and Indalsälven Rivers and their tributaries have wide valleys at low elevations, mainly below 400 m and in the mountains below 600 m (Figs. 6, 13A, 14). The wide valleys are located approximately on the saddle between the Northern and Southern Scandes in Jämtland (Fig. 2). Rudberg (1988) noted that glacial erosion had changed the topography of the Lake Storsjön basin and the course of Indalsälven (Fig. 14). He suggested a glacial deflection of the outflow to the present outflow through Indalsälven, which connects this river to a probably original tributary valley of Ångermanälven (Fig. 15, Lidmar-Bergström 1996). The low-positioned, wide valleys of the mountain rivers and the deflection of Indalsälven along its upper reaches indicate comparatively deep glacial erosion in the saddle between the Northern and Southern Scandes and in the Östersund area. This could explain the present water gaps inside the coast of the Bothnian Sea as being partly caused by glacial erosion upstream of easily erodible rocks (Rudberg 1988). The supposed deflection of Indalsälven to the narrow fracture zone close to the coast might be the result of river capture caused by glacial erosion at the coast downstream (Lidmar-Bergström 1996). These impressive water gaps as well as those of Ljungan and Ljusnan (Fig. 15) seem to have a complicated history related to structures, deep weathering, tectonic uplift and glacial erosion. It is clear that there is no single explanation for the location of the present valleys and water gaps. The story seems to be more complicated than previously thought.

### Incision of the Lule River and its implications

The Lule River is one of only two rivers with marked valleys incised into the Muddus Plains and all the way to the sea (Lidmar-Bergström 1994, 1996, Fig. 6). Major waterfalls occur just below the Upper Muddus level after a southward turn of the Stora Lule River (Fig. 16, Frödin 1914). Although it is obvious that landscape steps do occur in northern Norrland (Lidmar-Bergström 1994, 1996, Ebert et al. 2011), they cannot be directly related to the knickpoints at Porjus and Harsprånget (Frödin 1914). The profiles by Norlindh (1924, Fig. 12) show an anomalously steep curve here for the Lule River, which supports the views of Frödin (1914) of a young southerly river deflection with an increased water discharge along an old valley connected to the Pakko valley.

Frödin (1914) emphasised the importance of the fracture systems for river deflection, but since he noted that the new river channel was glacially polished, he thought river capture had occurred before the last glacial overriding. A changed water discharge, as suggested by Frödin (1914), may have caused the waterfalls and the deep incision of the Lule River downstream during the Quaternary, which in turn caused the hanging valleys of Muddusjokk and other rivulets along the Lule River (Olvmo 1989, Fig. 16). Sub-glacial meltwater during retreat of the late Weichselian ice has been shown to have contributed to the present shape of the gorges at Porjus and Harsprånget (Jansen et al. 2014). Incision by sub-glacial meltwater might thus have contributed to the abnormal incision of Stora Lule River at Porjus and Harsprånget (Fig. 12), but perhaps during more than one glacier retreat.

### Correlation of knickpoints and stepped peneplains

It is difficult to correlate landscape steps with river steps, particularly in a formerly glaciated country. Norlindh (1924) merely correlated the knickpoints in all Swedish rivers to one common staircase. Rudberg (1954) tried to correlate the knickpoints for Västerbotten rivers with the mapped landscape steps in this area. He described the difficulties and noted that the rivers do not always follow their preglacial courses and that their relation to mapped surface steps of the landscape is not straightforward. The steps of the Stora Lule River, discussed in the preceding section, illustrate this difficulty.

It seems more relevant to correlate extensive inselberg plains from one area to another than to correlate surfaces or knickpoints at the same elevation. The old idea of correlating steps at the same elevation was based on assumptions of uniform uplift relative to sea level (e.g. Lefèvre 1950).

## RELIEF TYPES AND GLACIAL EROSION

It has been documented that flat surfaces retain their flatness, and hilly relief is accentuated by glacial erosion (Johansson et al. 2001). It has also been shown that the landscape with joint aligned valleys in Blekinge, southern Sweden, is mainly a re-exposed sub-Cretaceous landscape (Lidmar-Bergström 1988, 1994, 1996) although it is affected by glacial scour (Kleman et al. 2008). However, what about the undulating hilly relief in central Sweden (Fig. 2)? Preserved hummocky moraines, from early glacial advances on the Muddus Plains (Hättestrand 1998, Fredin & Hättestrand 2002, Jansson & Fredin 2002), show that glacial erosion here has been less than further south in the undulating hillyrelief. Thus, glacial erosion must have been greater in areas of hilly relief during later glacial advances, since the hummocky moraines have disappeared. Glacial erosion might have helped in evacuating at least weathering remnants, and contributed to some reshaping. On the other hand, these areas do not belong to areas displaying glacial scour (Kleman et al. 2008).

Moreover, the border between the sub-Cambrian peneplain and undulating hilly relief in Svealand, central Sweden, (Figs. 1–2) is not related to any glacial pattern. The exposure of basement rocks during different periods with different weathering regimes and preservation of relief, plains and undulating hilly relief, by rocks of Cambrian and Mesozoic age respectively (Lidmar-Bergström 1995) is the only explanation to date for the origin of relief differentiation in Precambrian basement rocks.

It has been suggested that the residual hills of northern Norrland originate from larger rock compartments, based on a comparison of their different outlines (Fig. 9). If this interpretation is correct (Lidmar-Bergström 1995), the residual hills in the north are younger than the undulating hilly relief, which seems to have been affected more by glacial erosion during some periods (see above). The inselbergs (residual hills) in the north, on the other hand, are interpreted to be preglacial (Ebert & Hättestrand 2010). Together, these observations contradict glacial formation of the undulating hillyrelief. Nor are the stepped peneplains in northern Lapland (Lidmar-Bergström et al. 1994, 1996, Ebert et al. 2011) related solely to areas void of glacial erosion (Hättestrand & Stroeven 2002).

From all these observations it may be concluded that glacial erosion is not the cause of the relief differentiation, although it may have helped in accentuating hills. The identification and crosscutting relationships between peneplains of different age and shape, as analysed in southern Sweden (Lidmar-Bergström 1988, Lidmar-Bergström et al. 2013), instead supports the view that the different relief types, even in the north, originated during different times of the Phanerozoic.

## General conclusions

The present review shows how observations of bedrock relief have gradually improved. The interpretation of landforms has changed over time, but information has also sometimes been forgotten or neglected. Input from international geomorphological science has contributed to new interpretations, while interpretations of interrelationships between landforms in basement rocks and their former covers, in particular, have been developed in Sweden. This has subsequently been used to draw conclusions about Phanerozoic tectonics.

Wråk often underestimated glacial erosion, while De Geer overestimated it. Rudberg favoured fluvial action to explain the present landscapes, rejecting any structural and tectonic influences. Deep weathering was not considered to be a major process shaping relief in Sweden until the 1980s. Lidmar-Bergström then associated the "undulating hilly relief" with Mesozoic deep clay weathering of fracture zones. She and her coworkers also acknowledged the importance of gravelly weathering (gruss) for younger relief features. Ebert and co-workers attested to the importance of both gruss weathering and structure in the formation of inselbergs on the plains with residual hills and confirmed the limited effect of glacial erosion.

Högbom had already realised in the early 1900s that flat areas had been re-exposed from Cambrian cover rocks. De Geer identified fault scarps in relation to the sub-Cambrian peneplain south of Skellefteå on the Bothnian coast. Lidmar-Bergström stressed the importance of cover rocks of different ages resting directly on basement for preservation of old relief of different shape and with different saprolite characteristics. These observations led to insights about tectonic uplift and subsidence, which had long been regarded as hypothetical, although Ahlmann et al. (1942) had argued that tectonic uplift had occurred along the Bothnian Sea coast. The importance of the sub-Cambrian peneplain for identification of tectonic blocks along the whole Bothnian coast was shown by Lidmar-Bergström.

While Rudberg argued that the river pattern was ancient and stable, Lidmar-Bergström instead noted the frequency of river deflections. Some deflections seem to have been caused by glacial erosion or blocking Quaternary deposits, just as Rudberg thought, but tectonic causes must also be taken into account.

All authors reviewed, who have discussed the question of uplift, argue for post-Caledonian uplift of Scandinavia. Ahlmann et al. (1942) noted a late tectonic uplift along the coast of southern Norrland as the cause of the major water gaps and in the present paper we estimate the total uplift of the sub-Cambrian peneplain here to have been about 650 m. Rudberg was a careful and reliable describer of landforms but was cautious in his interpretations. He followed the general ideas of the early twentieth century and only implied that rising land was impacted by fluvial processes. He did not think tectonic explanations of landscape forms were needed. In contrast, Lidmar-Bergström et al. (2013) analysed relief differentiation using Stratigraphic Landscape Analysis and concluded repeated uplift and subsidence of Scandinavia.

In summary, it is concluded that tectonic explanations of the major relief features, with periods of uplift and relief formation, and periods of subsidence with covering and preservation satisfy the observations, while glacial explanations are only locally relevant for major landforms, particularly for the valley systems. Deep clayey weathering and structures have been of great importance in the shaping of relief during the Mesozoic warm and humid climates, while gruss weathering and structures have influenced relief formed during the late Cenozoic. Differential uplift of the Scandes, with its stepped peneplains and re-exposed relief at low elevations, seems to have occurred in the Neogene, and the latest uplift may have occurred as late as 4 Ma. Reorganisation of the river network in conjunction with glaciations seems to have been of greater importance than generally thought.


## Acknowledgements

We thank our two referees Piotr Migoń, Wroclaw, and Clas Hättestrand, Stockholm, for valuable comments, which helped us improve the manuscript.


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Geological Survey of Sweden
Box 670
SE-751 28 Uppsala
Phone: +46 18 17 90 00
Fax: +46 18 17 92 10
www.sgu.se

Uppsala 2015
ISSN 1103-3371
ISBN 978-91-7403-308-3
Print: Elanders Sverige AB