Strål
säkerhets
myndigheten

Swedish Radiation Safety Authority

Authors: Monica Beckholmen
Sven A Tirén

Research

2010:40

Rock-block characterization on regional to local scales for two SKB sites

Forsmark – Uppland and Laxemar – eastern Småland, south-eastern Sweden

Report number: 2010:40 ISSN: 2000-0456
Available at www.stralsakerhetsmyndigheten.se

Title: Rock-block characterization on regional to local scales for two SKB sites in Forsmark – Uppland and Laxemar – eastern Småland, south-eastern Sweden.
Report number: 2010:40
Author: Monica Beckholmen and Sven A Tirén
GEOSIGMA AB
Date: November 2010

SSM Perspective

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

Background

To get an overall impression of the general structural setting of a landscape, a remote study of bedrock structures should include studies of the geomorphology at various scales. Thematic maps improve the general understanding of an area. Digital elevation data in 500m, 50m and 10m grids were used for rock-block interpretations at regional, semi-regional and local scales of areas around the two SKB sites, Forsmark in Uppland and Laxemar in Småland, which are objects for SKB's site-investigation programme. The bedrock head in both areas is interpreted to be close to the surface of the sub-Cambrian peneplain and varying altitude may testify to block-faulting in a distorted peneplain. Topographic breaks and changes in the gradient also reveal possible zones of weakness that may conduct water.

Purpose

The purpose of the current project is to comprise interpretations made from digital elevation information on areas in the back land of the two site areas. The study is based on the idea that topography gives a clue to structures in the bedrock. Topographic breaks and changes in the gradient could reveal possible zones of weakness that may conduct water. Such changes can be shown on maps as lines and are denoted as lineaments. The distribution of earthquakes could strengthen the interpretation that the delineated pattern of lineaments and rock-block boundaries represent zones of weakness.

Results

The size of the regional area that needs to be studied for understanding the structural setting of a site should be related to the character of the structural terrain within which the site is located. Deformation zones with an increased porosity (less resistant to erosion) appear as a network of valleys. This outline of weathered valleys indicates structures that are softer than the bedrock in general and may form larger-scale transport paths for groundwater in the bedrock. A rock-block map may also show how regional structures can be intricately linked together during reactivation.

The rock-block interpretations were compared to bedrock and general correlation between major structures is seen. However, the distribution of rocks on a regional map often demonstrates the plastic deformation in a wider zone. There is also good agreement between the location of epicentres and rock-block boundaries. The Forsmark local area is situated in a relatively low block, while the Laxemar local area lies on a slightly elevated east-west culmination and stands out as a relative high.

Effects on SSM supervisory and regulatory task
The result of this study gives SSM new knowledge of the pattern of zones of weakness, their properties (plastic or brittle) and distribution of single fractures which are important for understanding the characteristics that might influence the long term safety of the repository for spent nuclear fuel.

Project information
SKI reference: SKI 14.9-00216/001374, 14.9-01230/011117 and SKI 14.9-031256/200309014
Responsible at SKI has been Fritz Kautsky and at SSM Lena Sonnerfelt

Table of Contents

ABSTRAKT

Digitala höjddata i 500 m, 50 m och 10 m nät användes för bergblock tolkningar i regional, semiregional och lokal nivå i områdena kring de två platser som är föremål för SKB:s platsundersökningsprogram. Båda områdena tolkas ligga nära ytan av det subkambriska peneplanet där varierande höjd och ställning kan vittna om blockförkastningar i det föpåverkade peneplanet. Topografiska avbrott och förändringar i gradient uppdagar också möjliga svaghetszoner som kan leda vatten.

Bergblockkartor har upprättats för hela Uppland i skala 1:750 000, norra Uppland i skala 1:450 000 och det lokala Forsmarksområdet i skala 1:150 000. Motsvarande bergblockkartor gjordes för östra Småland i skalorna 1:500 000 i regional skala, en för ett semiregionalt område i skala 1:250 000 och en för det lokala Laxemarområdet i skala 1:75 000.

Orienteringen av bergblockgränser och storleken på bergblocken behandlades statistiskt. Bergblock/polygoner analyserades utgörande medel-, lägsta- och högsta höjd och utbredning. Värdena återgavs i form av kartor.

Topografin i synnerhet i östra Småland domineras av en tydlig gradient där landet höjer sig ur havet i öster. Ansträngningar har därför gjorts att eliminera en uppskattad lutning för att bedöma återstående kännetecken (karakteristiska förhållanden) och samma analyser gjordes för medel-, lägsta- och högsta höjd och utbredning. I många fall förbättrades resultaten varför de två typerna av presentation utgör komplement till varandra.

Bergblocktolkningarna jämfördes med nuvarande berggrund varvid ett allmänt samband mellan stora strukturer kan ses. Men fördelningen av bergarter i regional kartskala visar ofta plastisk deformation i ett större område.

Epicentrum för jordbävningar kombinerades med bergblockkartor och förutsatt att tolkade bergblockgränser är ganska branta råder det god överensstämmelse mellan läget för epicentrum och bergblockgränser. I vissa fall kan man se hur seismiska störningar utbrett sig längs en struktur. Många jordbävningar uppstår vid korsningarna av stora lineament, t ex. i bergblockhörn. I andra fall inträffar den seismiska händelsen i en förlängning av en struktur där strukturen är mindre tydlig. Jordbävningarna i Gävlebukten är registrerade i ett område med ett underskott i den postglaciala landhöjningen jämfört med landhöjningsmodeller. Förknippat med detta område med "lägre" höjning är två större sedimentära bassänger med jotnisk sandsten och ett täcke från lägre paleozoikum. Frekvensen av jordskalv i östra Småland är lägre än i Uppland.

Det lokala Forsmarksområdet ligger i ett relativt lågt beläget block, medan det lokala området Laxemar ligger på en något förhöjd öst-västlig kulmination och framstår därför som en höjd.

Nyckelord: *digitala höjddata, topografi, peneplan, blockförkastningar, strukturer, lineament, bergblockyta, polygoner, jordskalvförekomst, Uppland, Småland, Forsmark, Laxemar, SKB platsundersökningar, förvaring av kärnavfall, platskarakterisering.*

ABSTRACT
Digital elevation data in 500m, 50m and 10m grids were used for rock-block interpretations at regional, semi-regional and local scales of areas around the two SKB sites, Forsmark and Laxemar, objects for the site-investigation programme. Both areas are interpreted to be close to the surface of the sub-Cambrian peneplain and varying altitude and attitude may testify to block-faulting in the distorted peneplain. Topographic breaks and changes in the gradient also reveal possible zones of weakness that may conduct water.

Rock blocks were constructed for Uppland at 1:750 000, northern Uppland at 1:450 000 and the local Forsmark area at 1:150 000, three sets were constructed for eastern Småland at 1:500 000, and one for the semi-regional area at 1:250 000 and one for the local Laxemar area at 1:75 000.

The orientation of rock-block boundaries and the size of the rock blocks were treated statistically. The rock blocks/polygons were analysed for their mean, minimum and maximum elevation and the range. The values were displayed by maps.

The topography in especially eastern Småland is dominated by a clear gradient, the land rising from the sea in the east. Efforts were therefore made to remove an estimated gradient to assess the residual features and the same analyses were then made for mean, maximum, minimum and range values. In many cases the results were enhanced and the two types of presentations are complementary to each other.

The rock-block interpretations were compared to bedrock and general correlation between major structures where identified. However, the distribution of rocks on a regional map often demonstrates the plastic deformation in a wider zone.

Earthquake epicentres were combined with the rock-block maps and assuming that interpreted rock-block boundaries are fairly steep, there is good agreement between the location of epicentres and rock-block boundaries. In some cases it can be seen how seismic disturbance migrated along a structure. Many earthquakes occur at the intersections of major lineaments, i.e. at rock blocks corners. In other cases the seismic event occurs in the prolongation of a structure where it is less obvious. The earthquakes in Gävlebukten are registered in an area with a deficit in post-glacial uplift as compared to uplift models. In connection with this area of “lower” uplift are two major sedimentary basins with Jotnian sandstone and Lower Palaeozoic cover. The seismicity in eastern Småland is lower than in Uppland.

The Forsmark local area is situated in a relatively low block, while the Laxemar local area lies on a slightly elevated east-west culmination and stands out as a relative high.

Keywords: digital elevation data, topography, peneplain, block-faulting, structures, lineament, rock-block surface, polygons, earthquake distribution, Uppland, Småland, Forsmark, Laxemar, SKB site investigation, nuclear waste disposal, site characterization.

ACKNOWLEDGEMENT

Thomas Sträng, Geosigma AB, made the transformations and calculations involved for the removal of the topographic gradient and producing residual maps.

The digital elevation data were published with the permission of the National Land Survey of Sweden (I 2007/1092).

1 INTRODUCTION

This study comprises interpretations made from digital elevation information on areas in the back land of the two site areas (Forsmark in Uppland and Laxemar in Småland, cf. Fig. 4) that are the objects for SKB´s site-investigation programme. It is based on the idea that topography gives a clue to structures in the bedrock. Topographic breaks and changes in the gradient reveal possible zones of weakness that may conduct water. Such changes are shown on maps as lines and are denoted as lineaments. The distribution of earthquakes strengthens the interpretation that the delineated pattern of lineaments and rock-block boundaries represent zones of weakness.

1.1 Topographic & Geological Setting

Both sites are situated on, or near, the Baltic Sea coastline (cf. Fig. 4) where the bedrock surface lies close to prisms of the sub-Cambrian peneplain, with a north-easterly slope in northern Uppland and an east-south-easterly slope in Småland. The relief of Uppland is, however, much lower than that in Småland, 115m for Northern Uppland and 286m for Eastern Småland with a steeper gradient.

The Uppland areas are all underlain by Svecofennian (1.91-1.75Ga) supracrustals and granites while the Småland areas are made up of somewhat younger TIB- (Trans-Scandinavian Igneous Belt) granitoids (1.81-1.76Ga) and only the north-eastern corner of the regional area touches into the Svecofennian domain. The Småland granitoids are intruded by 1.45Ga granite bodies. Both areas are cut by dolerite dykes. However, the Uppland area is bordered to the north and east by sedimentary fault-basins with Mesoproterozoic Jotnian sandstones (cf. Fig. 9), in particular, in the floor of the Ålands-hav basin where water depth reaches over 250m. The Jotnian basins are often linked to intrusives of rapakivi granites, e.g. the Åland Rapakivi body to the east (1.57-1.58Ga). To the north, the Jotnian sandstone is overlain by Palaeozoic sedimentary rocks. The Småland area is overlain by Palaeozoic sedimentary rocks in the Baltic Sea to the east. Cambrian(?) sandstone dykes in both areas testify to the closeness of the present bedrock surface to the sub-Cambrian peneplain.

The degree of exposed rock is considerably lower in the regional Uppland area (on average less than approximately 10%, cf. SKB (2005, Table 4-1) than in the Småland area (relative percentage of exposed rock 35%, SKB (2006, Table 4-1). In the northern part of the Småland area, at Götemaren, the degree of exposed rock is about 70%, while in its south-western parts it is very low, less than 5%. On remote mapping scales the thickness of the Quaternary sediments does not appear to significantly affect the ability to outline the structural pattern in the bedrock; less for the regional Laxemar area than for the Forsmark regional area. However, the sedimentary cover may affect the interpreted position of structures.
The erosion of the bedrock during glaciation may enhance the topographical signature of out-cropping fracture zones that are sub-parallel to the ice-movement, in Uppland roughly north-south on land and south-eastwards along the northern shoreline, and, in eastern Småland, towards the southeast on land and north-south in Kalmarsund (Lundqvist 1961, SNA 1994). The average

erosion of the bedrock during a glacial cycle has been estimated to be about one metre (Påsse 2004).

For a more detailed description of the geological setting the reader is referred to SKB (2005, 2006).

1.2 The Art of Lineament Interpretation

Lineaments may be drawn in many different manners. Basic to all, is that they reflect change along a linear feature on a 2-dimensional image/map. This change may reflect bedrock structure and is thus a tool to elucidate the bedrock pattern.

1.2.1 Definition and usage

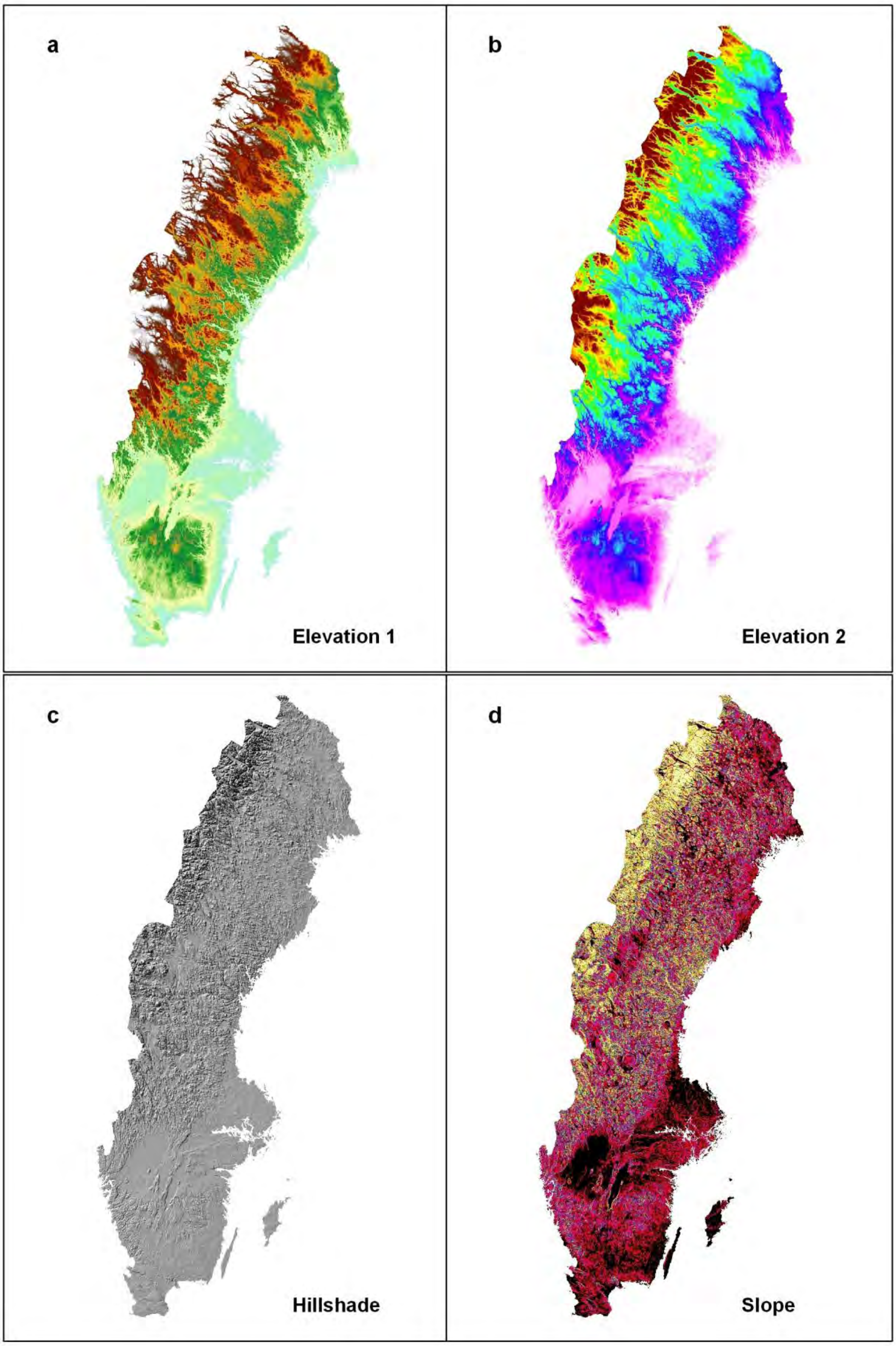
The relationship between linear and semi-linear landform breaks and structures in the underlying bedrock has been discussed for more than a hundred years. The early development of geographical maps revealing landforms was to a large extent a military concern for the defence; transport of troops and other logistics. At the end of the 19th century geologists realized the relation between landforms (e.g. valleys) and fractures in the bedrock. Svedmark, in 1887 presented an "orographic" study of the Roslagen area in northern Uppland where he mapped the "Öregrund-Singö valley" and the "Forsmark-Granfjärden valley", in close vicinity to the Forsmark site, as fracture lines. The lineament concept, however, was introduced first in 1903 by Hobbs, who in 1912 wrote that "significant lines of landscape which reveal the hidden architecture of the basement are described as lineaments". The present study has adopted Hobb´s definition and interprets sharp and sudden landforms as potential brittle structures.

The "orographic" lineament studies later developed into maps presenting "rock blocks" (e.g. Asklund 1923). Systematic tilting of large-scale basement blocks was described by De Geer in 1910 and 1913.

1.2.2 Base maps

Lineament interpretations may be based on various topographic data, a map, a satellite image, an air photo, etc. but are also made from, e.g. geophysical images. Satellite images and air photos give a rendering of the Earth‟s surface while geophysical images may display features in the ground not outcropping at the surface but occurring at some depth. Digital elevation data display topography only, without the visual disturbances caused by roads, power lines and forestry on air photos.

Figure 1. Digital elevation data covering Sweden, a) and b). Altitude shown by the two most used palettes in the investigations. C) Relief map produced by using the hill shade tool. D) Slope map produced with the slope tool, yellow displays the steepest gradients and black the flattest areas.



Mathematical manipulation of digital data may effect the placing of the lineament line when drawing the lineament. Depending on the nature of the base map the interpretation may enhance different structures, i.e. the scale at which the lineament interpretation is performed, colouring, etc. The method of producing a lineament map influences the result. A hand-drawn lineament that is drawn with a pencil on the map differs from a hand-drawn lineament drawn on a plastic sheet with a felt-tip pen. The style differs even more if the interpretation is made on a screen with a digital tool.

The basis for lineament interpretations has long been a paper-based media, a map or an air photo with an overlay that can be extracted from the base media. Sometimes the interpreter has had the possibility to enhance the base map by colouring of isolines in different ways or choosing between photos taken at different sun elevation and azimuth, vegetation cover, etc.

The possibility to manipulate the base map has much improved with the digital revolution (Fig. 1). The possibility to change colour palettes with varying resolution in different segments of a population (i.e. at different altitudes) and the possibility to increase the resolution by excluding parts of the population makes it possible to enhance the picture in a certain area. The possibility to zoom in and out changes the viewing scale in reference to the resolution. However, these increased possibilities may result in an overwhelming amount of labour which may not improve the result in proportion to the efforts.

1.2.3 Reproducibility of an interpretation

It is of course essential that a lineament interpretation does represent solid information about the bedrock. However, the reproducibility of an interpretation is heavily dependent on the base maps used, and also the theme the interpreter wants to enhance, such as major lines, rock blocks, changes in elevation, internal mosaic, etc. This is reflected in the way single elements are connected, e.g. the amount of interpolation and curvature allowed. The main components may well agree, while the linkage and connection give a different impression of the lineament pattern.

1.2.4 The location of a lineament

The placing of the line when interpreting an image may be the result of the consideration of several choices and is dependent on the theme and scale of the specific interpretation. A major structure may be drawn with a line in its centre (Fig. 2), but also, depending on the nature of the structure, as two separate lines on either side, as a series of en echelon lines in a slightly different orientation, as composite lines in two-three different orientations, or as lenses. There is a choice whether to draw a line as a middle line, the bottom line or at the largest step in altitude.

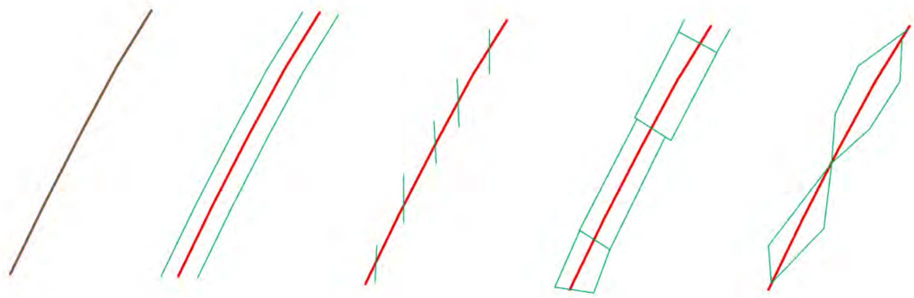


Figure 2. Structures (green) that may constitute an interpreted lineament (red), from left to right, a line, a corridor – e.g. clay-filled valley, en echelon smaller scale structures, complex structures – rock blocks, lenses.

If the base map is a mathematically manipulated map (e.g. a relief map, derivative, 2nd derivative or based on geophysical data, etc.), the trace of the structure may shift in relation to the trace of the original topographic data.

1.2.5 Scale, resolution and pixel size

Scale and resolution influence the result. A readily visible feature may disappear when zooming in on it. Reduction of the size of a map gives an overview and lets the eye connect features that within an enlarged area may loose their coherence. Two maps of the same scale may yield different results due to the details in, e.g. isolines or size of pixels.

A pixel gives an estimated value for the square covered by the pixel. If the pixel is 10m x 10m the uncertainty in the location of a lineament is on the order of 10m, while for a pixel of 500m x 500m the uncertainty is in hundreds of metres. This is important to bear in mind when comparing interpretations made at different scales and resolutions.

The smallest lineament detected generally runs over 8-10 pixels which in a database for a 10m grid gives a length of about a hundred metres and for a 500m grid a length of c. 5km.

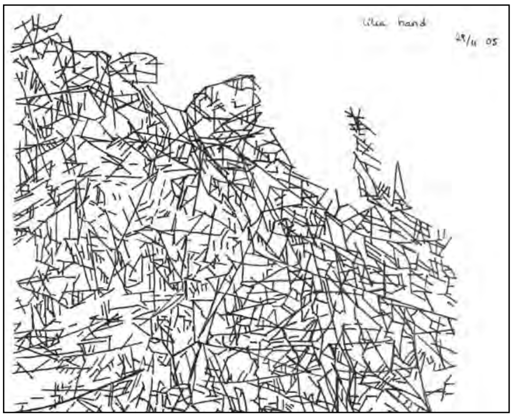
1.2.6 Hand-drawn interpretations

A hand-drawn lineament is shaped by the hand and, mostly, organically follows the image in its characteristics. This involves curvature and enhances a dynamic picture and a thematic interpretation.

1.2.7 Digitally drawn interpretations

Digitally drawn lineaments are easily clicked on the screen from one point to the other leaving a straight line between them. This may give a static, dead picture especially in an environment where lineaments have an internal lensoid pattern (Fig. 3b). When put on top of the base map a digitally drawn lineament interpretation may lie as a grid on top and does not sink into and unite with the base map as it would Fig. 3a.

If the interpretation is made close to the limits of the resolution, the overview is easily lost.

a.  b.

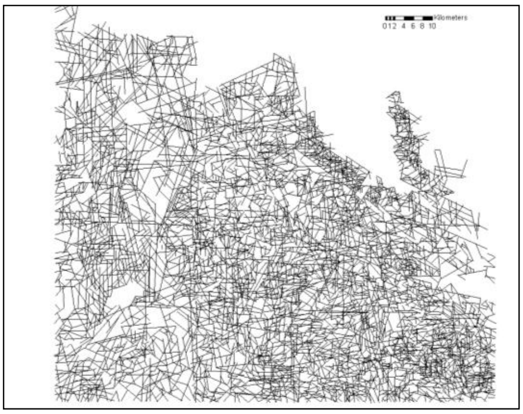


Figure 3. Examples of, a) a hand-drawn lineament interpretation, and b) a lineament interpretation made on screen.

1.2.8 Rock blocks

Construction of rock-block maps is a test of the lineament interpretation in the sense that a rock block has to be circumscribed by block boundaries. Block boundaries represent structures that potentially have low cohesion, i.e. have low tensile strength, and thereby may be water-conductive.

Rock blocks occur on all scales, i.e. large-scale rock blocks consist of many minor-scale blocks, and like people, a piece of bedrock may belong to different kinds of block networks depending on the emphasis of the interpretation. Rock-block maps may give the impression that structures outlining rock blocks terminate against other structures. This is, in many cases, a false picture as structures often continue into the next block but may diminish and stop inside the rock block. Such blind terminations are not usually displayed on rock block maps.

2 BASE DATA

Digital elevation data have been modelled for the two areas in eastern Sweden around the investigation sites at Forsmark in northern Uppland and Laxemar in eastern Småland (Fig. 4).

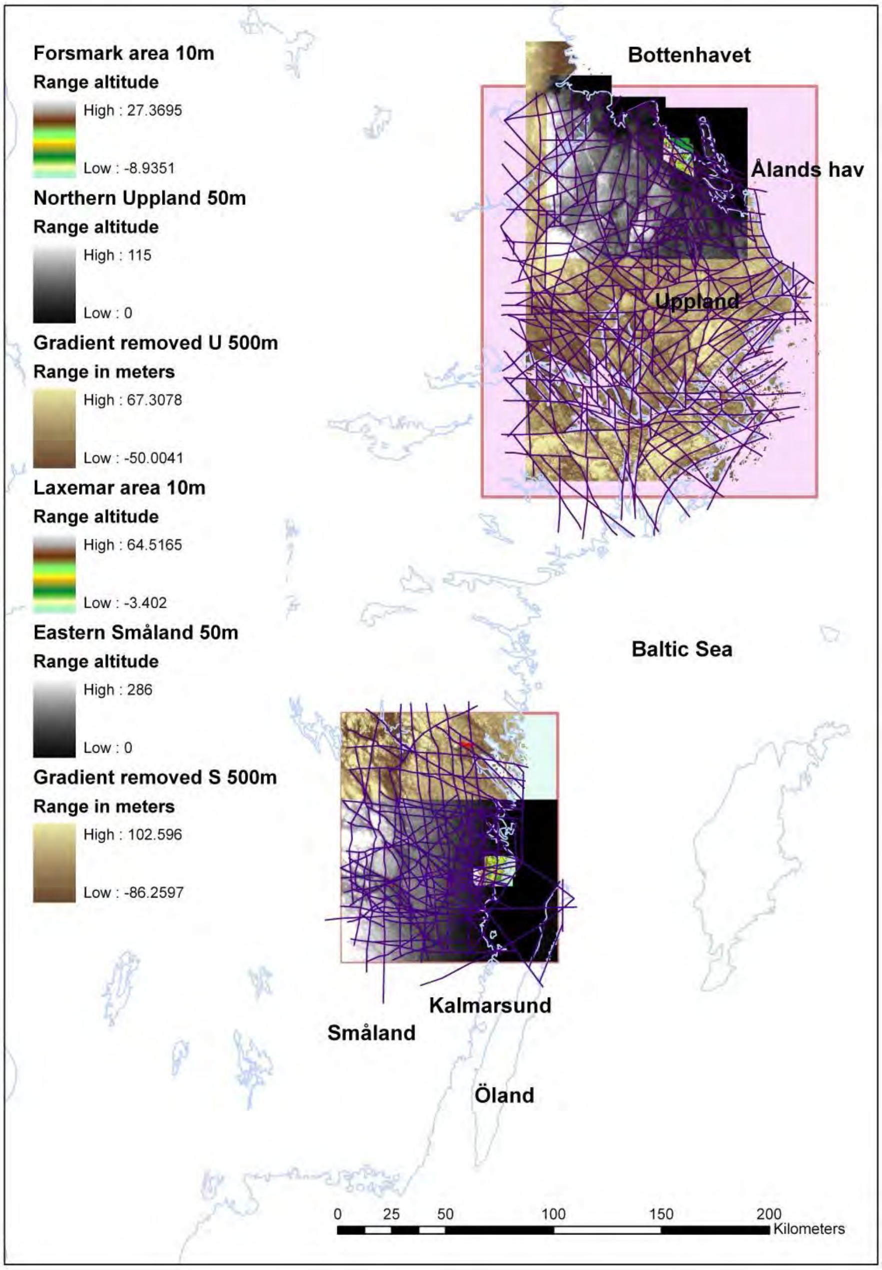


Figure 4. The coverage of different data sets and interpretations made on these. Pink square with red outline – regional Uppland area, 500m grid from data base in Fig. 1. Turquoise square with red outline – regional Småland area, 500m grid from data base in Fig. 1. Brown-and-yellow palette – areas where a postulated gradient has been removed from the data base in Fig. 1. Black-and-white palettes – areas covered by the 50m grids. Colour palettes - the local areas covered by the 10m grids around Forsmark in Uppland and Laxemar in Småland. Line network – areas covered by interpretations.

Table 1. Properties for elevation data (all received data were in different formats, including header).

Area/Files	Producer	File Produced When	Data delivered From	Pixel size (m)	Source	Uncertainty ‰
UPPLAND						
Svehojd	LM	2000 (1996 data)	SKB	500 x 500m	Profiling / stereo modelling and topographical maps	0-4m
Sttiehoj3323	LM	2005 (2000 data)	SKB	50 x 50m	Profiling / stereo modelling and topographical maps	0-4m
Met_hoj_1301	Metria/LM	2004 (2001-02 data)	SKB	10 x 10m	Air photos Flight altitude 2300m	lat 0.1; vert 0.15 open ground 1m forest 2m
SMÅLAND						
Svehojd	LM	2000 (1996 data)	SKB	500 x 500m	Profiling / stereo modelling and topographical maps	0-4m
Hul_osk_hojd	LM	2000	SKB	50 x 50m	Profiling / stereo modelling and topographical maps	0-4m
Met_hoj_1302	Metria/LM	2004 (2001-02 data)	SKB	10 x 10m	Air photos Flight altitude 2300m	lat 0.1; vert 0.15 open ground 1m forest 2m

Both areas have the disadvantage, for these kinds of studies, that they are situated on the coastline. This reduces the data coverage of the surroundings almost by half since the water-covered areas give no information on the relief. Elevation data in a 10m grid for very local areas of the sea bottom outside the existing storage facilities have been provided but these do not cover the distances to the closest island (e.g. Gräsö). The various data sets have different coverage along the shoreline. Other sea data (ordinary paper sea charts) that the authors encountered after the construction of the figure for this paper, reveal that important information could have been gained by inspecting also this kind of media.

2.1.1 Digital elevation data

Three sets of elevation data have been used: the 500m grid covering all of Sweden have been interpreted for the areas shown in pink and turquoise in Fig. 4. Special sets with a 50m grid have been given for northern Uppland and a part of eastern Småland in a black-and-white palette, and with a 10m grid for the local areas around Forsmark and Laxemar in a multicoloured palette in Fig. 4. The range in altitude for the different data sets is given in the legend. More detailed information on the different grids is given in Table 1.

2.1.2 Uncertainties

The sets of detailed elevation data (10m grid; Wiklund, 2002) covering the two SKB sites Forsmark and Simpevarp were produced during the winter 2001-2002 by Metria, a corporation belonging to the National Land Survey of Sweden (LM). The base for the detailed elevation model was air photos taken at 2 300m, and the uncertainty in the position of measured points was 0.1 ‰ laterally and 0.15‰ vertically of the flight altitude when considering well defined objects in open areas. Estimated uncertainties in the detailed elevation data is 1m for open ground and 2m for wooded ground for areas based on the 2 300m altitude photos.

For the 50m grid the location of the grid points are fixed in the RAK coordinate system. Depending on used base data in the processing of the 50m elevation data bank (GSD, Land survey of Sweden) the uncertainties in elevation may vary. In northern Uppland, c. 55% of the area has an uncertainty of 0-2m, c. 42% an error of 2-3m and the remaining less than 3%, scattered in the area, 3-4m. In north-eastern Småland, c. 62% of the area have an error in the elevation of 0-2m, 34% have an error of 2-3m and for c. 2% the range is 3-4m. The larger errors in altitudes in eastern Småland are found preferentially in the northern and southern parts of the area and the smallest error in altitude are most common in the central and western parts of the area.

The data base for the 500m grid was extracted from a 50m-grid database and the error in altitudes is identical to that of the 50m grid.

2.1.3 Removed gradient of the sub-Cambrian peneplain

Since both areas are characterized by flat, but slightly tilted, prisms of the sub-Cambrian peneplain the digital elevation data sets have been processed to reduce the influence of this gradient. The areas reproduced for the 500m grid are shown with a brownish palette in Fig. 4; the areas covered by the 50m and 10m grids are the same as those for the primary elevation data. The range of the new calculated numbers is given in the legend.

2.1.4 Tools

Preliminary lineament investigations (not shown in the present paper) were carried out on relief presentations using Surfer software 8.0 (Golden Software) with displays of a comprehensive selection of inclinations and azimuths. Further lineament interpretation and the construction of rock-block maps were performed by using ArcGIS 9.2 and ET GeoWizards 9.6 for ArcGIS 9.2 (Tchoukanski 2007). Statistics on rock-block boundaries were achieved with the assistance of the Lineament analysis module for Arc View 3.x and Excel. Polygons at different scales were analysed with ArcGIS Spatial Analyst. Removal of topographic gradients was done with Surfer 8.0.

2.1.5 Earthquake information

When demonstrating the locations of earthquakes, data from the Swedish National Seismic Net (SNSN) and the Helsinki Catalogue of earthquakes in Northern Europe since 1375 have been used. The accuracy of the coordinates of the 2000-2005 and some 2006 SNSN-registrations of earthquakes can probably be improved since these positions were transferred from analogue maps. Still, they may well fall within the precision error of the true location. These adjustments will most probably not affect the interpretation of the relationship between earthquakes and block boundaries. However, depth of an earthquake is essential here, if it occurs along an inclined fault surface. Access to fault-plane solutions of earthquakes would increase the accuracy in the correlation between earthquakes and structures.

There is an apparent gap in earthquake data between 1915 and 1962. This must reflect different ways of collecting data. Muir-Wood (1993) showed that the distribution of recognized earthquakes during the 19^{th} century was very much dependent on the existence of newspapers covering the area. There might have been a new sampling technique in the second half of the century. All of a sudden in 1981 there is a series of very frequent earthquakes occurring in association with the geological surveying in the Finnsjön area just southwest of Forsmark. The new SNSN-net registers earthquake data that we probably would not have heard of previously – but is excellent for the mapping of active structures.

2.1.6 Areas of interpretations

The regional Uppland area (cf. Fig. 4) covers a larger area than the regional Småland area. This is due to the wish to include the southern limit of the east-west Mälaren structure and the central north-south Södertälje lines. A wish also to include the structures of Ålands hav has been more difficult to accomplish. The area covered by the interpretation is envisaged by the purple net of lineaments.

The Småland area is smaller (cf. Fig. 4). It could have included the Loftahammar Shear Zone and gone further into the Svecofennian domain but this was not deemed essential.

2.1.6 Scale

As pointed out earlier, a scale for an interpretation is an important part of the metadata in GIS, where information is connected to other information by its geographical coordinates. This does not only apply to size of pixels. The accuracy for the position of an interpreted line or a geological border is dependent on which scale the map was drawn and how the map functions; e.g. there is a need for the possibility to enlarge certain areas on the map, such as the shorelines.

3 CONSTRUCTION & INTERPRETATION OF ROCK BLOCK MAPS

3.1 Method

Three sets of digital elevation data (500m, 50m and 10m grids) have been used and the following types of digital models were produced for each set in the present study: an elevation model (displayed by a series of different colour palettes), topographical relief models (a succession of models applying a sequence of magnitudes of vertical exaggeration, directions and inclinations of illumination and models showing the slope angle of landform breaks, (cf. Figs. 1, 5 and 6).

For each set that has been investigated, a lineament/rock-block map has been produced and checked against different models produced from the elevation data to reduce bias due to visual delusion. Digital elevation data for eastern Småland, 50m grid with a colour palette on top of a relief image, are shown in Fig. 5, both with and without a rock-block-boundary interpretation. Fig. 6 shows a slope map created for the 10m grid in the Laxemar area. Steep slopes are shown in yellow and flat areas in red and black (the sea, lakes and clay-covered areas). Where the range in altitude allowed to use the same colour palette, images were produced with two data sets, the one with larger pixels half transparent to achieve a picture with the best data available for the area (cf. e.g. Figs. 9, 10 and 12).

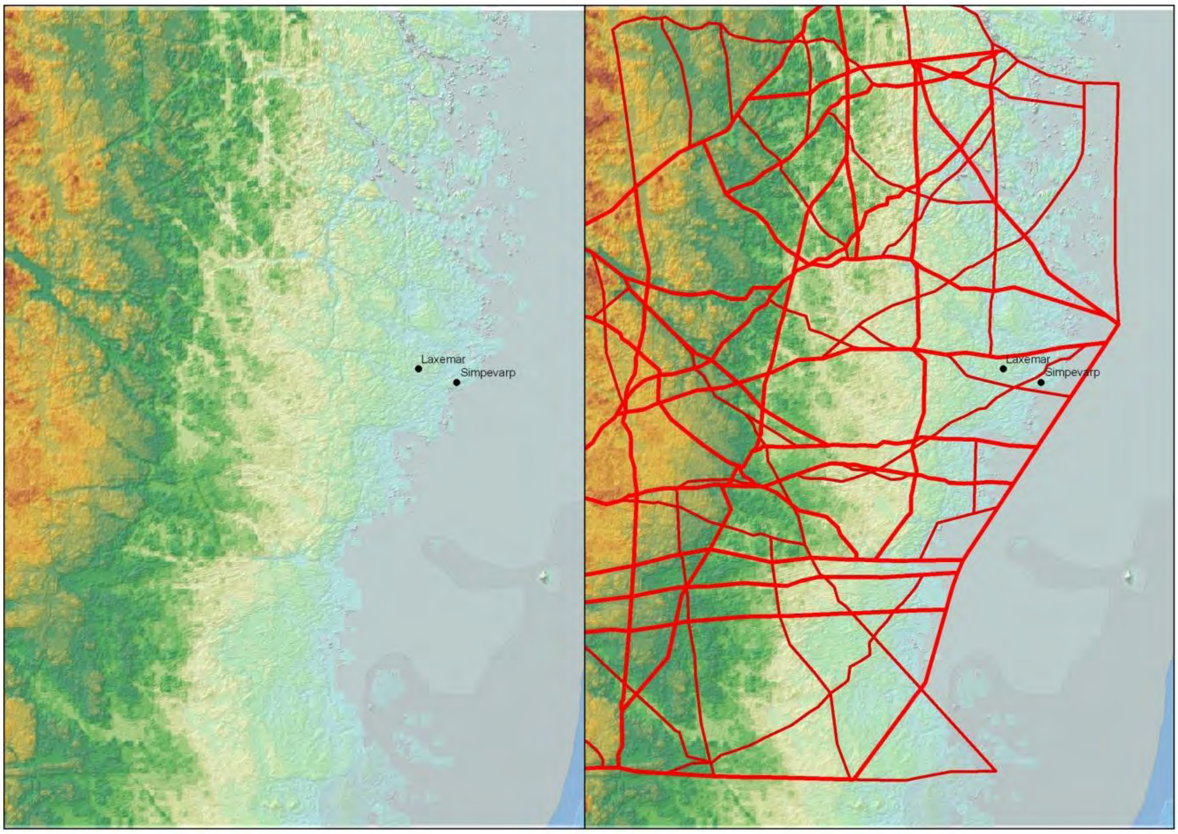


Figure 5. The Swedish east-coast around Laxemar as shown with a hill shade-map produced from the 50m grid, covered by the half transparent 50 and 500m grids with elevation above 300m excluded. To the right is the same map with the network of major and intermediate rock-block boundaries.

3.2 Morphology

The ground surface in Uppland as well as in south-eastern Småland is flat and lies close to the mosaic of sub-Cambrian peneplain surfaces (cf. Fig. 1). The peneplain was extensively developed and presumably covered major parts of the Fennoscandian Shield. It had a relief of just a few tenths of metres (Rudberg 1954, Lidmar-Bergström 1994) and formed more than 0.55Ga ago. Palaeozoic platform sediments were then deposited on the peneplained crystalline basement rocks and a few remnants of these rocks still occur on the Swedish mainland. Weathering and erosion of the peneplain are related to the time it has been exposed, the climate and the topographical gradient.

The investigated areas are thus relatively planar with low altitudes and low ranges in altitude, and it is here assumed that the landform breaks that occur in the two areas reflect distortion of the sub-Cambrian peneplain. In other words, the erosion of the re-exposed crystalline basement surface has not yet levelled the traces of the distortions that the peneplain experienced since it was formed and covered by sediments.

Although similar in many aspects, the differences in geological and topographic setting of the two areas led to rock-block interpretations of the Uppland areas in three separate scales, one for each data set. The Småland area, however, was interpreted at three separate scales at first, but since covering a smaller area it was preferable to construct larger rock blocks more comparable to the regional Uppland interpretation in size. In Uppland as well, you will find a rock-block interpretation for the 500m area with smaller rock blocks than in the regional interpretation.

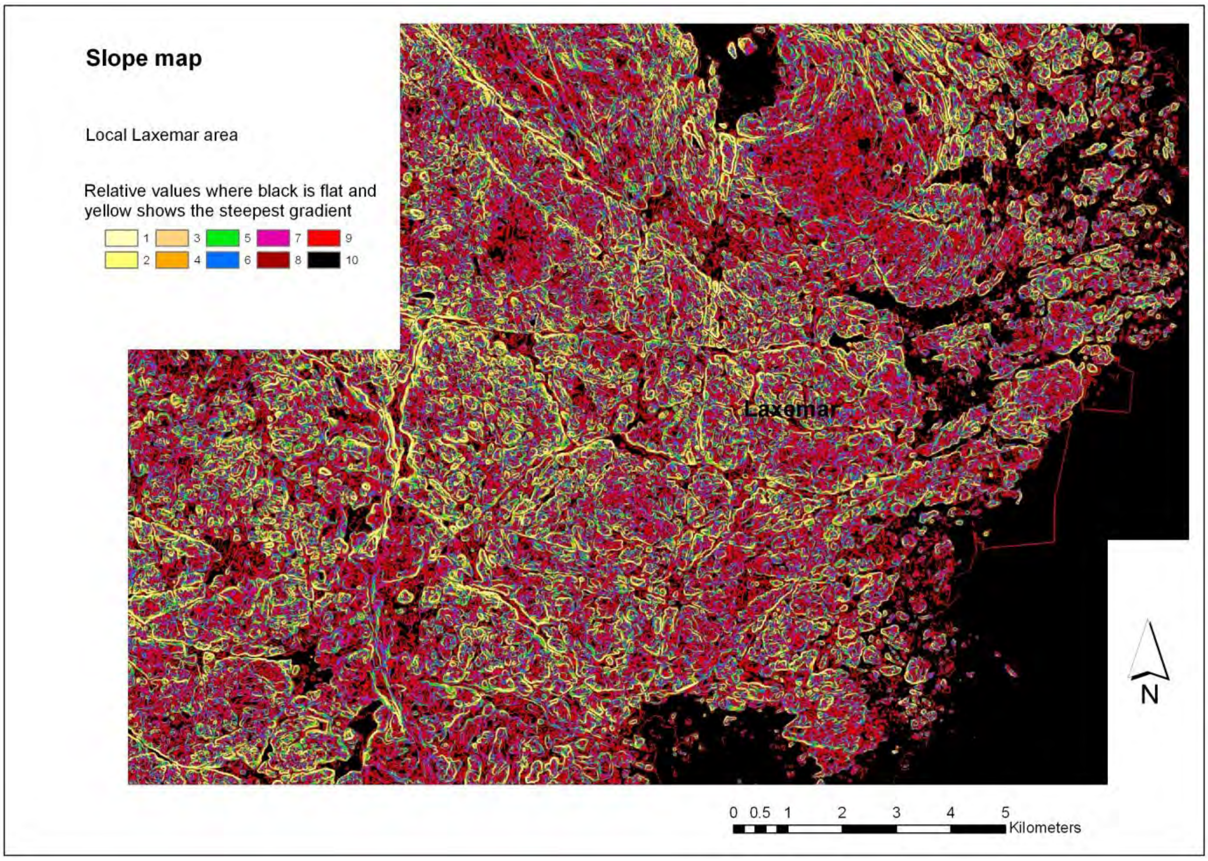


Figure 6. Slope-map showing the local area around Laxemar, produced from the 10m grid with relative values where black is flat and yellow shows the steepest gradient.

These are shown in Fig. 4 and 9 as „lineament digital elevation data" and in Fig. 56, but no rock-block polygons were constructed since there were far too many lineaments for the programme version used.

3.2.1 Uppland 500m

Uppland is the low part of Sweden and was last to emerge from under the sea, and large areas are still gained within the span of a human lifetime (cf. Figs. 1 and 9). The outskirts of the higher grounds of the Scandinavian Peninsula merely reach the westernmost part of the investigated area. Uppland is bounded to the south by the Mälaren basin and the Sörmland horst, which together with the slightly higher ground northeast of Stockholm acts as backbone to the Sörmland-Uppland "bulb" on the otherwise north-south trending Swedish east coast. To the north, the land sinks into the water of the Bothnian Bay and is bounded by the sedimentary basin of Jotnian sandstones and Palaeozoic sedimentary rocks (Axberg 1980). To the east, the archipelago has a rather sharp limit to the Jotnian Sandstone basin of Ålands hav, with depths over 250m below sea level (Flodén 1977).

The investigated area divides into segments along east-west lines; the Sörmland horst in the south with a funnel-shaped configuration of lineaments centred on Södertälje, the Mälaren basin, and Uppland north of the Örsundsbro-line.

North of the Örsundsbro line, a north-north-easterly pattern interferes with a north-north-westerly belt emerging from the sea in the southeast and disappearing into the sea in the north. Within these belts, individual blocks/segments tend to have a higher western (and northern) side like many islands in Ålands hav.

3.2.2 Northern Uppland 50m

A close up in the northern 50m grid area involves a western part with higher ground dominated by north-north-easterly and north-south trending structures, and an eastern part with lower ground and north-westerly structures (cf. Fig. 10). The north-eastern corner is marked by an even lower block, framed in the northeast by the somewhat higher ribbon of Singö-Gräsö.

3.2.3 Forsmark 10m

The local Forsmark area is characterized by west-north-westerly structures cutting a north-south, north-north-westerly and north-north-easterly grain (cf. Fig. 11). A c. 5km wide west-north-westerly lath along the coast generally, but not always, displays higher ground than the surrounding land. Low areas occur in north-north-westerly streaks, some covered by water. The northern central part is lowland covered by water where a major valley bottom runs north-north-westwards in the sea west of Gräsö.

3.2.4 Eastern Småland 500/50m

In eastern Småland the land exhibits a stepwise rise to the west until it becomes a part of the South Swedish Highland (cf. Fig. 12). A major valley winds its way in a north to north-north-westerly direction.

To the east the Palaeozoic cover in the Baltic basin reaches the outer archipelago with Cambrian sandstones on some islands. The Ordovician limestone outcrops on Öland while the Island of Blå Jungfrun is protruding rapakivi granite.

The north-eastern corner of the map is dominated by a very strong northwest trend of structures from north of Öland towards Västervik and across the mainland in the Loftahammar shear belt (Beunk and Page 2001). In the south the area the east-west Oskarshamn line dominates.

3.2.5 Semi-Regional Laxemar area 50m

A close up further elucidates the east-west grain in the south and the north-westerly in the northeast (cf. Fig. 13). The shoreline and structural pattern faintly resemble the Uppland-Sörmland "bulb" on the otherwise straight north-south east-coast, but on a much smaller scale. Here the land rises gradually westwards in smooth steps; north-south segments with higher ground are displaced further to the east, as you go northwards.

3.2.6 Laxemar 10m

The Laxemar area is characterized by major structures in roughly north-south and east-west, in the eastern part swinging towards the northeast along the shore (cf. Fig. 14). Higher ground occurs in triangles with their point towards the east. Lower land reaches westwards and north-westwards from the sea. In the northern central part, Lake Götemaren comprises a low spot.

3.3 Rock Blocks

The sub-division of the bedrock into rock blocks is based on several factors regarding:

a) character of the demarcation structures/block boundaries, e.g. topographical expression such as length, width, and relative altitude of the base of erosion along these structures, and
b) characteristics inside the blocks such as elevation, topographical relief and structural pattern of the ground surface/bedrock head relative to that in the surrounding blocks.

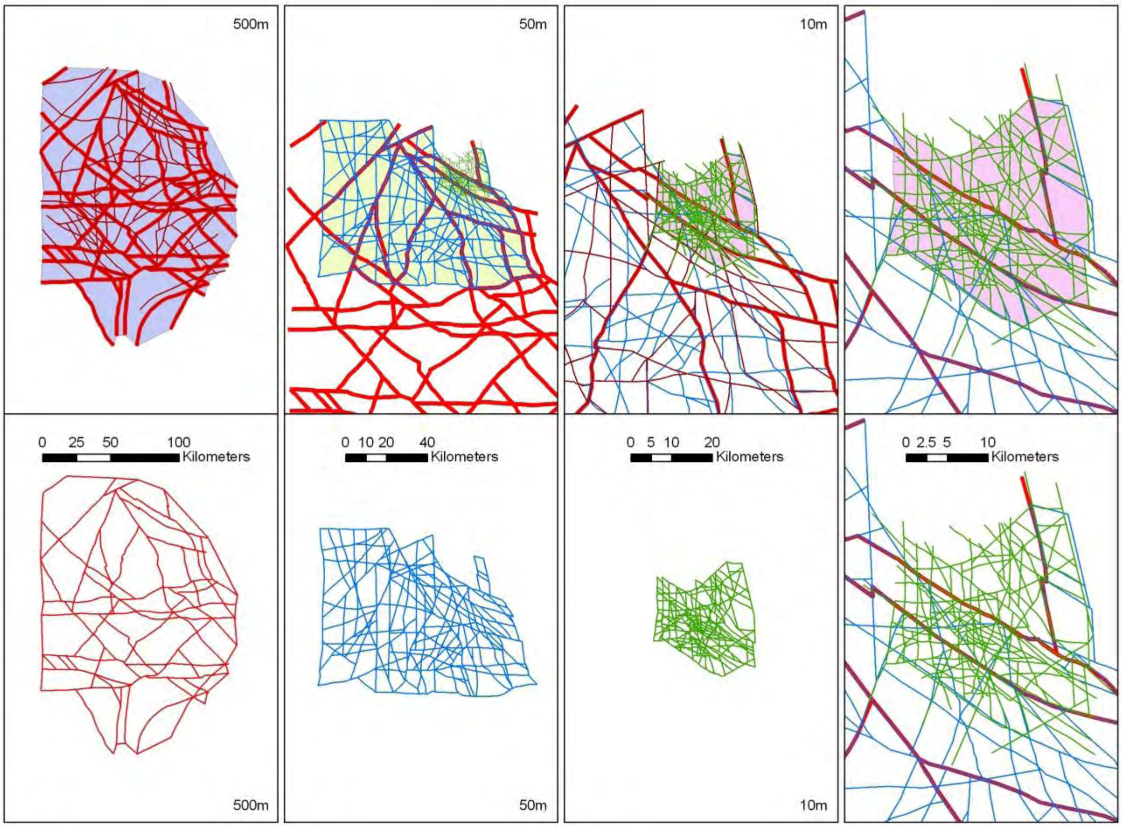


Figure 7. Polygons for the Forsmark areas in Uppland. The upper row from left to right: Rock-block interpretations at regional scale – the 500m grid, semi-regional scale – the 50m grid, and local scale – the 10m grid, lineaments are successively stacked on top of each other, colours showing the areas covered by the rock-blocks interpreted for a given grid. Lower row shows the rock-block pattern/polygons for each specific set. Far right is a zooming in on the local Forsmark area.

Rock block polygons were constructed for the three sets of grids in Uppland, Uppland 500m, Northern Uppland 50m and Forsmark 10m (Fig. 7) and in Småland an additional two sets of polygons (Fig. 8). Fig. 7 displays the relationships between the Uppland rock blocks. The upper row gives the lineaments stacked on top of each other and the colour shows the area covered by the rock-block polygons of a specific set. The lower row shows the rock-block pattern/polygons for the specific set. The lower far right shows the three lineament sets on top of each other. The slight discrepancies between the lines from different scales stem from the fact that the interpretations were made using different scales and different resolutions. For the 500m grid many of the outer boundaries do not represent true block terminations, but just close the polygons.

For Småland, Fig. 8, the lower row again shows the rock-block pattern/polygons, the middle, far right, showing all the sets combined and again discrepancies depend on scale of construction. The upper row shows the rock-block pattern stacked on top of each other from the largest in thick red with blue background, zooming in to the Laxemar area in purple.

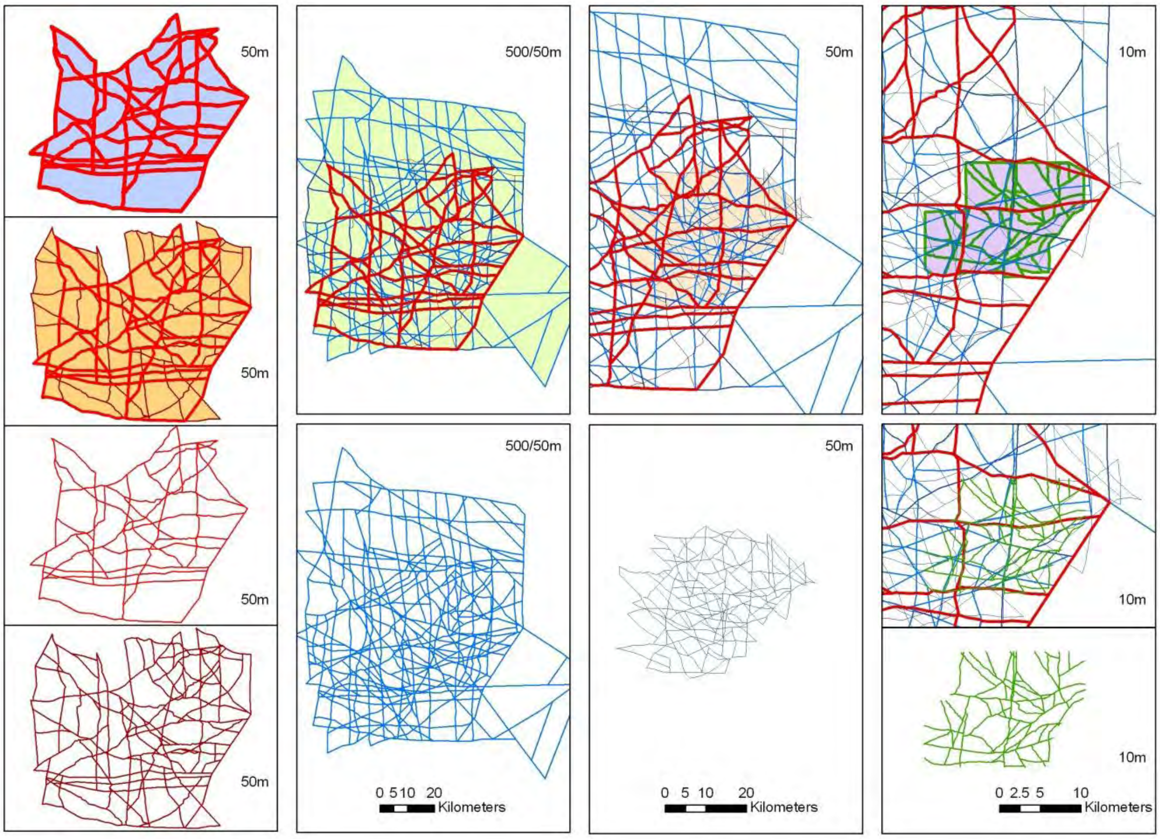


Figure 8. Polygons for the Laxemar areas in Småland. The upper row from left to right: Rock-block interpretations at regional scales - the 50/500m grids, semi-regional scale - the 50m grid, and local scale - the 10m grid, rock-block boundaries successively stacked on top of each other, colours showing the areas covered by the rock blocks interpreted for a given size of rock blocks. Lower row shows the rock-block pattern/polygons for each specific set.

These polygon patterns are shown together with topography, displayed with a colour palette, in Fig. 9-11 for Uppland and 12-14 for Småland. Shown in the Fig. are also the epicentres of earthquakes recorded in Sweden since the 14th century, in Uppland since 1698 and Småland since 1375.

3.3.1 Uppland – Regional Forsmark area 500m

In Fig. 9, „major rock block boundaries" are the lineaments defining the polygons for the 500m base in Uppland. Shown is also a finer division into rock blocks by „lineaments, digital elevation data" that are not treated as polygons in this study. In the water-covered areas lineaments mapped by Axberg (1980) and Flodén (1977) have been added along with the bedrock geology compiled from Axberg (1980), Flodén (1977), Rämö (2005) and the Swedish part of the Fennoscandian Shield map (2001), to add to the structural impression.

Extensive, straight north-south trending structures are common in the western half of the map area but are rare and less extensive in the east (Fig. 9).

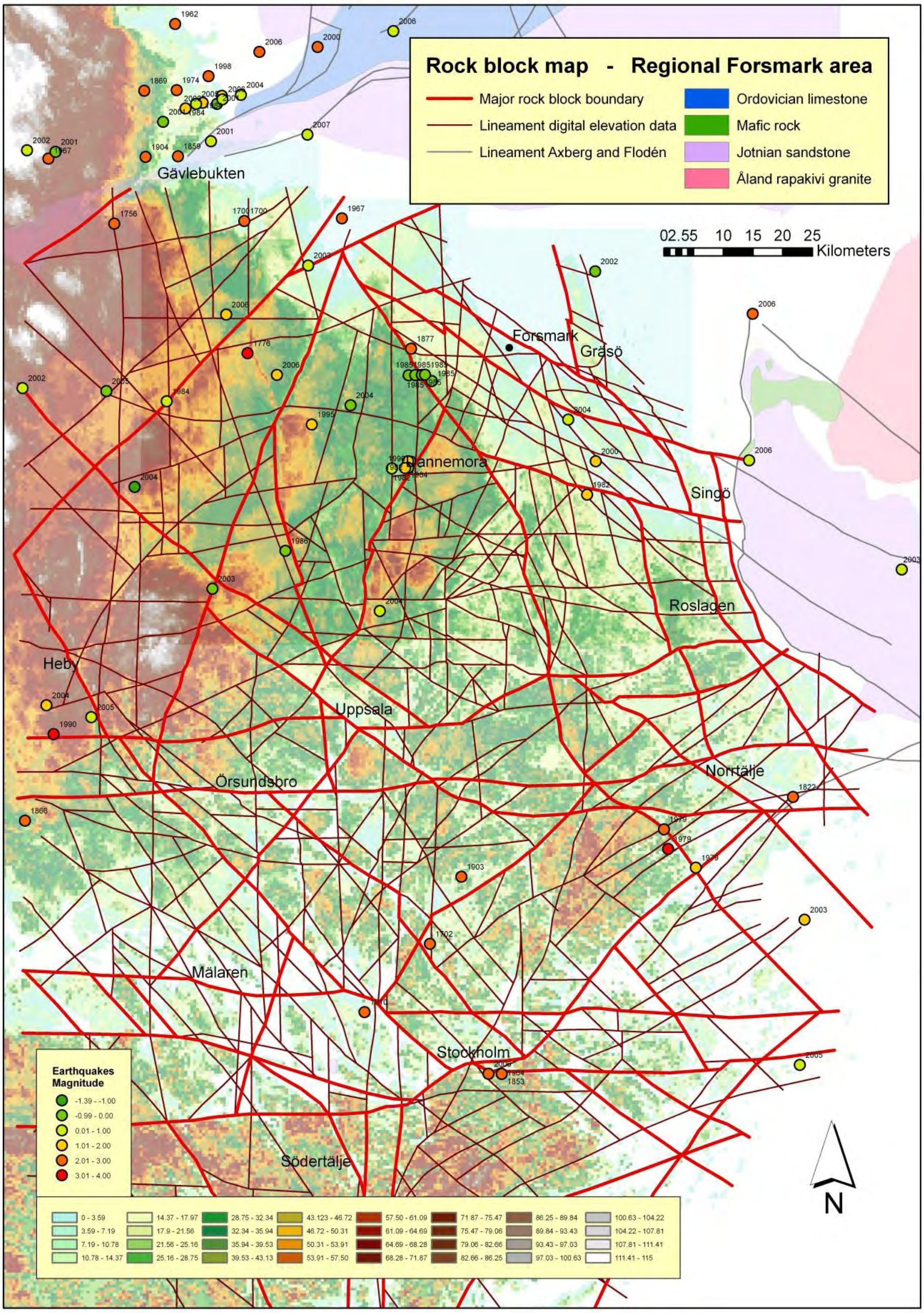


Figure 9. Rock block map of Uppland – Regional Forsmark area. Elevation displayed by the 500m grid with the exclusion of altitudes above 115m, half transparent and the 50m grid. Bedrock geology from the Fennoscandian Shield Map 2001, Axberg 1980, Flodén 1977 and Rämö 2005. Earthquake data from (SNSN) and the Helsinki Catalogue of earthquakes in Northern Europe since 1375.

Major east-west trending structures occur in two groups; one in the central and one in the southern part of the map. In the western and central parts of the area, between these two east-west trending groups of structures, Lake Mälaren is situated, with an outline governed by northwest and east-west trending structures. The eastern part of the area, between the east-west trending groups, has a northeast trending structural grain. The east-west trending major structures in the southern part of the map are the faults that form the northern side of the east-west trending Sörmland horst. In the horst area there is a flower-like configuration of structures around a north-south symmetry axis.

Fault-bounded areas with Jotnian sediments (in Satakunta, Finland, cut by c. 1.26Ga old dolerite dykes, Suominen 1991, Söderlund et al. 2004) occur in the sea-areas north and east of Uppland. The latter, eastern occurrence of Jotnian sediments is conformed to northwest to north-south trending rock segments on the Uppland coast and also to the boundary of the Åland Rapakivi batholith (c. 1.58Ga) to the east. The Jotnian sediments in the block to the north are bounded by regional faults that outline Gävlebukten (the Bay of Gävle).

A 30km wide, north-northwest trending belt of major rock blocks along the Uppland east-coast, partly conform to the Jotnian sandstone basin in the sea between Sweden and Åland and cuts the north-north-easterly rock block pattern further to the west. This north-northwest structure may be related to the Åland Rapakivi batholith.

In the northern part of the regional Uppland area, vertical displacement between rock blocks is a common feature. Bedrock segments outlined by pronounced and slightly curved north-south trending block boundaries, on their western side have a higher ground surface than the block to the west. Blocks with west-north-westerly block boundaries often have lower ground to the northeast, but the opposite occurs. North-westerly to west-north-westerly structures appear within an approximately 20km wide belt along the northern coast of Uppland, including the Singö and Forsmark fault zones. Within this belt north-south and west-northwest trending faults interfere. The southern boundary of this belt is demarcated by a topographical break, northern side down. North-south trending blocks, e.g. Gräsö, with their surface gently inclined eastwards, occur north of the Singö line.

The displacement and rotation of the ground surface indicate that the west-northwest trending structures and the curved north-south structures may be listric faults. These faults distort the sub-Cambrian peneplain within the whole northern map area (north of Mälaren) and testify that the entire bedrock surface is affected; blocks were descended or elevated depending on the character of the tectonic deformation.

Structurally, northern Uppland can be seen as a triangle standing on its base on the Örsundsbro line with north-northeast stretching blocks towards Hållnäs (for location see Fig. 10) in the west and sheared north-northwest segments in the northeast including the Hållnäs Peninsula as a cap on the tip of the triangle.

A lensoidal pattern appears in some northwest and northeast trending features.

3.3.2 Northern Uppland - Semi-Regional Forsmark area 50m

In Fig. 10, „major rock-block boundaries" are the same as in Fig. 9, while the „intermediate rock block boundaries" are not identical to, but have much in common with, the „lineament, digital elevation data" in Fig. 9. These intermediate rock block boundaries have evolved into the polygons of Fig. 7 and are further analysed below.

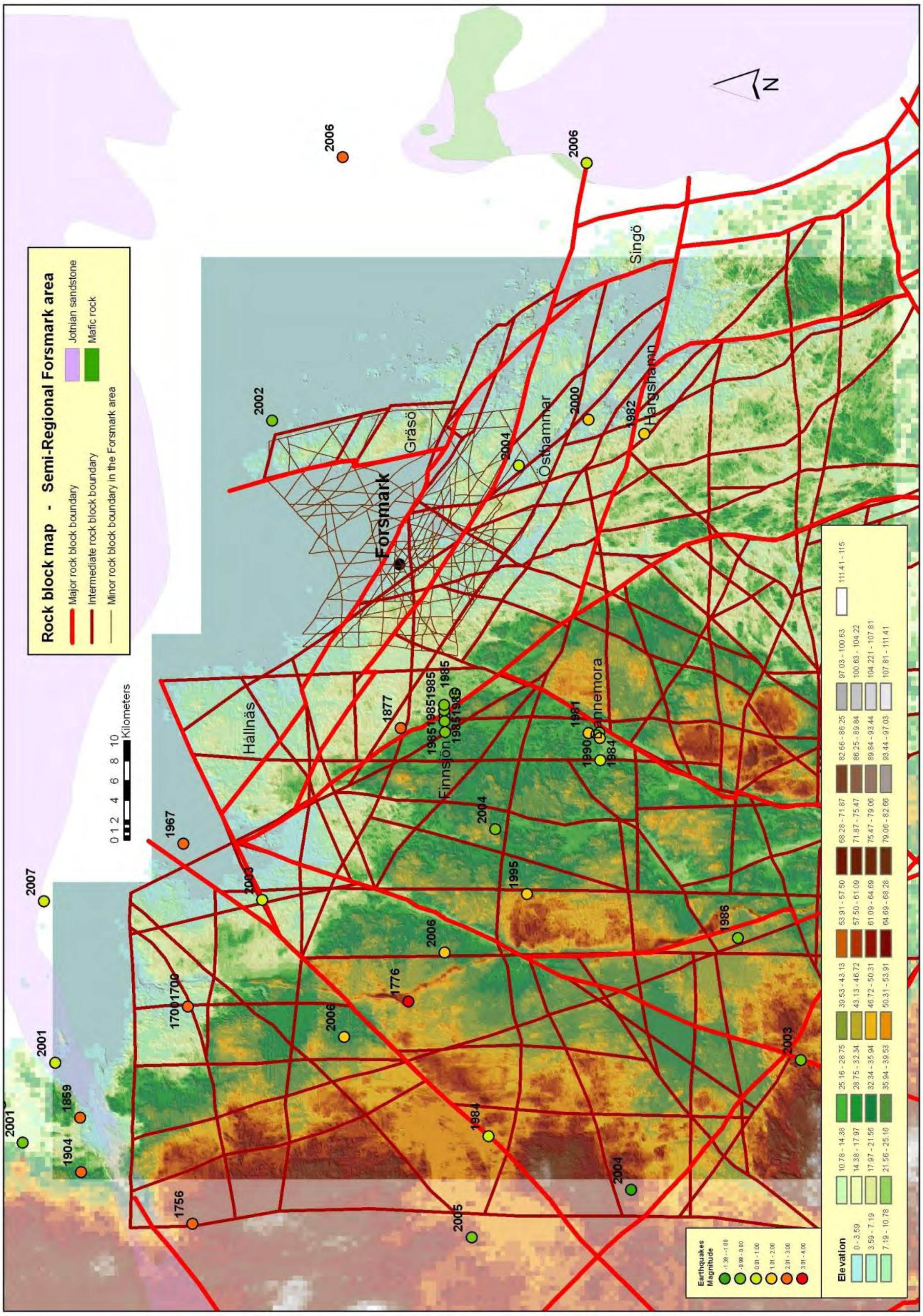


Figure 10. Rock block map of Northern Uppland – Semi-Regional Forsmark area. Elevation displayed by the 500m grid with the exclusion of altitudes above 115m, half transparent, the 50m grid and a hill shade from the 50m grid. Bedrock geology from the Fennoscandian Shield Map 2001. Earthquake data from (SNSN), and the Helsinki Catalogue of earthquakes in Northern Europe since 1375.

The map area easily divides into a western and an eastern half along a major north-westerly line. West of this line the land is generally characterized by rectangular blocks with very straight continuous north-south boundaries and less straight and continuous east-west boundaries. East of the major dividing line the land forms part of a broad, some thirty kilometres wide, north-north-westerly belt along the coast. The triangle in the lower middle part of the map has a north-easterly pattern between major northeast and northwest boundaries.

The south-eastern corner of the map is a distorted rectangle with a very prominent west-of-north-stretching in the western part of the block along a winding, lensoidal north-northwest to northwest zone, east of the major dividing line. North of this rectangle is a lower block (possibly displaced westwards in relation to the southern block). The southern, N70W boundary of this block diffusely connects to the N25W western boundary of the Hållnäs peninsula. This gives the low north-eastern block configuration the shape of an open arrowhead, or "knee", pointing southwest, transacted by the sharp N55W Forsmark fault/lineament with a higher north-eastern rib parallel to the coastline.

Southwest of this arrowhead are two major units with conspicuously higher land at their western north-northeast trending boundaries. Generally, the land steps down towards the southeast, but the blocks are not obviously tilted; rather the stepping appears as sub-blocks with their surface at different altitude. The eastern of these two blocks is a distorted triangle, west of the rectangle described above. Together with the block to the west it has a northeast trend which terminates against the north-northwest to northwest belt.

In the south, these blocks are cut by an east-west line that separates areas with slightly different internal patterns.

3.3.3 Forsmark – Local area 10m

Major structures, inherited from the interpretations of the larger areas, form the major northwest trending dividing line of the 50m-base area, the western limit of Gräsö and the three N50-60W structures on opposite sides of Forsmark and a bit further south (Fig. 11). Intermediate rock-block boundaries are those of the rock blocks of the Semi-Regional area. Minor rock blocks are mapped only in a) the areas covered by the 10m grid, seen as a somewhat darker, slightly more yellowish part in the central, middle-left, and b) parts of the sea between Forsmark and Gräsö with blocks based on information on the type of soft bottom sediments, and, c) the sea closest to land, area covered by a 10m-grid database (classified) for depth to bottom and interpreted depth to bedrock. This interpretation was made on available digital elevation data, but could be improved using information from analogue sea charts.

The Forsmark local area lies at the crossing of the wide Norrtälje-Östhammar north-northwest trending belt along the coast and the north-northeast trending structures of inner Uppland. These are intersected by west-northwest lines controlling the coastline.

The area is divided in a north-eastern and a south-western segment along a conspicuously sharp N55W line, the Forsmark line, along which central parts of the northern segment are uplifted and the southern parts are lower and partly filled with sediments. Parallel lines run along the coast and to the south at c. 4.5km distance. A winding, wide north-northwest structure runs from the south-eastern corner, northwards, just east of the Forsmark power plant.

Extensive, straight north-south structures occurring at some kilometres interval are common in the western half of the map area but are rare and less extensive in the east. The local rock-block pattern is made up by these north-south lineaments, with a westerly touch in the very east, and a west-north-westerly set. East-west and north-easterly structures are less continuous.

Rock-block nuclei often have a longer north-south axis except for in the south-east. Most blocks have corners with oblique angles. Lines often meet in triplets at 120 degrees and one line may continue across between the two others. Some longer lines stop or change orientation across the central N55W line. However, lines in general are short and do not connect into long continuous lines.

The central part is lower especially compared to the western. The relatively higher ground occurs in the rib north of the N55W-dividing line and a block in the southwest corner. Topographic lows appear in triangles delimited in the west by higher grounds along a north-south structure.

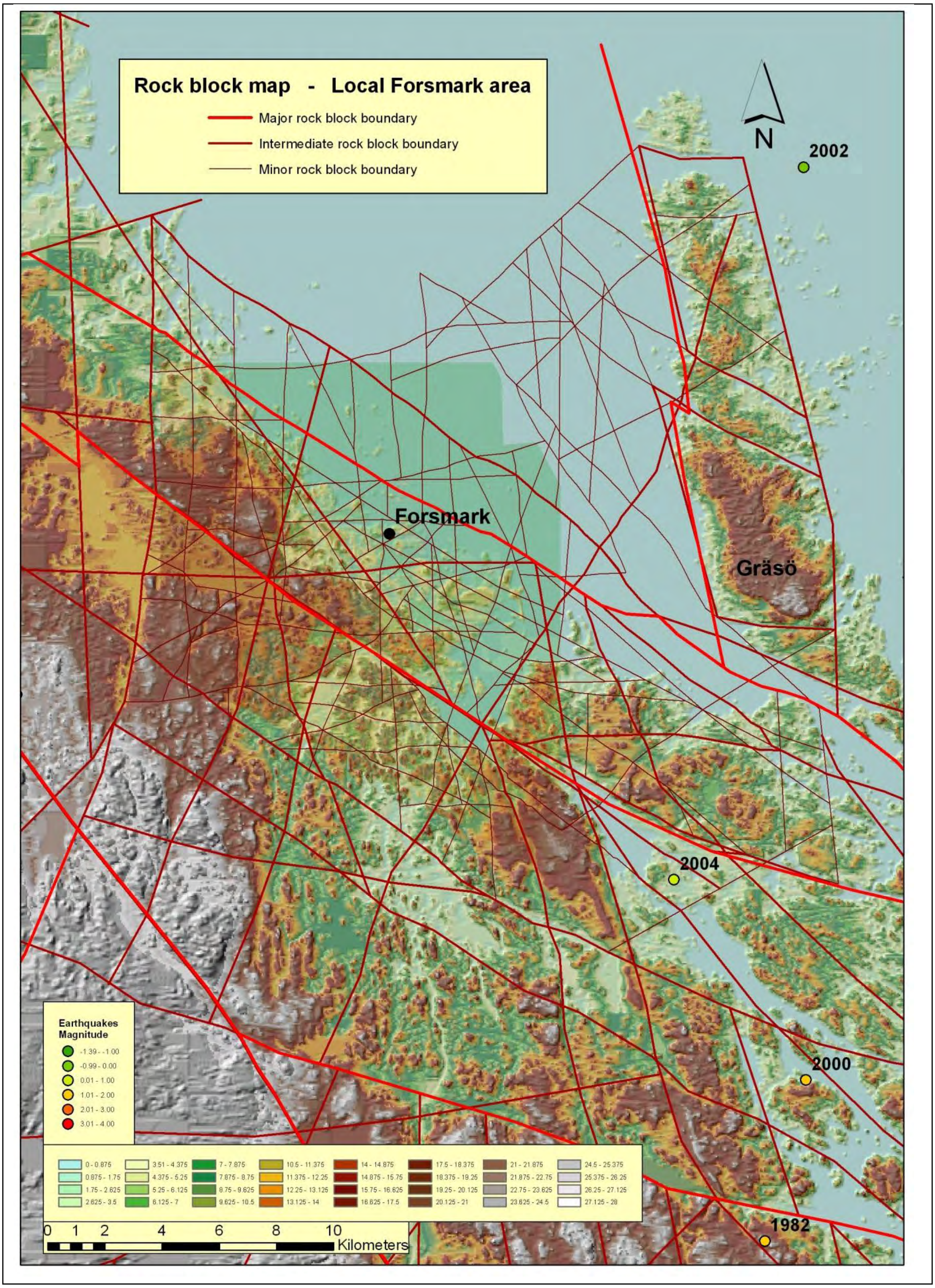


Figure 11. Rock block map of the Local Forsmark area. Elevation displayed by the 50m grid with the exclusion of altitudes above 27m, half transparent, the 10m grid and a hill shade from the 50m grid. Earthquake data from (SNSN), and the Helsinki Catalogue of earthquakes in Northern Europe since 1375.

3.3.4 Eastern Småland – Regional Laxemar area 500/50m

In Fig. 12, the „regional block boundaries‟ cover the largest area interpreted in Småland. The „major and intermediate rock-block boundaries‟ were drawn later to achieve rock-block nets more similar in size to the Uppland regional blocks. These polygon sets were constructed mainly using existing database lines and only for the area covered by the 50m database.

The main structures appear in two orthogonal systems oriented north-south, east-west, northeast and northwest. Most north-south and many east-west lineaments are extensive across most of the mapped area, especially the series of east-west lineaments through the Oskarshamn area. Many northwest structures bifurcate and open up towards the sea in the southeast. North-easterly structures occur in multiples in the central part of the mapped area. Areas in the north have not been subdivided in the same extent as the main area covered by the 50m grid. The polygons covering the sea are large due to lack of data but are included as they give indications of the structure.

The broad lath between the north-south winding valley to the west and the coastland in the east sees many of the through-going lineaments diminish in size and order.

3.3.5 Eastern Småland – Semi-Regional Laxemar area 50m

Fig. 13 is a close up of Fig. 12 and does also show the semi-regional rock-block interpretation. Discrepancies in the location of lines are due to interpretation at different scales.

The semi-regional interpretation centres around a huge north-south rock block segmented in east-west rectangles. North-south structures are broken and trend more westwards going southwards. East-west structures show a wavy pattern. Many northwest structures are continuous across the areas while others are cut and/or displaced by yet other structures. Many east-northeast structures terminate against northwest and north-south structures.

3.3.6 Laxemar – Local area 10m

The „major and intermediate rock block boundaries‟ in Fig. 14, are equivalent to the local polygons, at the far right in Fig. 8.

Again, structures are arranged in north-south, east-west and northwest and northeast, the south-eastern quadrant with a pattern “sheared” north-eastwards. The east-westerly lines can be traced through the area, as can also the central north-south lineament although it is complex, comprising multiple lines, shifting and distorted traces. Other north-south lines are displaced or vary in intensity along strike. The north-easterly Ävrö belt along the coast is the only through-going in this direction. Northwest structures often change character or disappear across northeast structures, even the prominent northwest system in the north-western quadrant is cut by the Ävrö belt. The topographic signature of mapped structures may change remarkably along the trace of a single structure and this reflects the natural variability of the character of a deformation zone.

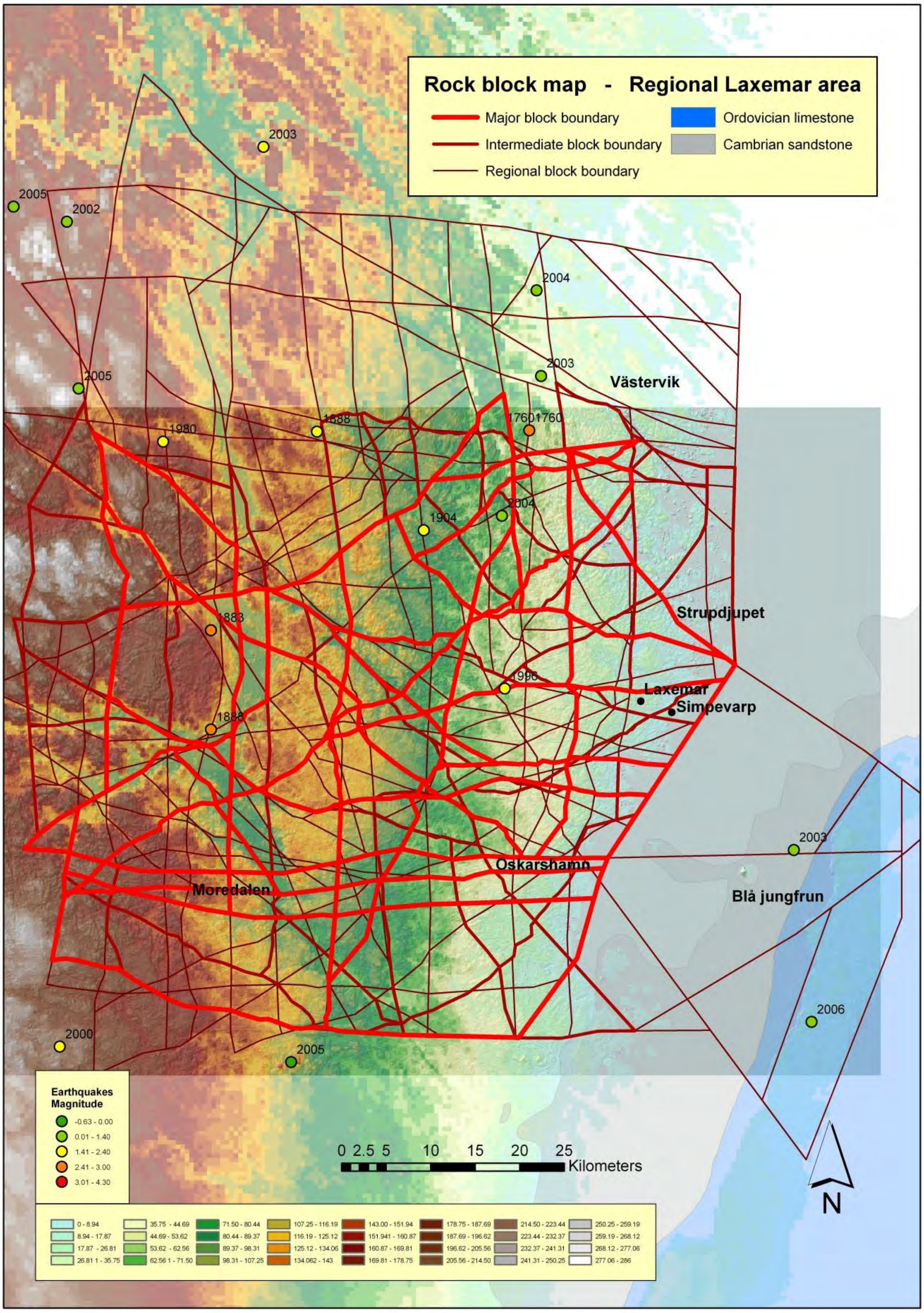


Figure 12. Rock-block map of eastern Småland – Regional Laxemar area. Elevation displayed by the 500m grid with the exclusion of altitudes above 299m, half transparent, the 50m grid and a hill shade from the 50m grid. Bedrock geology from the Fennoscandian Shield Map 2001. Earthquake data from (SNSN), and the Helsinki Catalogue of earthquakes in Northern Europe since 1375.

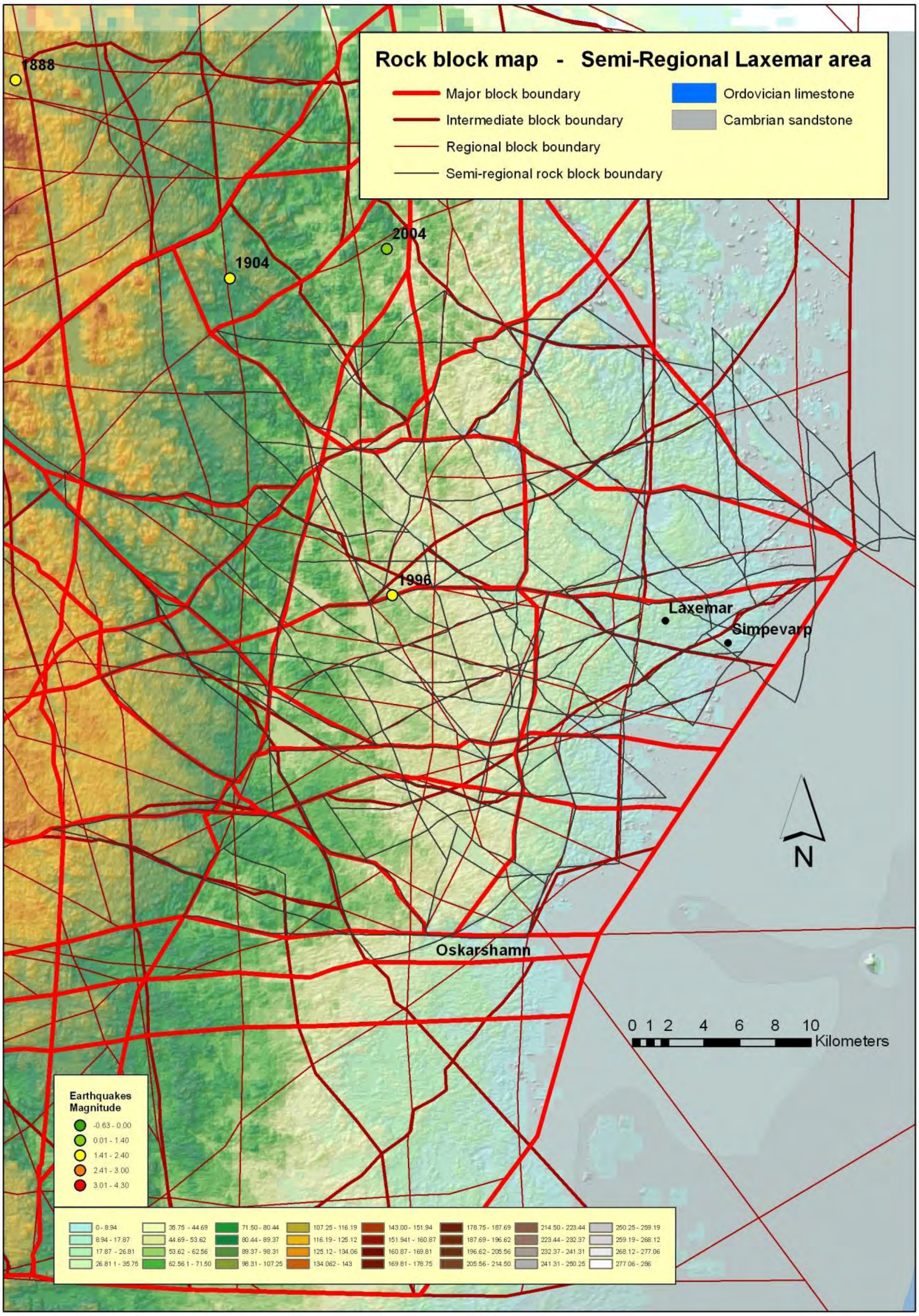


Figure 13. Rock block map of eastern Småland – Semi-Regional Laxemar area. Elevation displayed by the 500m grid with the exclusion of altitudes above 299m, half transparent, the 50m grid and a hill shade from the 50m grid. Bedrock geology from the Fennoscandian Shield Map 2001. Earthquake data from (SNSN), and the Helsinki Catalogue of earthquakes in Northern Europe since 1375.

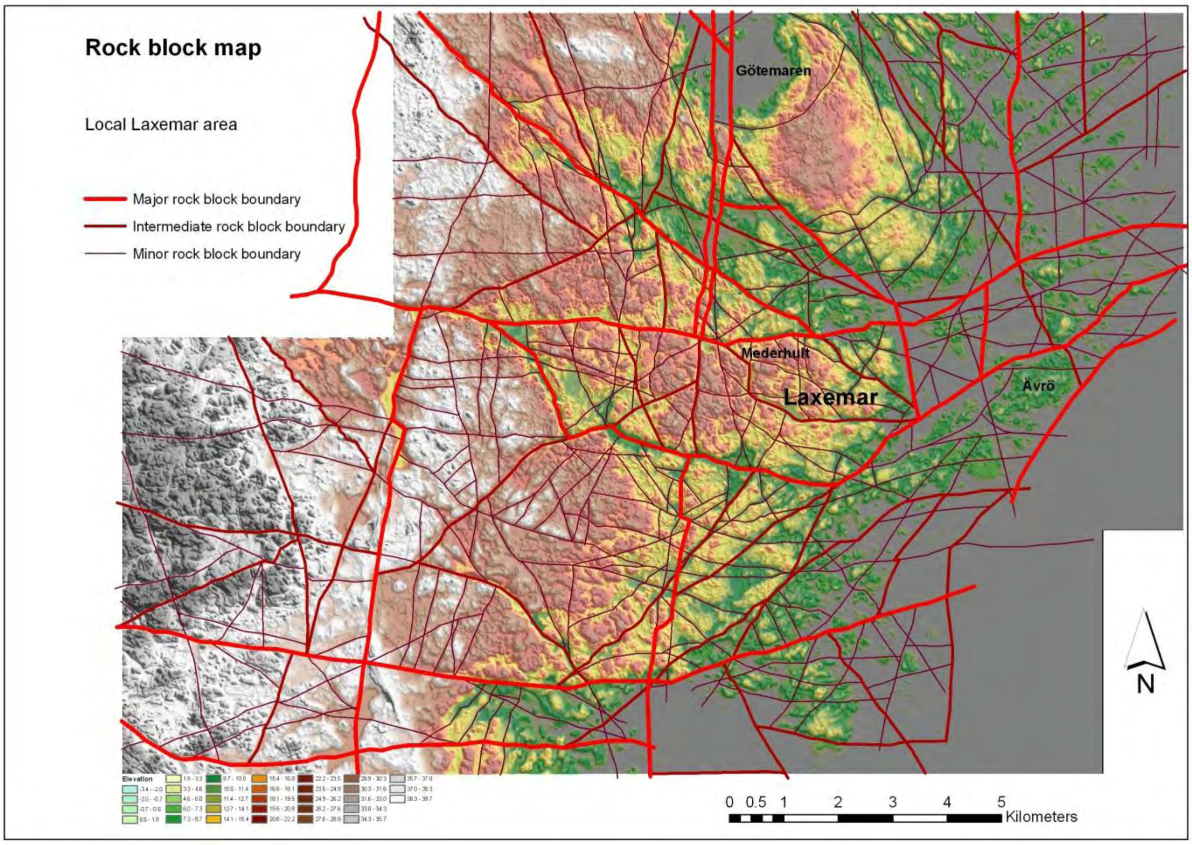


Figure 14. Rock block map of the local Laxemar area. Elevation displayed by the 10m grid, half transparent and a hill shade from the 10m grid. Bedrock geology from the Fennoscandian Shield Map 2001. Earthquake data from (SNSN), and the Helsinki Catalogue of earthquakes in Northern Europe since 1375.

Northwest structures are more frequent in the northern part of the map area, north of the central east-west structure (the Mederhult zone), while northeast structures are most prominent in the south-eastern part. The northwest and northeast structures interfere with the north-south and east-west structures, and these four sets of structures form rock blocks of various scales and shapes.

In the northern part of the map area, north of the Mederhult zone, the rock blocks are mainly demarcated by north-south and northwest to north-northwest trending structures with minor contributions of northeast and east-west trending structures. Rock blocks have triangular to polygonal shapes.

In the south-eastern part northeast structures are more frequent and blocks have a northeast elongation.

In the central part of the map, south of the Mederhult zone, extensive north-south and east-west trending structures outline a c. 10 x 13km size rectangle. However, this rectangle does not represent a single large-scale rock block since its north-eastern corner is cut by a south-eastward-going branch from the Mederhult zone. The westernmost part of this branch is revealed by a west-northwest trending valley which proceeds eastwards via a north-northwest structure into an east-west trending open valley that meets northeast trending valleys just west of the Simpevarp peninsula. The width of the east-west part of this topographical feature indicates that the underlying bedrock structure is wide and/or represents an intersection of structures (e.g. a sub vertical deformation zone and a gently-dipping zone). This branching structure together with the Mederhult zone and a north-south structure just west of Äspö are here interpreted to outline a higher order of rock block containing the SKB "Laxemar sub-area". A similar structure, on a smaller scale, occurs inside the sub-area. The central and eastern parts of this higher order block constitute an elevated part of the terrain.

The area south of Götemaren (the Götemar granite, a circular body on the geological map cf. SKB 2006, Fig. 3-8) shows a semi-circular pattern comparable to an onion. However, the pattern is not concentric but rather shows a pattern similar to a set of rings of different dimensions that hang on a needle; the centre of the smallest ring is located in the north-western part of the granite. The east-west Mederhult zone curves northwards as it passes just south of the Götemar granite.

4 LINEAMENTS – THE ROCK-BLOCK BOUNDARIES

Lineaments in this study were drawn as thin lines and have no area.

4.1.1 Orientation and length of rock-block boundaries

Lineaments - rock-block boundaries - interpreted from various visual displays of the elevation data were analysed for their azimuth and length and shown in Fig. 15-17 for Uppland and Fig. 18-22 for Småland. The mean lengths for every 10° interval are given in Table 2.

In the figures the number of lineaments and the lineament length are given in both rose diagrams and histograms as their visual impression complement each other. The peak direction may vary between number and length; many short lineaments in one direction and few long lineaments give different pictures. The directions also vary between regional and local scales.

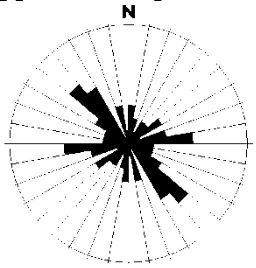
4.2 Uppland

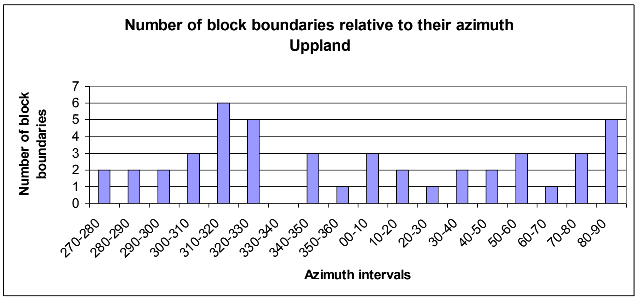
In the *regional area* (Fig. 15), east-west and northwest block boundaries are the dominant and the east-west ones are also proportionally long. North-southerly structures show a split peak where the just-east-of-north are relatively longer.

In *northern Uppland* (Fig. 16), north-north-westerly block boundaries are common but east-west and just-east-of-north lineaments are relatively longer. Minor peaks occur in northeast and north-northeast.

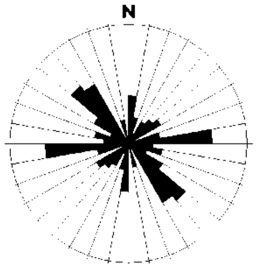
In the *local Forsmark area* (Fig. 17), north-south boundaries are abundant, followed by east-west and west-northwest lineament. In length however, the northwest direction is dominating with more than 10% of the population. North-south boundaries are also relatively long.

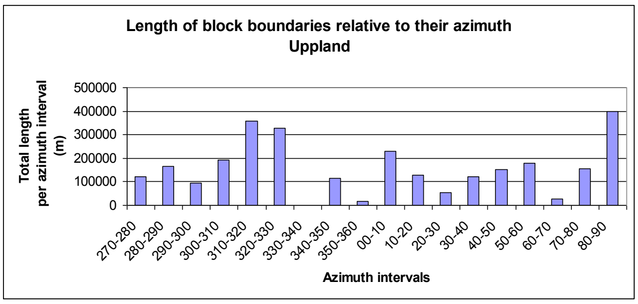
Uppland – Regional area





a

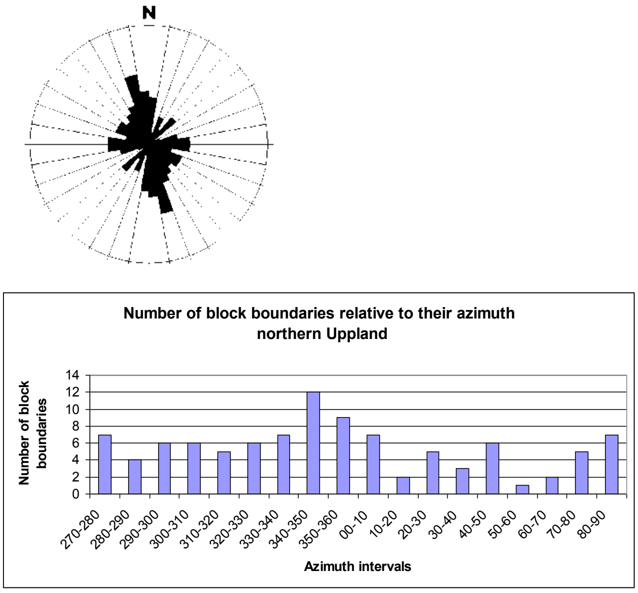




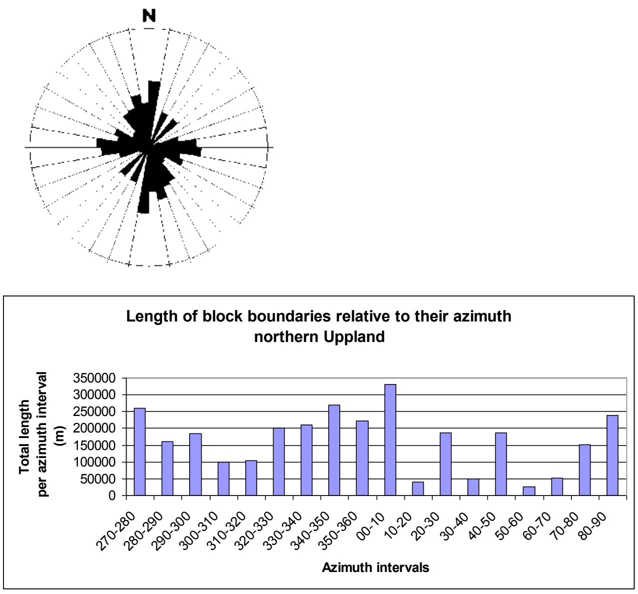
b counts 46 length 2836057

Figure 15. Orientation of rock-block boundaries in Uppland – Regional Forsmark area displayed by rose diagrams (outer circle 10%) and histograms, a) Number of lineaments for 10° intervals, N=46, and b) Length of lineaments within 10° sectors, total length 2836057m.

Northern Uppland – Semi-Regional area



a

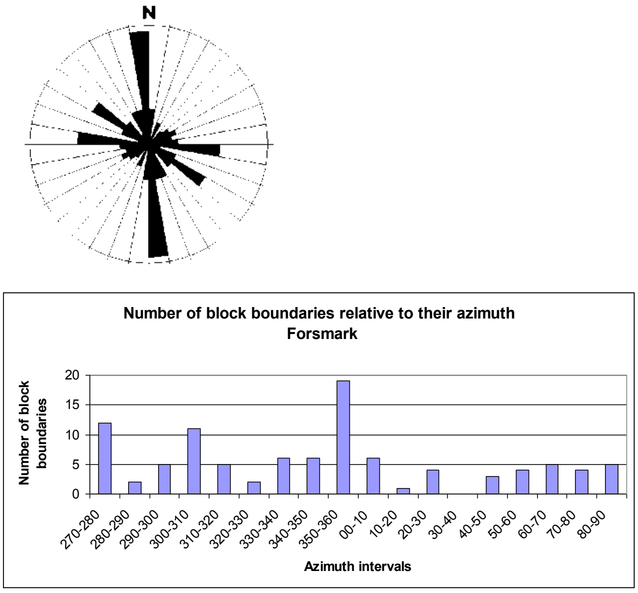


b counts 100 length

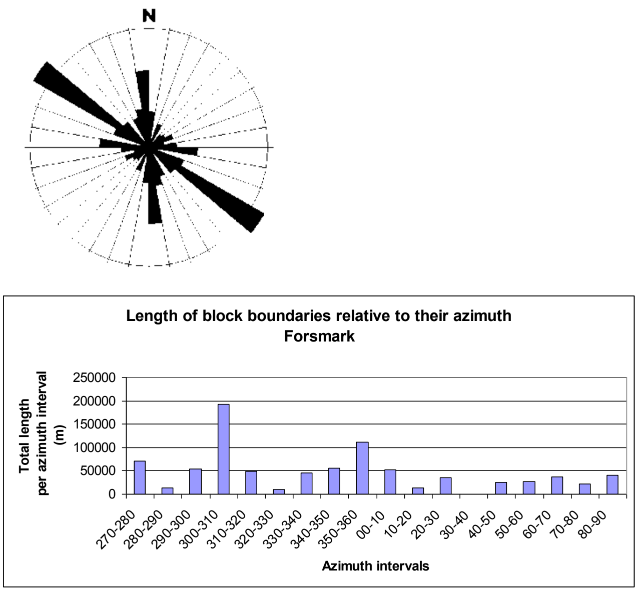
2978828

Figure 16. Orientation of rock-block boundaries in northern Uppland – Semi-Regional Forsmark area displayed by rose diagrams (outer circle 10%) and histograms, a) Number of lineaments for 10° intervals, N=100, and b) Length of lineaments within 10° sectors, total length 2978828m.

Forsmark – Local area



a



b counts 100 length

859293

Figure 17. Orientation of rock-block boundaries in the Local Forsmark area displayed by rose diagrams (outer circle 10%) and histograms, a) Number of lineaments for 10° intervals, N=100, and b) Length of lineaments within 10° sectors, total length 859293m.

4.3 Småland

For the *largest rock blocks* (Fig. 18), there is an orthogonal arrangement with many and long north-south and east-west boundaries. There is a slight shift clockwise in the orientation from numbers to lengths. The northwest lineaments have two peaks.

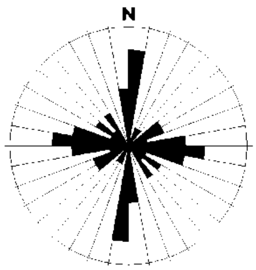
For the *second largest rock blocks* (Fig. 19), the north-south lineaments are dominant in both number and length. East-west to west-northwest boundaries have a wide spread. Fewer east-west boundaries are relatively longer. There is an anti-clockwise shift for north-south lineaments from the largest to second largest population.

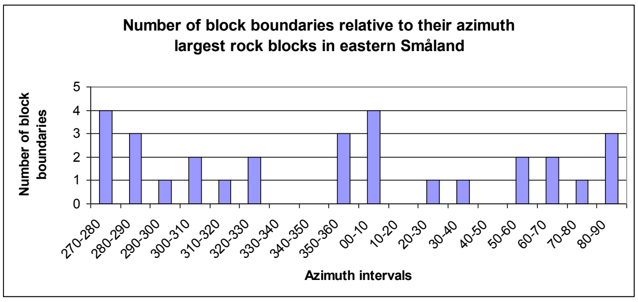
In the largest and most *detailed regional area* (Fig. 20), north-south boundaries show the most dominating azimuth for numbers while length also has a prominent east-west population. Northeast lineaments occur in a well defined interval while northwest boundaries have a wide spread towards west.

Yet, in the S*emi-Regional area* (Fig. 21), northwest-trending rock-block boundaries along with east-west boundaries are the main sets. North-south lineaments are fewer but proportionally longer.

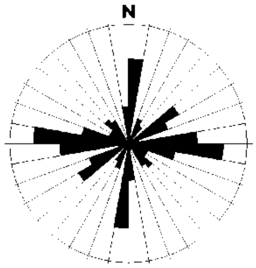
The *local Laxemar* area (Fig. 22), has rock-block boundaries in most directions with dominance for the north-south direction, especially in numbers but also in length. Again east-west are relatively longer as are the northeast ones. The northwest is split.

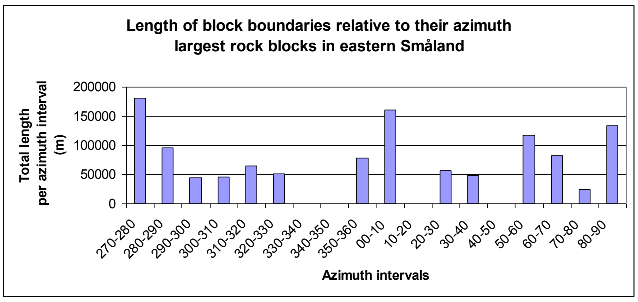
Eastern Småland – largest rock blocks, Regional area





a

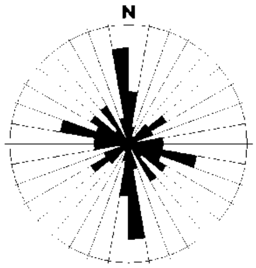


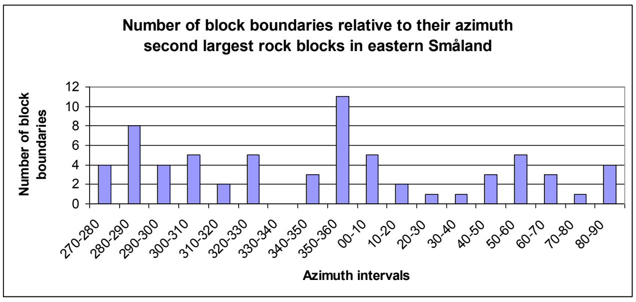


b counts 30 length 1186054

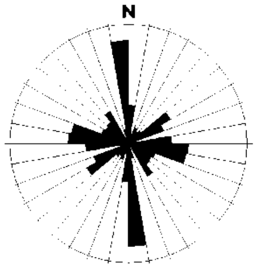
Figure 18. Orientation of rock-block boundaries in Eastern Småland – Regional Laxemar area, largest rock blocks, displayed by rose diagrams (outer circle 10%) and histograms, a) Number of lineaments for 10° intervals, N=30, and b) Length of lineaments within 10° sectors, total length 1186054m.

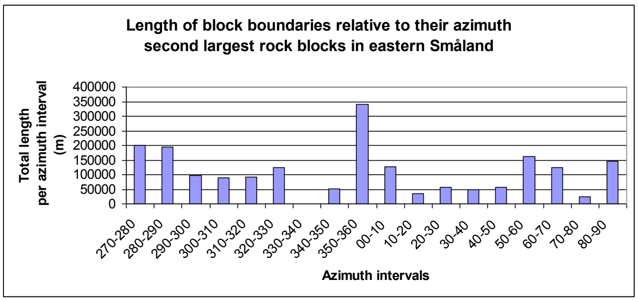
Eastern Småland – second largest rock blocks, Regional area





a

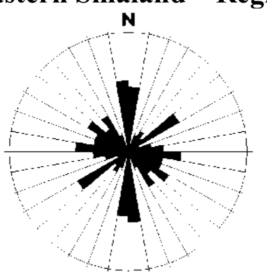


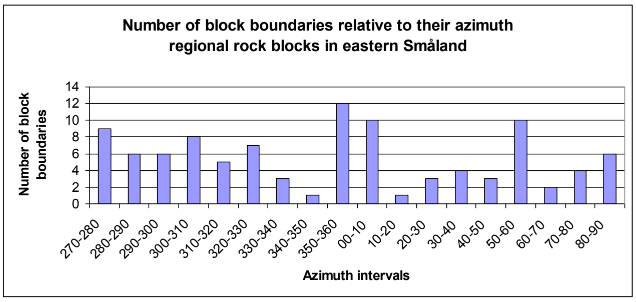


b counts 67 length 1974168

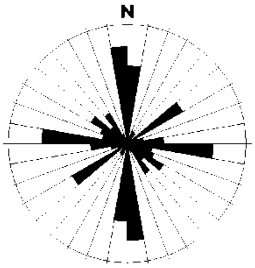
Figure 19. Orientation of rock-block boundaries in Eastern Småland – Regional Laxemar area, second largest rock blocks, displayed by rose diagrams (outer circle 10%) and histograms, a) Number of lineaments for 10° intervals, N=67, and b) Length of lineaments within 10° sectors, total length 1974168m.

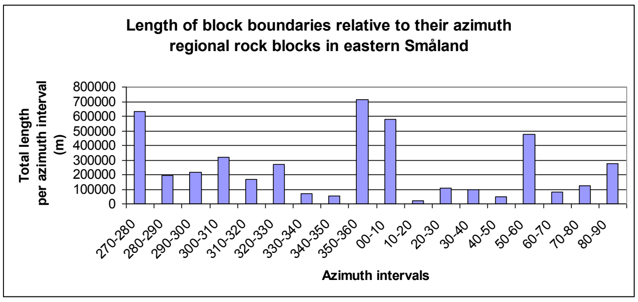
Eastern Småland – Regional area





a

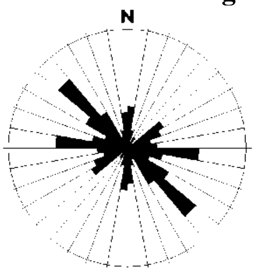


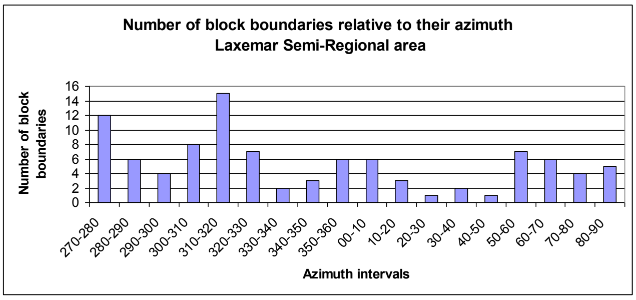


b counts 100 length 4450983

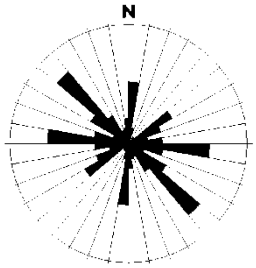
Figure 20. Orientation of rock-block boundaries in Eastern Småland – Regional Laxemar area, displayed by rose diagrams (outer circle 10%) and histograms, a) Number of lineaments for 10° intervals, N=100, and b) Length of lineaments within 10° sectors, total length 4450983m.

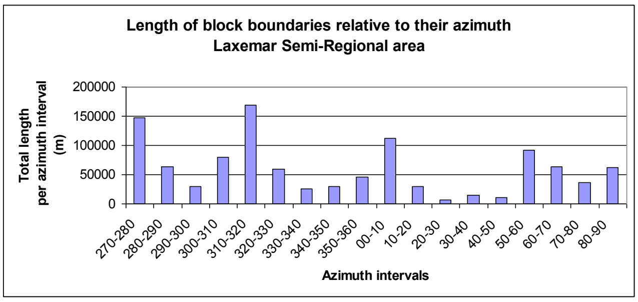
Laxemar - Semi-Regional area





a





b counts 98 length 1081500

Figure 21. Orientation of rock-block boundaries in Eastern Småland – Semi-Regional Laxemar area, displayed by rose diagrams (outer circle 10%) and histograms, a) Number of lineaments for 10° intervals, N=98, and b) Length of lineaments within 10° sectors, total length 1081500m.

Table 2. Arithmetical mean length (m/number of block boundaries) for every 10 degrees interval in the model areas below.

	Region-alUpp-land	Semi-Region-alNort-hern Uppland	Local Forsmark	Småland Regional Largest blocks	Småland Regional Second largest	Småland Regional Detailed	Semi-Regional Laxemar	Local Laxemar
Mean all	61653	29788	8593	39535	29465	44510	11036	3550
Intervals								
270-280	60906	37315	5945	45183	50168	70350	12304	5584
280-290	82954	40294	6615	32036	24324	32268	10698	2569
290-300	47440	30894	10812	44325	24238	36479	7534	3460
300-310	63870	16448	17517	22677	17839	39626	9993	3727
310-320	59658	20956	9716	64938	46089	33950	11294	1732
320-330	65207	33579	5369	25715	25067	38474	8447	3200
330-340	n.a.	30116	7676	n.a.	n.a.	23895	12738	1995
340-350	38587	22420	9423	n.a.	16922	52305	9950	2761
350-360	15834	24719	5840	26177	31013	59284	7665	2778
00-10	76790	47347	8646	40341	25509	57894	18628	4301
10-20	63401	20392	14033	n.a.	18215	23015	9962	3477
20-30	54763	37423	9033	57409	57409	35286	6596	2278
30-40	61105	16567	n.a.	48864	48864	24701	7559	2341
40-50	75872	31045	8396	n.a.	19141	16081	10505	6243
50-60	59315	25069	6958	58732	32289	47605	13223	5504
60-70	28492	26081	7437	41232	41637	40940	10653	3109
70-80	51395	30474	5655	23784	24533	31019	9242	3368
80-90	79951	34131	8047	44431	36194	46171	12480	5826

Max	82954	47347	17517	64938	57409	70350	18628	6243
Min	15834	16448	5369	22677	16922	16081	6596	1732

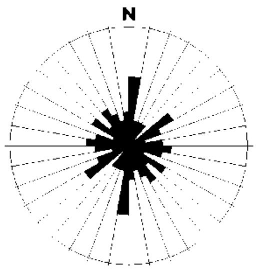
The minimum and maximum values for arithmetical mean length do not fall in the same intervals for the different scales.

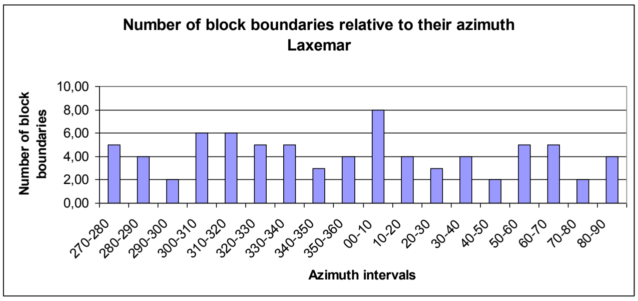
5 ANALYSIS OF ELEVATION DATA FOR INDIVIDUAL POLYGONS

Lineaments producing the rock-block boundaries were combined to polygons, i.e. rock blocks, and these were analysed statistically. The ground surface of the rock blocks, related to rock type, internal structures, topographical gradient, climate, time, etc, is assumed here to be a measure of the deformation of the sub-Cambrian peneplain and the erosion of brittle deformation zones. Simple statistical parameters such as the mean, maximum, and minimum elevation and the range values for the ground surface within individual polygons are therefore used to describe the morphology of the rock blocks.

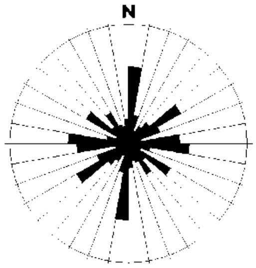
Area, mean, range, minimum and maximum values for each polygon are displayed in histograms. The mean value gives an average altitude for the polygon surface and the range gives the relief within a polygon, while the minimum shows the base level for the erosion and maximum the top ("constancy") level – sometimes the level of the sub-Cambrian peneplain.

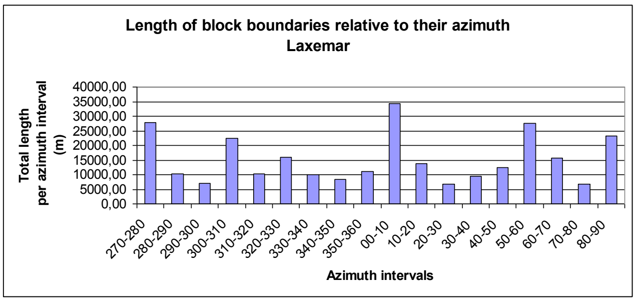
Laxemar – Local area





a





b counts 77 length
273334

Figure 22. Orientation of rock-block boundaries in the Local Laxemar area, displayed by rose diagrams (outer circle 10%) and histograms, a) Number of lineaments for 10° intervals, N=69, and b) Length of lineaments within 10° sectors, total length 273334m.

5.1 Statistics on the Rock Blocks

The representativity of sampled parameters is related to the size of the sample for each rock block. The 500m grid in many cases gives too small a sample; small rock blocks may contain no grid point. The statistical description below is based on elevation data in the 50m grids, Fig. 23-28.

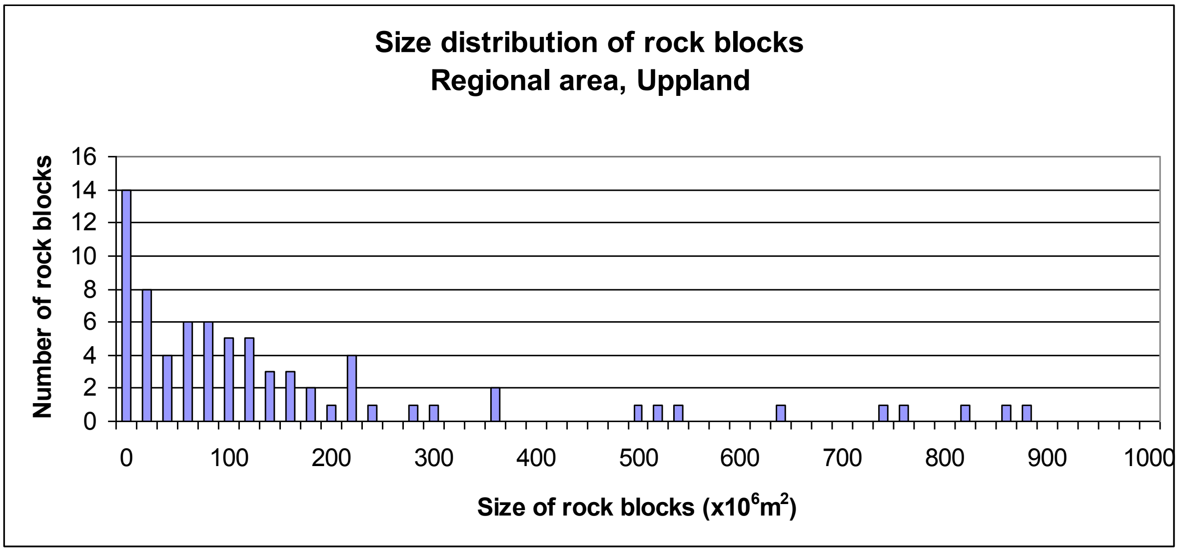
5.1.1 Size of rock blocks

Histograms displaying the size of the area for individual polygons are shown in Fig. 23 for Uppland and 24 for Småland and the statistics are given in Table 3.

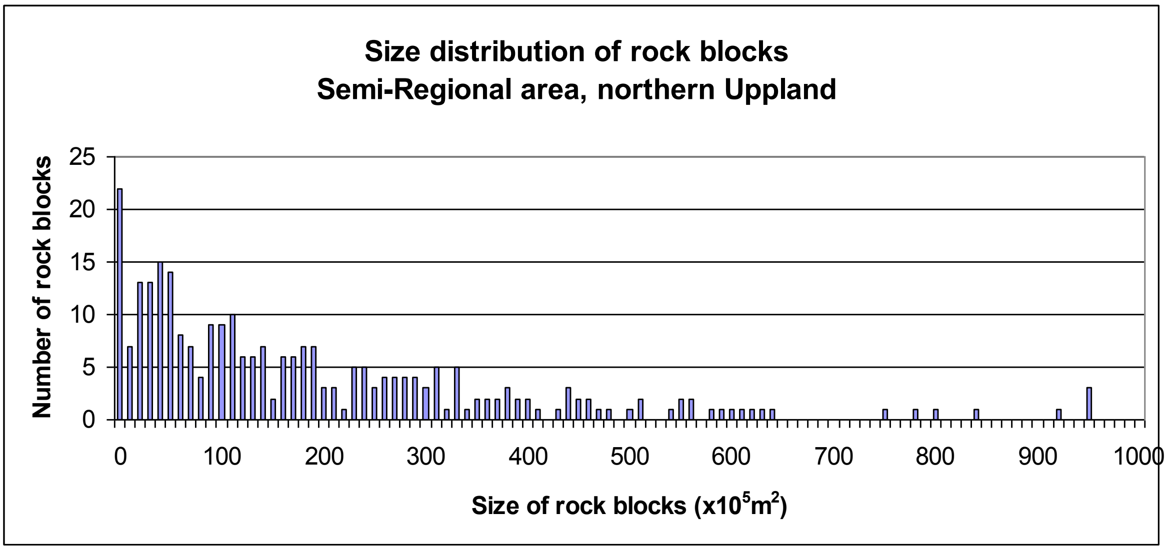
The lineament density and thereby the number of interpreted block boundaries is not directly comparable from one area to the other. The size of rock blocks in the detailed local areas (based on 10m grids) for the Forsmark and Laxemar local areas are of the same order. However, the number of rock blocks in the Forsmark local area is about four times as high. The rock blocks in the Laxemar area are more apparent due to a higher relief (and a much finer net exists that, as the finer division in the Regional Uppland area, has not been treated, shown in Fig. 14 as „minor rock block boundaries").

All block-size distribution curves display a decrease in number with increasing block size. Small irregularities may occur. Several isolated values for large rock blocks in the very right of the diagrams are due to marginal blocks; in the detailed regional Småland study, rock-block boundaries were extended to the east, to Öland, creating outsized blocks.

a



b



c

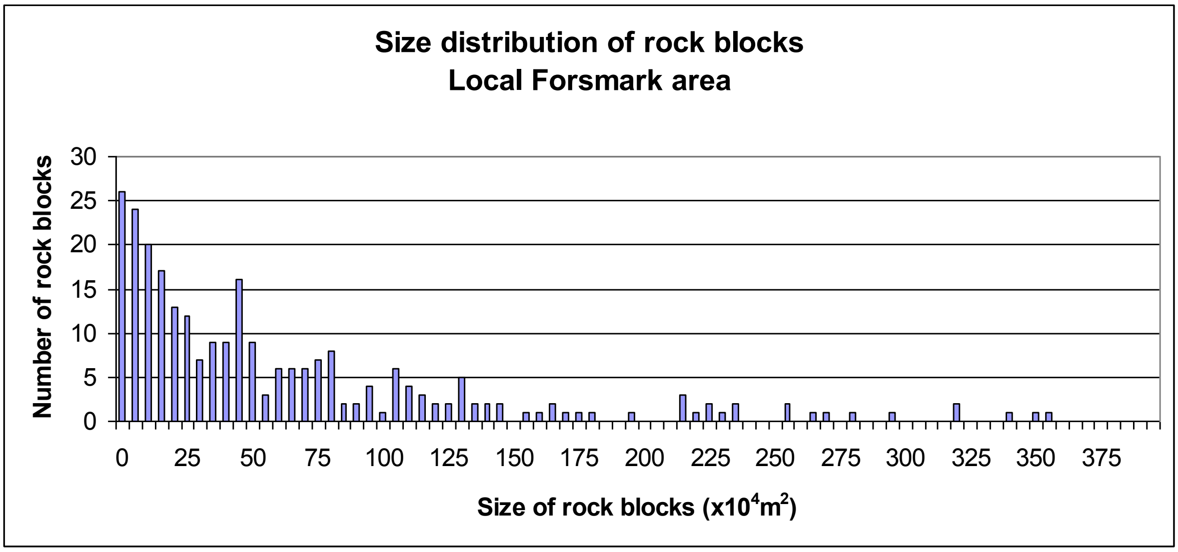


Figure 23. The distribution of size for rock blocks in, a) Uppland - Regional Forsmark area, 500m grid, 79 blocks, 4 blocks larger than 10^9m^2 are not included in the Figure, b) Northern Uppland – Semi-Regional Forsmark area, 50m grid, 304 blocks, and c) Local Forsmark area, 10m grid, 267 blocks, 4 blocks larger than 400x10^{4}m^2 are not included in the Figure.

Table 3. Parameters for rock blocks in Forsmark – Uppland and Laxemar – eastern Småland.

Base map	Elevation data Grid used (xm*xm)	Size of map area/tot. rock block area (x10^{9}m^2)	Number of rock blocks	Mean size of rock blocks (x10^{6}m^2)	Standard deviation (x10^{6}m^2)	Total length of rock block boundaries (x10^{6}m)	Density of rock-block boundaries (m/m^2)
Uppland Regional area	500	17. 86	79	226.09	309.27	2.8361	0.00016
Northern Upland Semi-Regional area	50	5.78	304	37.84	21. 21	2.9788	0.00052
Forsmark Local area	10	0.19	267	0.72	0.95	0.8592	0.00452
Eastern Småland Largest	500	3.48	73	46.67	62.35	1.1860	0.00034

rock blocks Regional area							
Eastern Småland Second largest rock blocks Regional area	500	4.22	185	22.83	27.29	1.9741	0.00047
Eastern Småland Regional area-	500	6.67	650	10.26	16.88	4.4509	0.00067
Laxemar Semi-Regional area	50	6.16	647	9.52	22.68	1.0815	0.00018
Laxemar Local area	10	0.21	64	3.24	3.13	0.2733	0.00130

In the regional area of eastern Småland, the relative density of rock blocks (number of blocks divided by area) decreases with a factor of approximately 2.5 – 3.5 when intermediate and minor rock blocks are added to the major rock blocks (largest blocks).

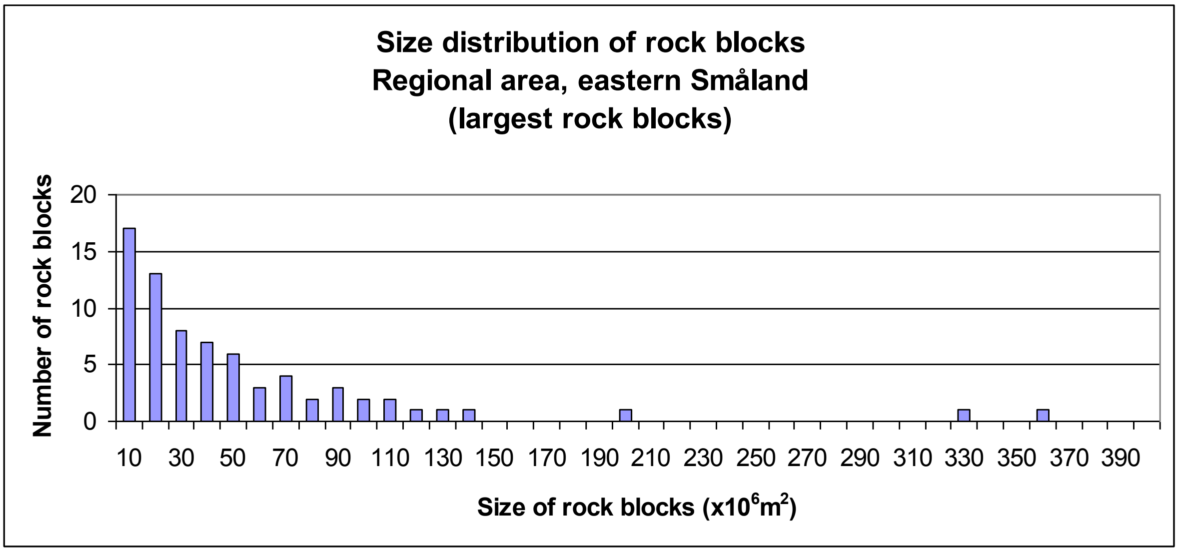
5.1.2 Comparison between mean and median altitudes of rock blocks

In the analyses of rock blocks the mean values have been used throughout the study since median values were given only in the analyses of the 50m grids.

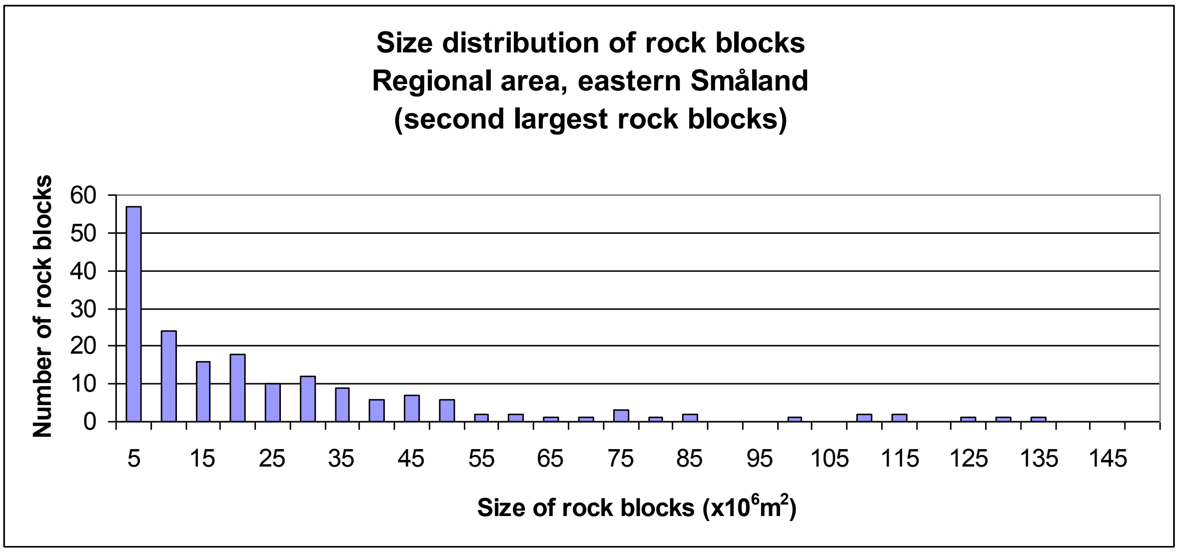
The actual differences between mean and median values are small. The relationships between these parameters in Uppland and Småland are shown in Fig. 25. The calculated differences for the rock blocks display normal distributions both for the northern Uppland and eastern Småland areas.

The topographic range within rock blocks is greater in eastern Småland than in northern Uppland. When plotting the median altitude against the mean altitude (Fig. 26), there is a linear relationship but with a wider scatter for higher altitudes.

a


Size distribution of rock blocks
Regional area, eastern Småland
(largest rock blocks)
Number of rock blocks
0
5
10
15
20
10 30 50 70 90 110 130 150 170 190 210 230 250 270 290 310 330 350 370 390
Size of rock blocks (x10^6m^2)

b


Size distribution of rock blocks
Regional area, eastern Småland
(second largest rock blocks)
Number of rock blocks
0
10
20
30
40
50
60
5 15 25 35 45 55 65 75 85 95 105 115 125 135 145
Size of rock blocks (x10^6m^2)

c

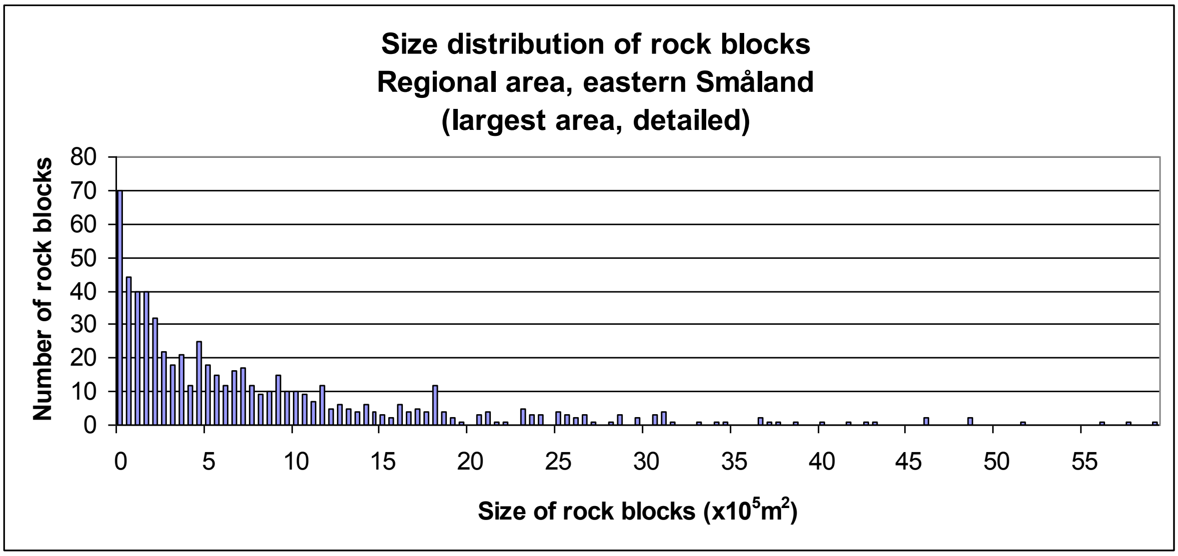
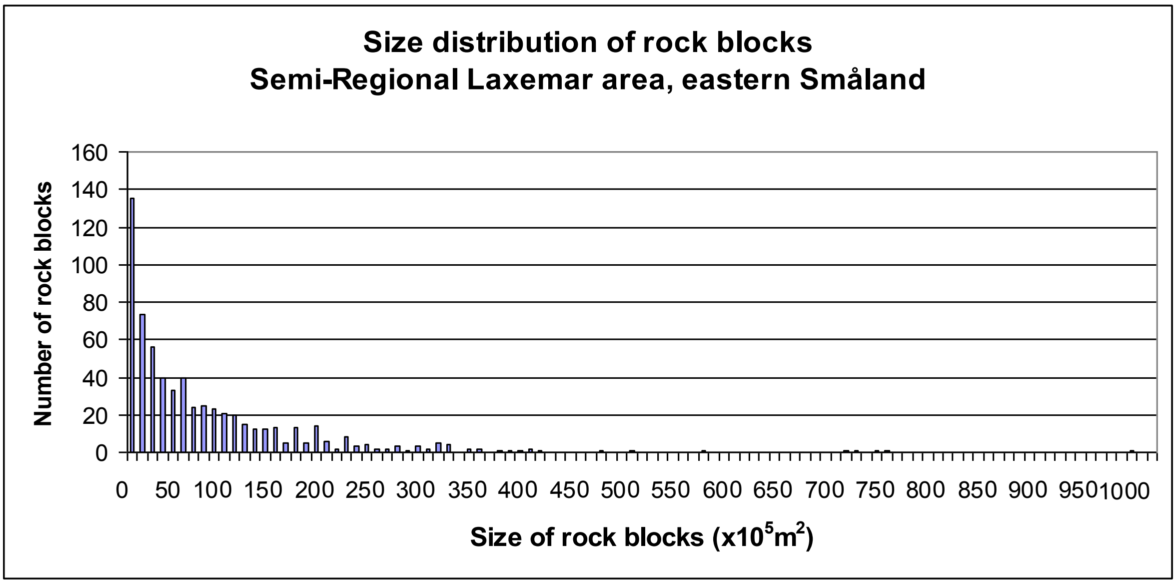


Figure 24. The distribution of size for rock blocks in, a) Eastern Småland, major block boundaries, 500m grid, 73 blocks, b) Eastern Småland, intermediate to major block boundaries, 500m grid, 185 blocks, c) Eastern Småland, minor to major block boundaries 500m grid, 650 blocks, 14 blocks larger than $60x10^5m^2$ are not included in the figure.

d



e

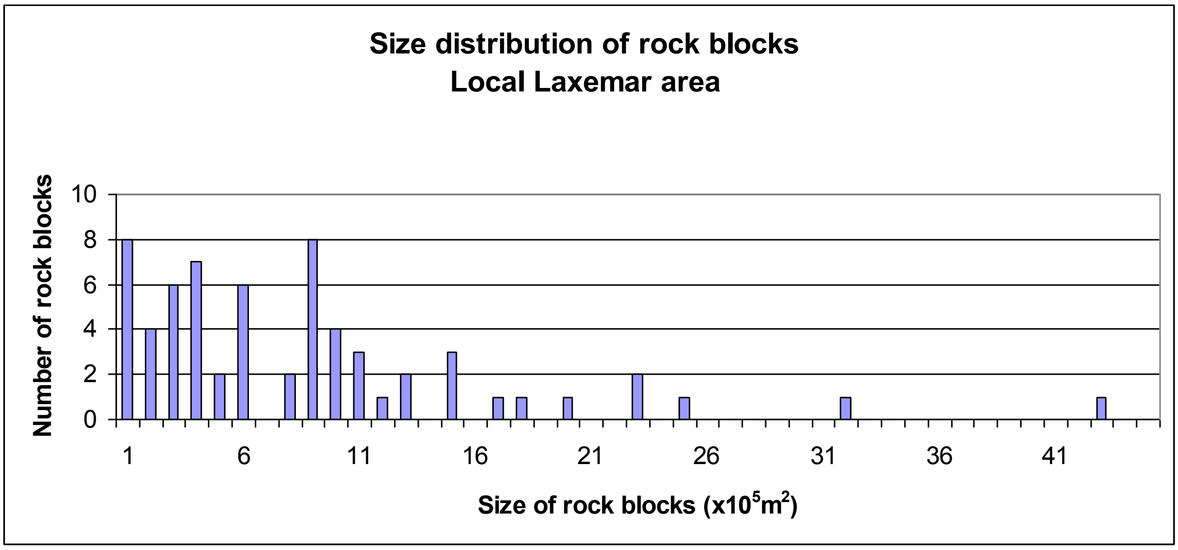


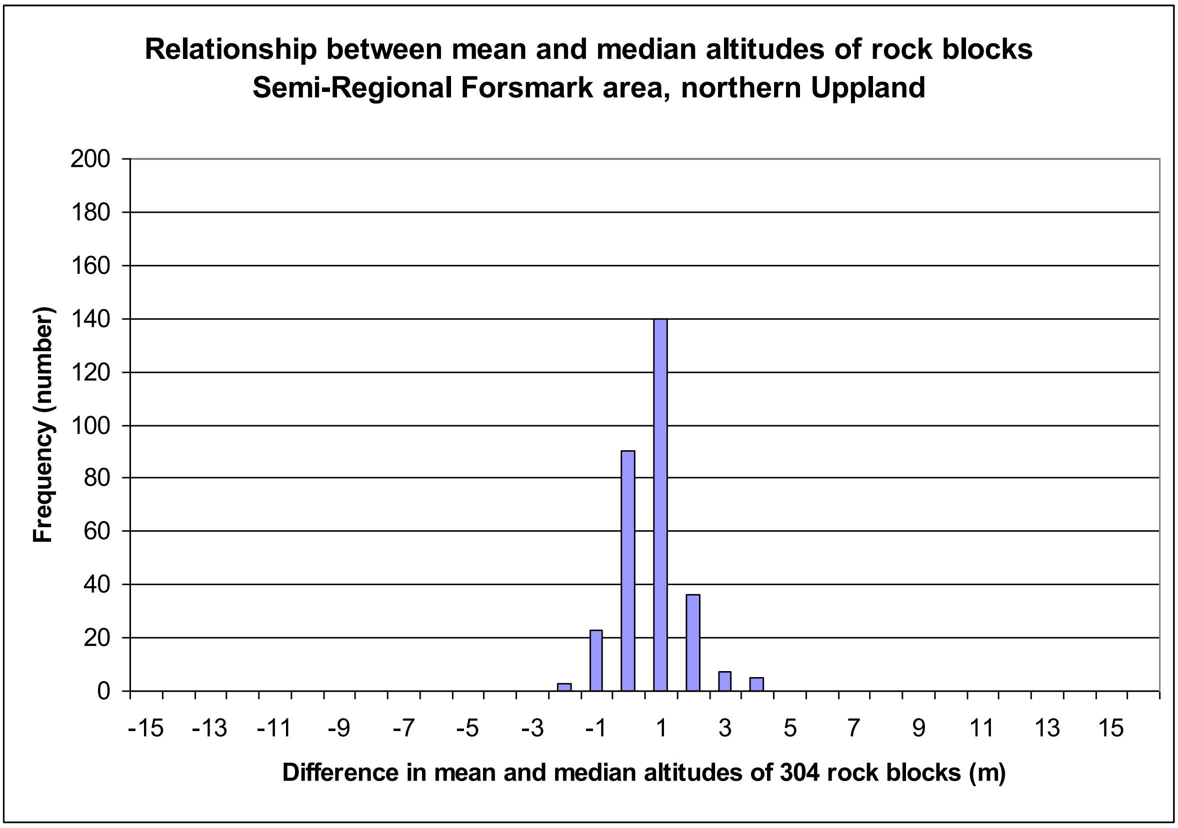
Figure 24 cont. The distribution of size for rock blocks in, d) Semi-Regional Laxemar area, 50m grid, 647 blocks, 5 blocks larger than $10^8 m^2$ are not included in the Figure, and e) Local Laxemar area, 10m grid, 64 blocks.

The difference for rock blocks with low altitudes is mainly related to rock blocks that are located close to the coast and mainly covered by water.

In plots displaying the difference between mean and median altitudes versus size of rock blocks (Fig. 27) it is apparent that these differences are not related to the size of the rock blocks. The difference is more related to the depth of erosion along the structures forming the rock-block boundaries. There is no obvious relationship between the differences of median and mean amplitudes and block size in the Forsmark area. This indicates that the ground surface within the rock blocks is relatively flat and that the erosion of brittle-deformation structures is limited and/or lows may be filled with sediments.

Eastern Småland has a more pronounced relief than Uppland and in eastern Småland the differences in the mean and median altitudes is greater than in northern Uppland. This indicates that the regional surface is more uneven and may also suggest the occurrence of wider valleys.

a


Relationship between mean and median altitudes of rock blocks
Semi-Regional Forsmark area, northern Uppland
Frequency (number)
200
180
160
140
120
100
80
60
40
20
0
-15
-13
-11
-9
-7
-5
-3
-1
1
3
5
7
9
11
13
15
Difference in mean and median altitudes of 304 rock blocks (m)

b

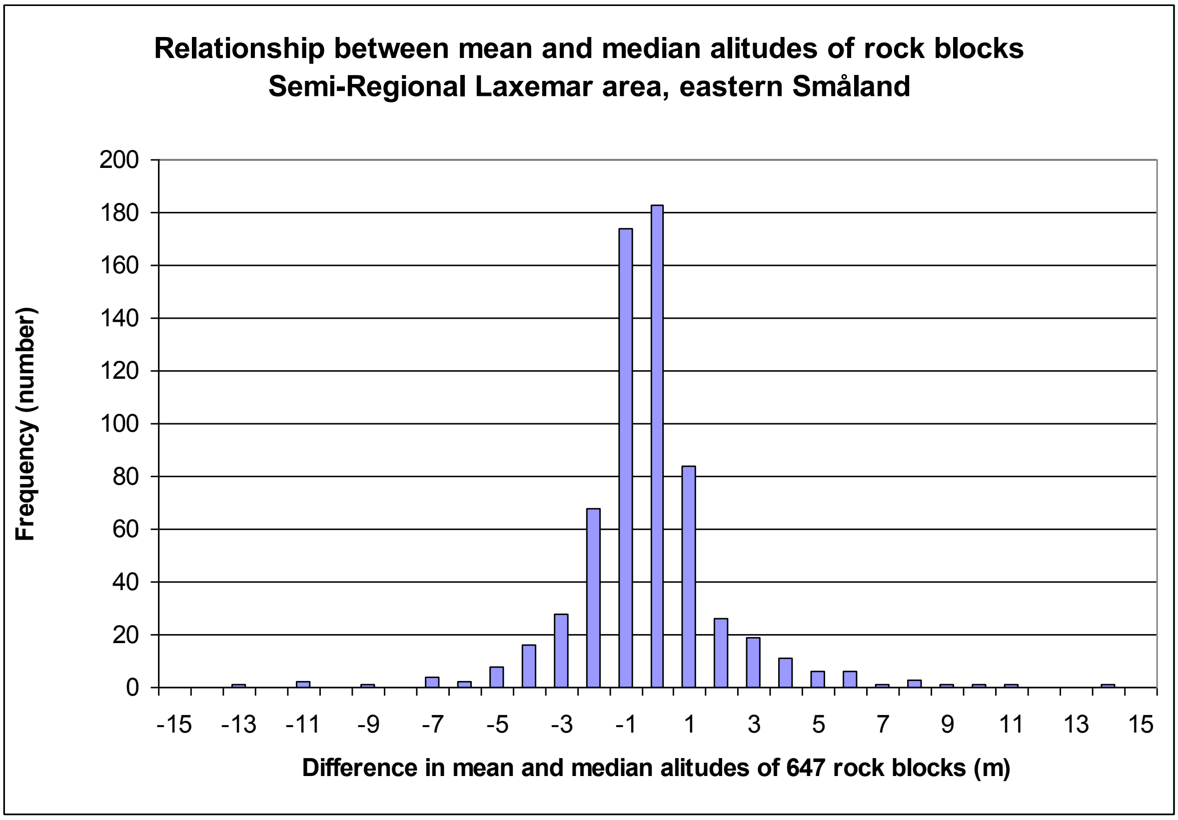
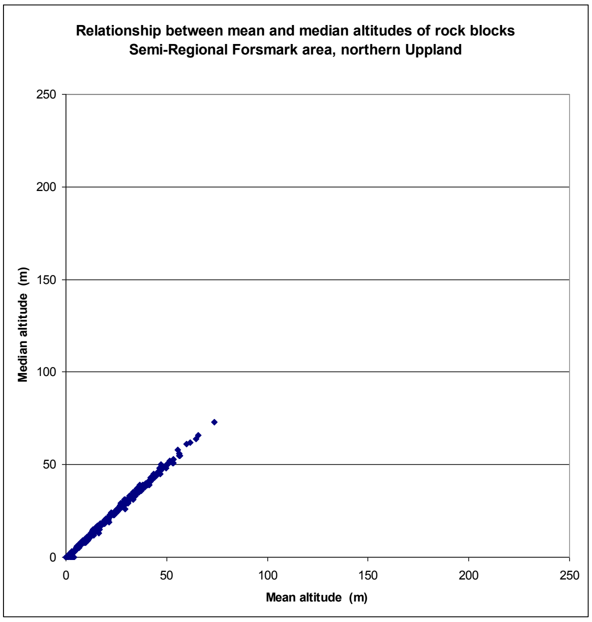
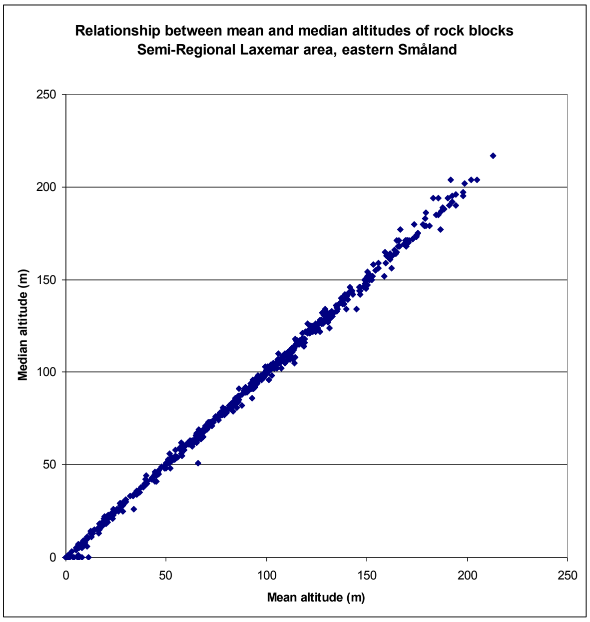

Relationship between mean and median alitudes of rock blocks
Semi-Regional Laxemar area, eastern Småland
Frequency (number)
200
180
160
140
120
100
80
60
40
20
0
-15
-13
-11
-9
-7
-5
-3
-1
1
3
5
7
9
11
13
15
Difference in mean and median alitudes of 647 rock blocks (m)

Figure 25. The relationship between mean and median values for altitude of rock blocks. Frequency of rock blocks for the difference between mean and median values, a) Northern Uppland – Semi-Regional Forsmark area (50m grid), and b) Eastern Småland - Semi-Regional Laxemar area (50m grid).





a b

Figure 26. The relationship between mean and median values for a) Northern Uppland - Semi-Regional Forsmark area, and b) Eastern Småland - Semi-Regional Laxemar area.

However, there are rock blocks in eastern Småland that have a distinctly low relief. These blocks do not deviate in altitude when compared to surrounding blocks. It is not apparent that these blocks should have a lower density of internal structures, as extensive structures are traceable across the blocks, but they do have less pronounced topographical expression inside the blocks. This suggests that the difference in internal relief in these blocks may be related to time of exposure. The removal of the Cambro-Silurian cover may have occurred recently (cf. the remnant of sedimentary rocks in Västergötland and Östergötland).

5.1.3 Maximum and minimum altitude of rock blocks

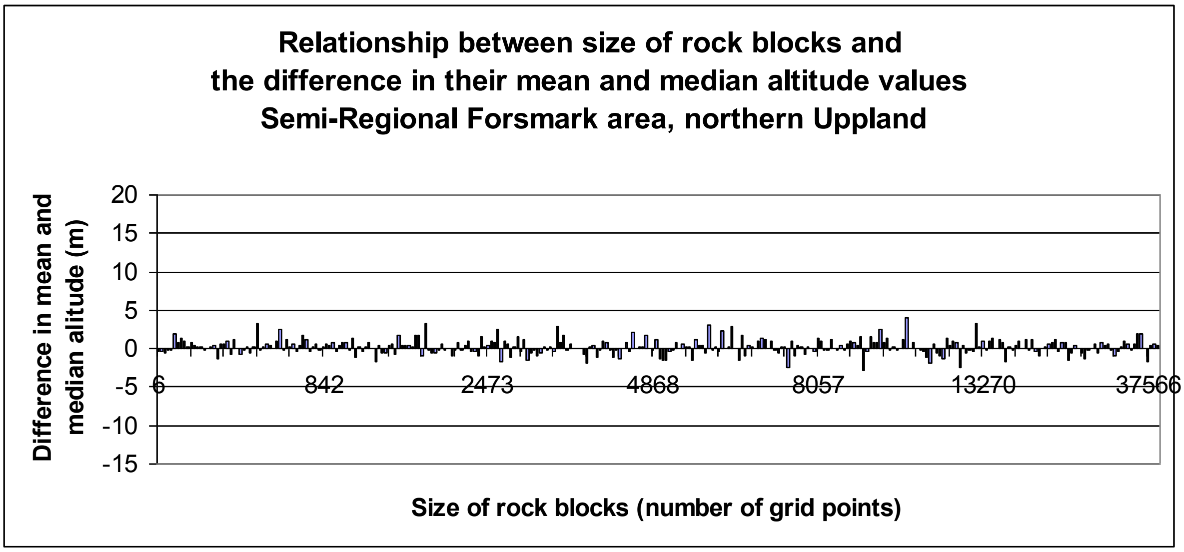
The spread in the minimum and maximum values is larger in eastern Småland, where the relief is greater, than in northern Uppland. The Semi-Regional Forsmark area is located below the highest shore line.

The minimum values are located in valleys and in coastal areas represented by the level of the sea. The thickest sedimentary cover is generally found in the valleys. The minimum elevation may reflect the base of erosion. The maximum value may be relatively close to the surface of the sub-Cambrian peneplain with only a thin cover of soil.

In eastern Småland minimum altitudes for rock blocks show an anomaly at c. 105m a.s.l. (Fig. 28). This altitude is identical to the highest shore line in the area after the deglaciation. Basins and valleys west of the north-south trending central ridge in the regional areas may have been filled with glacifluvial sediments (e.g. deltas and outwash plains). Above the highest marine level the relief is greater than below this level.

The range, the difference between maximum and minimum altitude within a rock block, roughly reflects the relief.

a



b

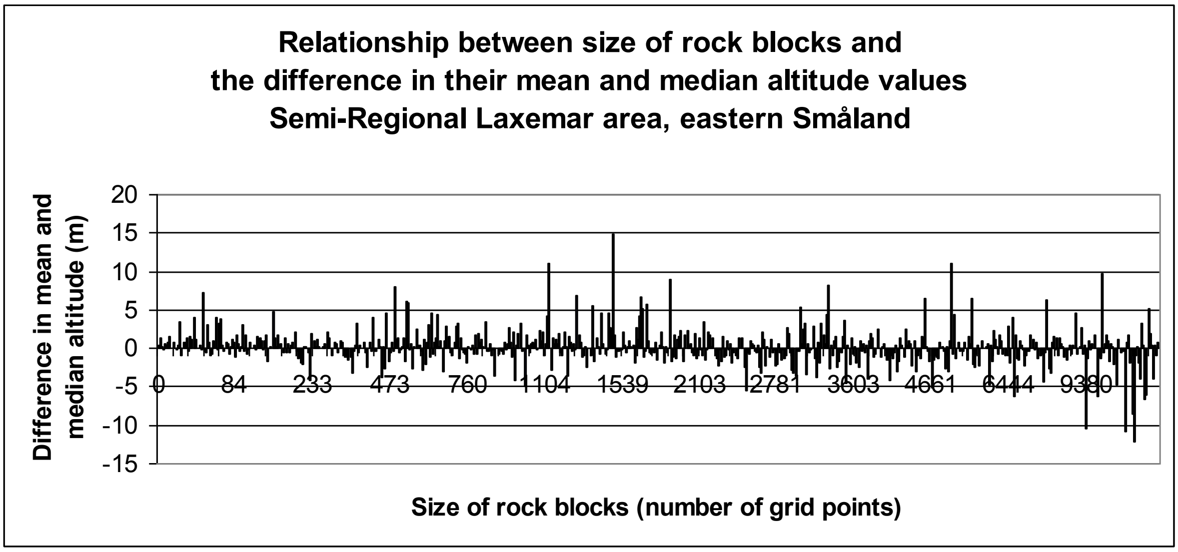
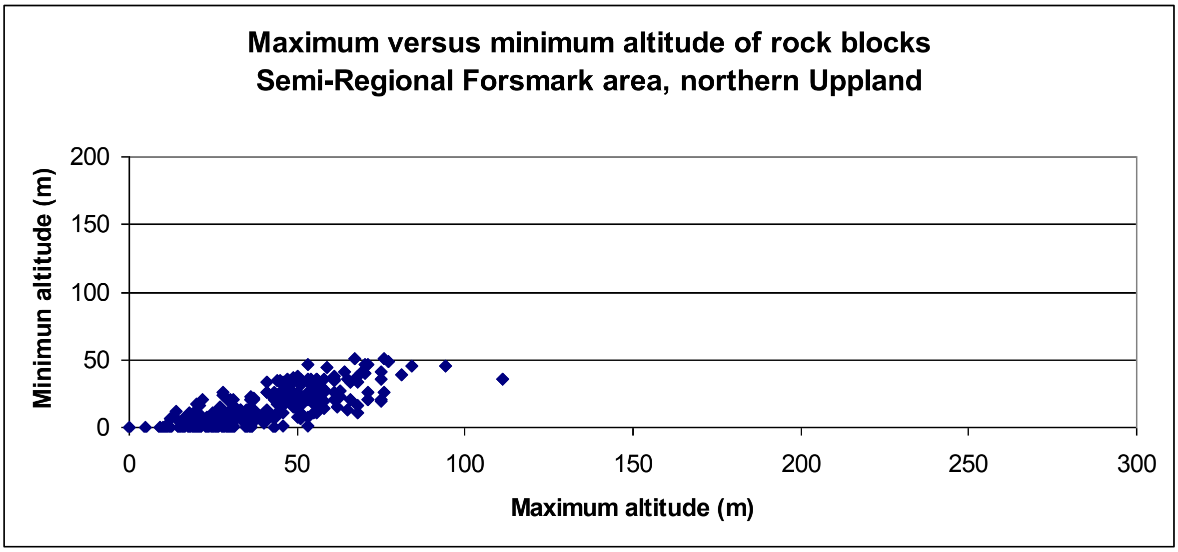


Figure 27. The relationship between mean and median values for altitudes of rock blocks plotted as the difference between the two parameters and the size of the rock blocks measured in grid points, 50m grid, a) Northern Uppland - Semi-Regional Forsmark area, and b) Eastern Småland - Semi-Regional Laxemar area.

5.2 Maps

Mean, range, minimum and maximum values for each polygon are displayed in maps in Fig. 29-36 where high numbers are shown in red and low in green, independently covering the total range for each individual map. For the 50m and 10m grids peripheral polygons may include area not covered by the elevation data.

a



b

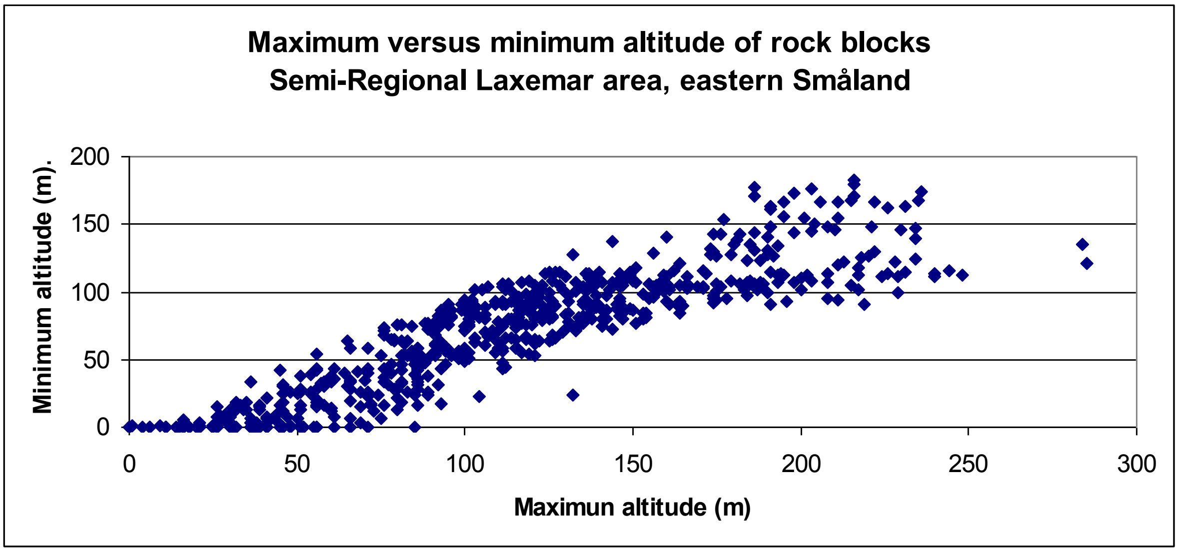


Figure 28. The relationship between maximum altitude and minimum altitude of rock blocks (50m grid), a) Northern Uppland - Semi-regional Forsmark area, and b) Eastern Småland - Semi-Regional Laxemar area.

5.3 Uppland

The regional 500m base (Fig. 29) clearly shows the three-fold division into east-west segments around the Mälaren basin. The lower-elevation north-north-westerly belt along the coast also stands out clearly. The higher ground in the northwest, northeast of Stockholm, and in the Sörmland horst have high means, range and maximum altitude. The minimum values show the base of the drainage system where the inner areas around and northwest of Uppsala are the only ones with values significantly above sea level. On the maximum and range maps Upplandsslätten, the plain around Uppsala, stands out very well. Interesting is the large triangular block in the junction between the north-easterly and north-westerly trend that on the rock-block map (Fig. 9) shows low altitude and a fragmented appearance, here showing intermediate yellow minimum values.

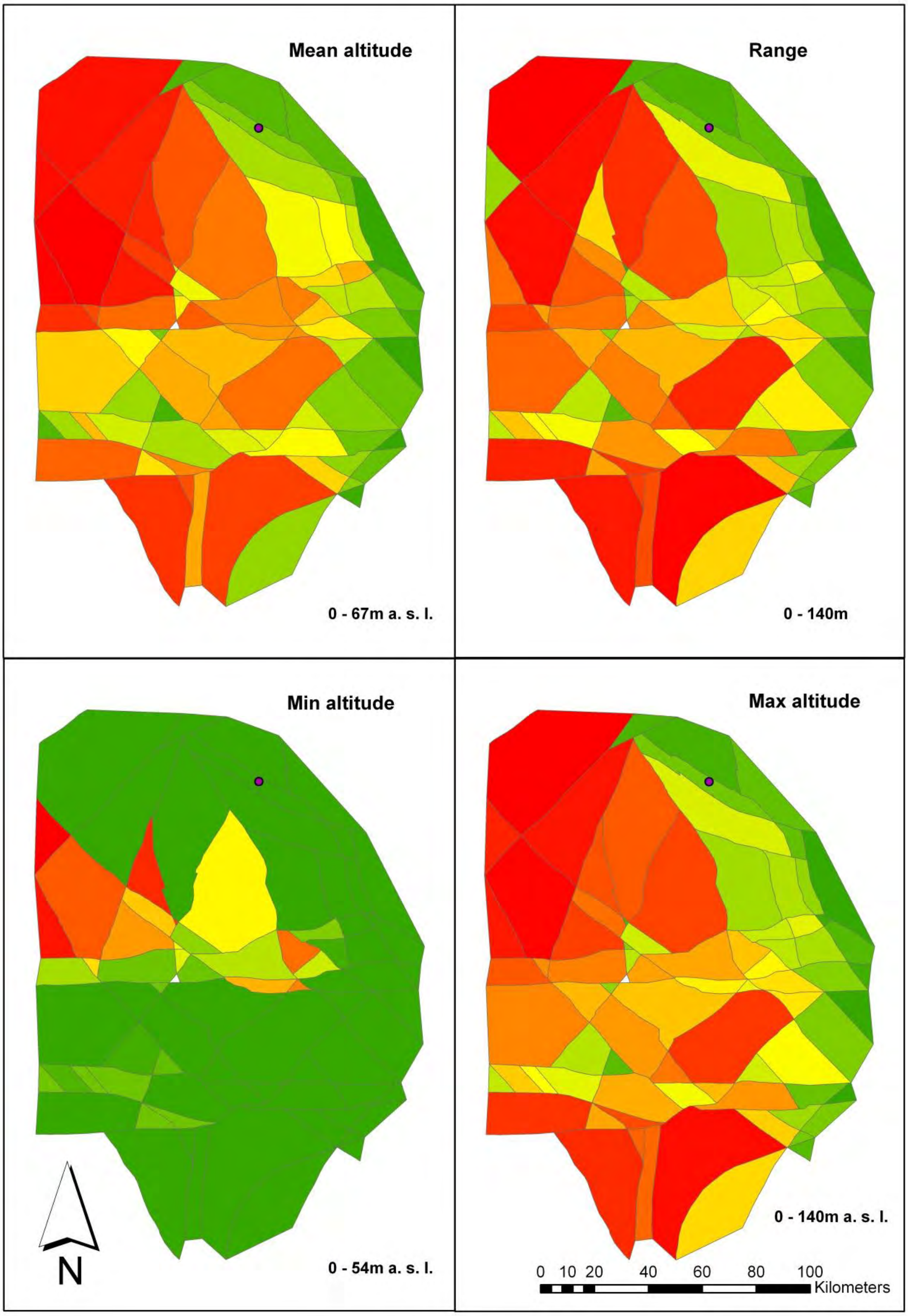


Figure 29. Polygons in Uppland – Regional Forsmark area, elevation data. Mean altitude, range, minimum and maximum values for the regional rock blocks based on the 500m grid. Note that the colour palette shows relative colours spanning the range of values and thus has different values for each set of polygons. The span is given in metres for each map. Violet dot = the Forsmark SKB site.

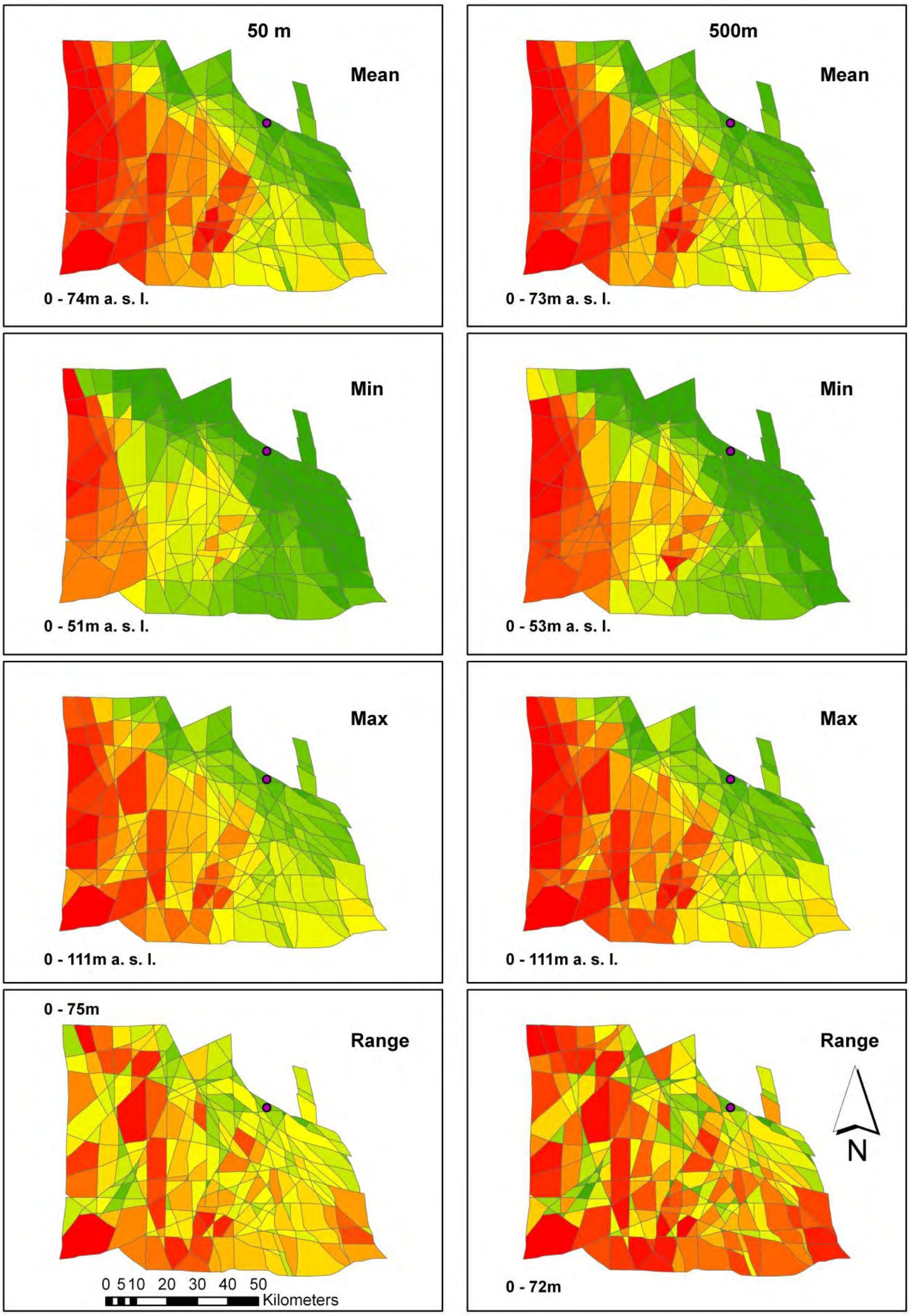


Figure 30. Polygons in Northern Uppland – Semi-Regional Forsmark area, elevation data. Mean altitude, range, minimum and maximum values for the semi-regional rock blocks based on the 50m and 500m grids. The colour palette has different values for each set of polygons. The span is given in metres for each map. Violet dot = the Forsmark SKB site.

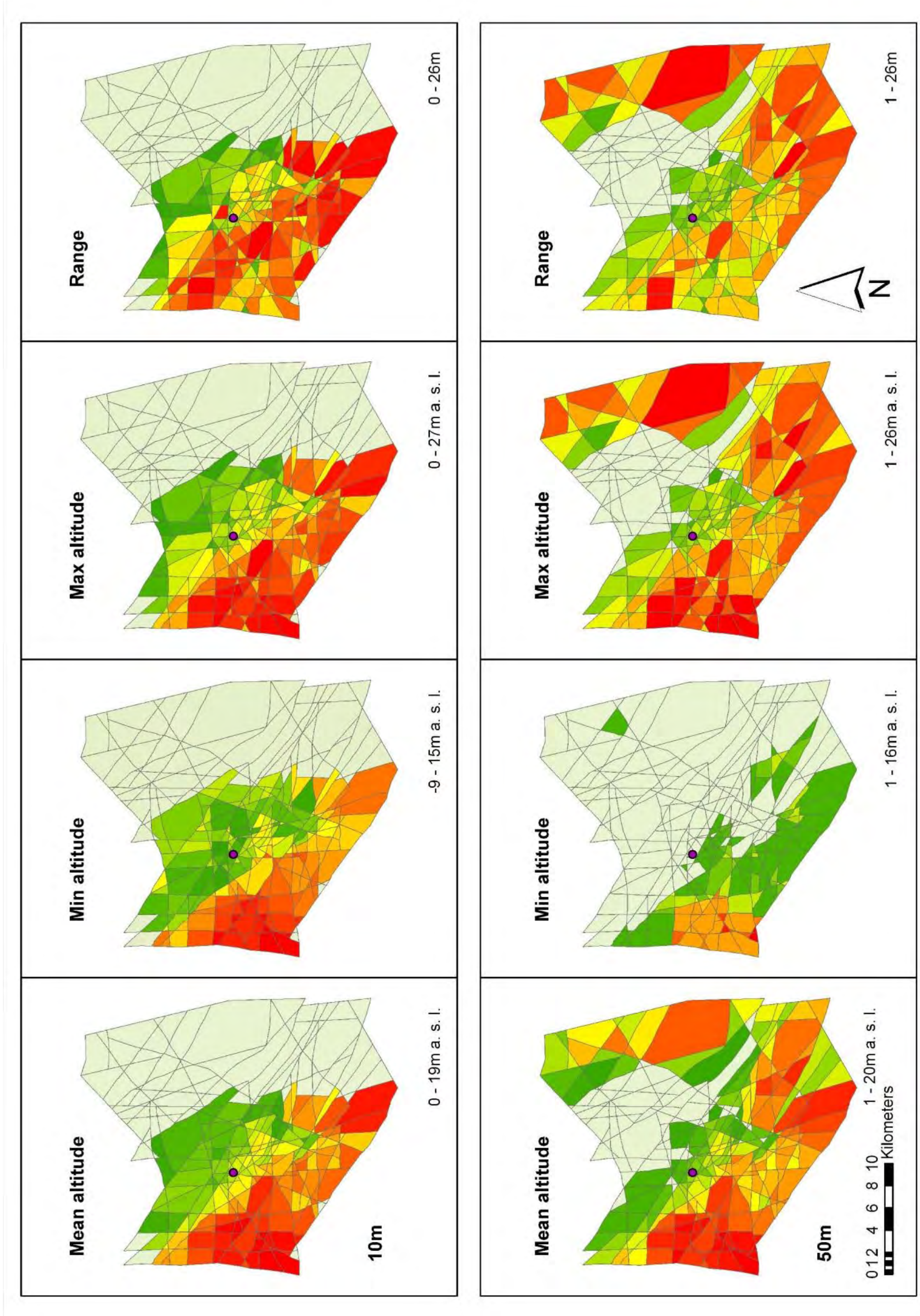


Figure 31. Polygons in the Local Forsmark area, elevation data. Mean altitude, range, minimum and maximum values for the local rock blocks based on the 10m and 50m grids. The colour palette has different values for each set of polygons. The span is given in metres for each map. In the values for the 50m grid the zero level is excluded to facilitate the evaluation of "no data" due to water cover. Violet dot = the Forsmark SKB site.

In fig. 30, the same values for the polygons in the *semi-regional area* covered by the 50m grid are compared for the 500m and 50m data sets. The overall picture is very similar, the 50m set showing slightly lower relative values.

In the higher western ground, a clear north-north-westerly trend in altitude is revealed, especially in the 50m minimum. Scattered small polygons with lower mean, minimum and maximum values also have a lower range.

Figure 31 makes the same comparison between the 50m and 10m data bases in the *local Forsmark area*. Here the different coverage and the handling of water-covered areas by the two data sets make a comparison less straightforward, cf. especially the minimum values where the 10m grid provides a greater number of pixels above the zero level and also gives values for pixels below 0m b. s. l. Both bases give the main orientation of structures, north-westerly, west-north-westerly and, the orthogonal north-south and east-west pattern. The elevated west-north-westerly rib south of Forsmark stands out more clearly on the 50m base.

5.4 Småland

For the polygon sets in Småland the same analyses were made. In the *three regional sets,* based on major, intermediate and regional rock-block boundaries in Fig. 12, the east-west gradient is the most obvious characteristic feature (Figs. 32-34). The fact that the minimum and maximum values yield the same pictures shows that the erosion level in the valleys has not approached the sea level yet. The inner north-south valley in the western part is displayed on most maps.

For the *largest rock blocks* (Fig. 32) the 50m and 500m bases are almost identical. The gradient is clearly displayed in the mean, minimum and maximum values. The range however, shows a more diverse picture, particularly in the area south of the east-west Oskarshamn lines.

Smaller blocks on the east rim of the polygon row east of the inner valley have relatively high minimum values. Smaller, mostly triangular, blocks have low maximum and range values.

The *somewhat smaller rock blocks* in Fig. 33 do not change the impression. The range values give a more varied picture showing blocks with less range close to the sea; especially the 50m base displays blocks of the whole spectra.

Figure 34 gives the *most detailed interpretation of the largest area*, but beware that the 50m grid does not cover the upper two rows of polygons! The minimum values show that the erosion base has reached lower around the “eye” in the southern part between the coast and inner valley. Generally, the 50m base shows lower colours, especially for the range values. Note the little standing triangle two thirds from the left just below the middle with higher maximum and much higher range values than the surroundings. Again, smaller green and yellow triangles and elongate irregular rectangles occur between larger reddish blocks. The comparatively high colours for maximum and range in the very large block in the southeast are due to the Blå Jungfrun morphology.

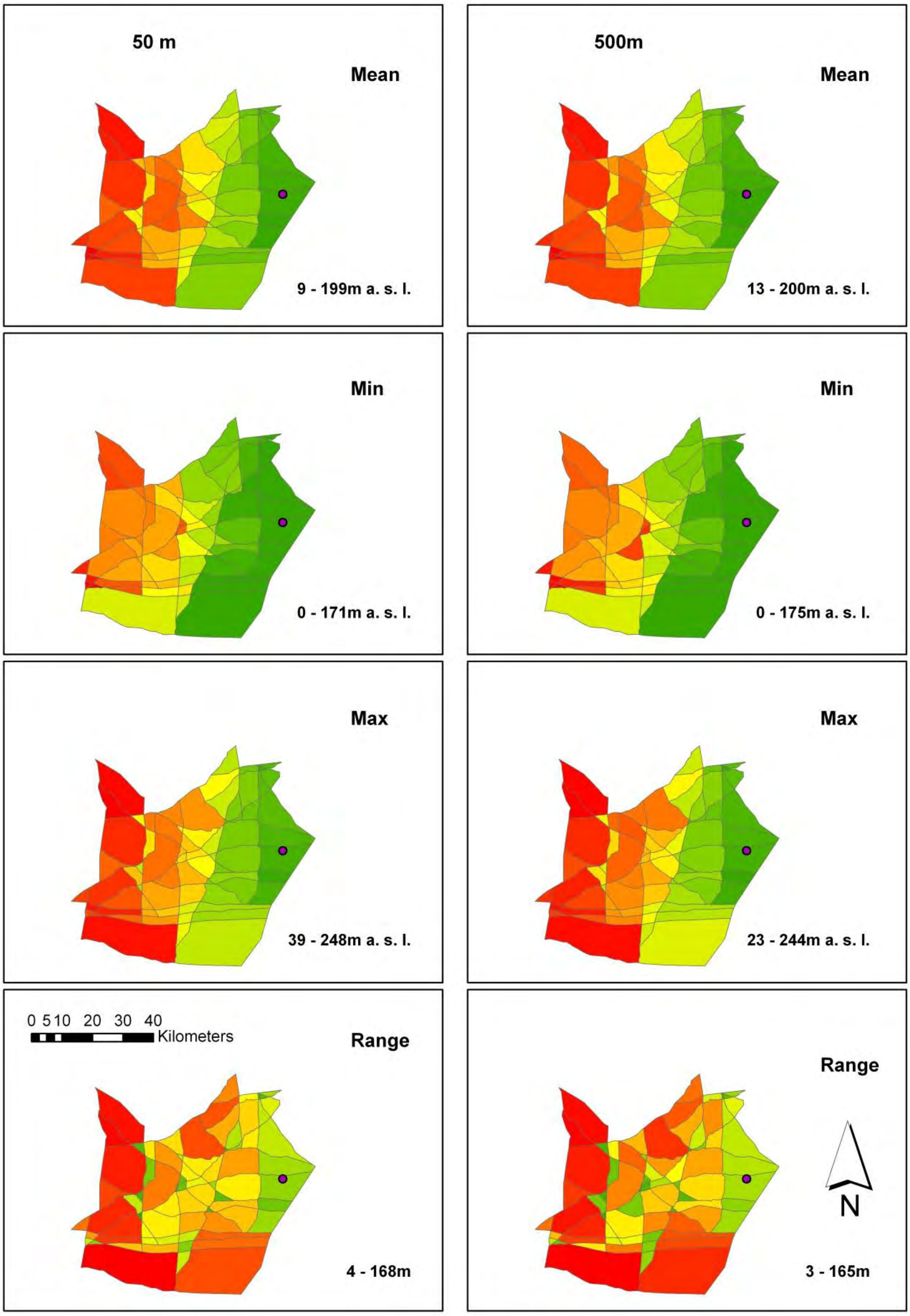


Figure 32. Polygons in eastern Småland - Regional Laxemar area, elevation data, major rock-block boundaries in Fig. 12. Mean altitude, minimum, maximum and range values for largest regional rock blocks based on the 50m and 500m grids. The colour palette has different values for each set of polygons. The span is given in metres for each map. Violet dot = the Laxemar SKB site.

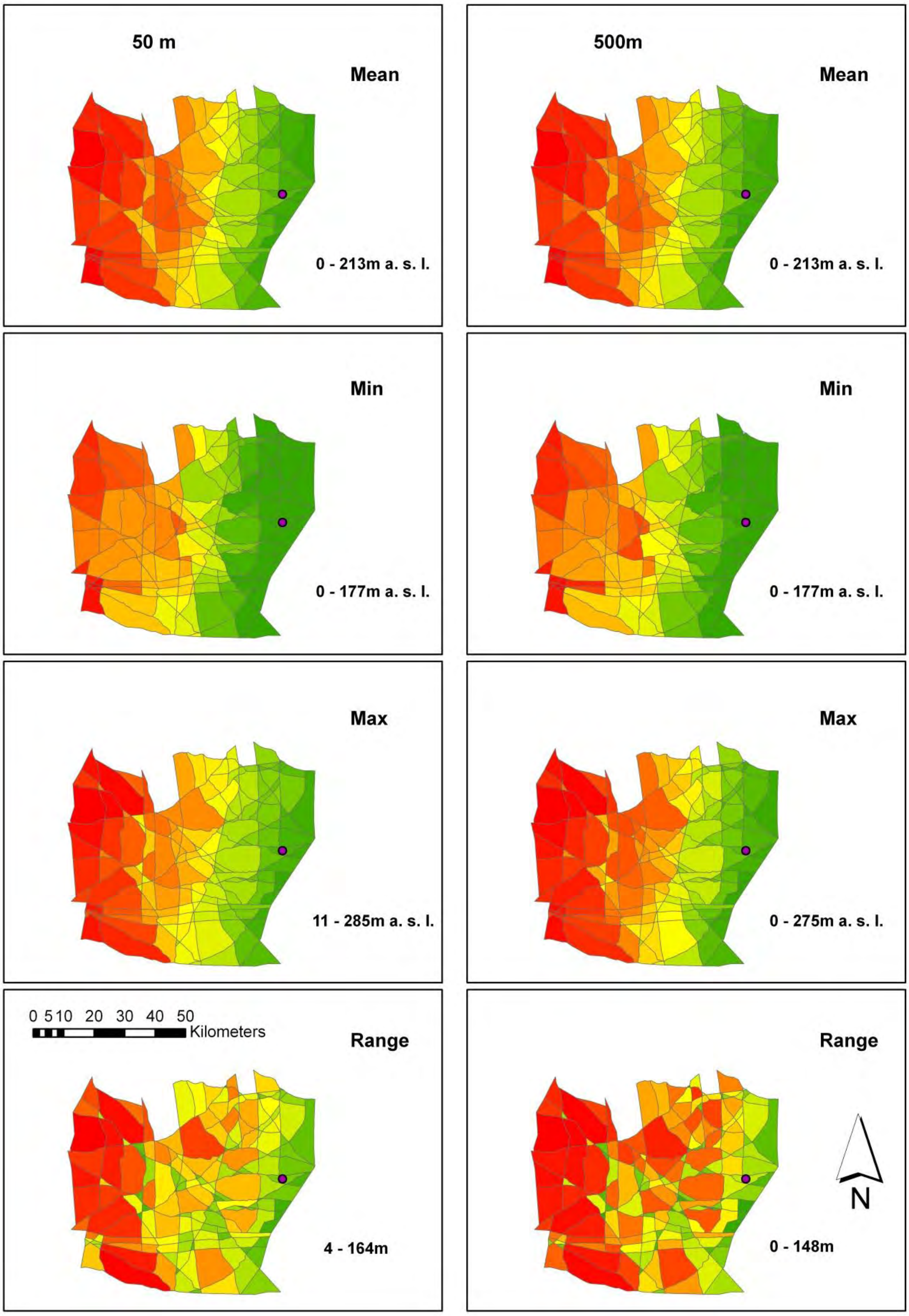


Figure 33. Polygons in eastern Småland - Regional Laxemar area, elevation data, intermediate rock-block boundaries in Fig. 12. Mean altitude, minimum, maximum and range values for the second largest regional rock blocks based on the 50m and 500m grids. The colour palette has different values for each set of polygons. The span is given in metres for each map. Violet dot = the Laxemar SKB site.

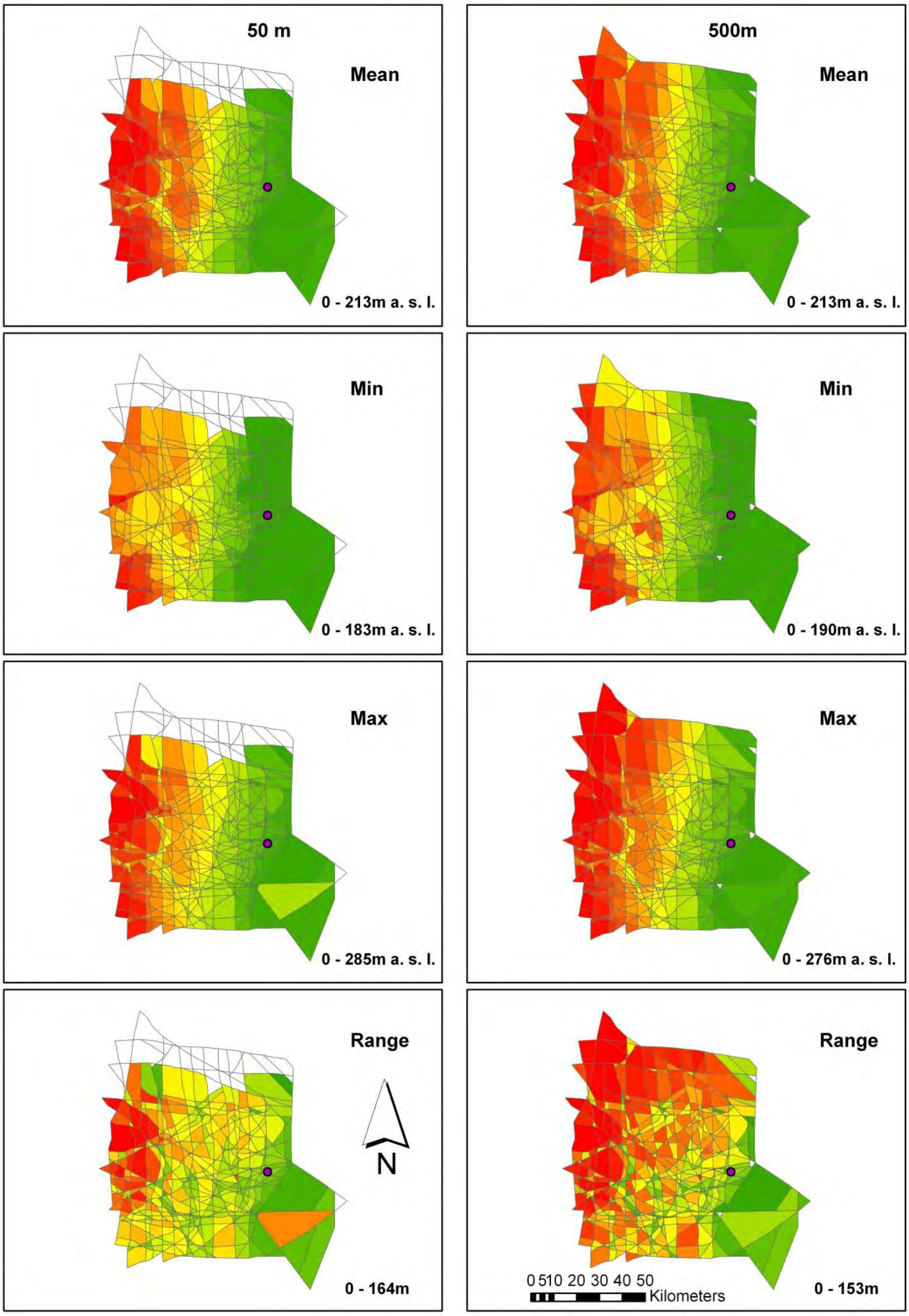


Figure 34. Polygons in eastern Småland - Regional Laxemar area, elevation data, regional rock-block boundaries in Fig. 12. Mean altitude, minimum, maximum and range values for the regional rock blocks based on the 50m and 500m grids. The colour palette has different values for each set of polygons. The span is given in metres for each map. Violet dot = the Laxemar SKB site.

The main features on these regional interpretations are the east-west Oskarshamn lines in the southern part of the maps. A parallel set of lines occur in the northern part of the most detailed interpretation (Fig. 34). Another conspicuous feature is the larger triangular pattern that occurs around the “eye” in Fig. 33 and 34, comprising north-easterly, south-easterly and north-north-easterly components.

The S*emi-Regional area* (Fig 35) shows the same general picture of gradual rise towards the west. Mean and maximum values give very similar pictures. The half-sphere pointing eastwards of higher minimum values are also shown in lower range values. Note the very small rectangular block in the middle north-south system that especially in the 500m base stands out with relatively higher values.

Northwest, north-south and east-west structures govern the overall rock block pattern where triangles are very common. Some north-south structures are through-going but most end towards(/in) another block or are linked into a different direction.

The local Laxemar area (Fig. 36) is dominated by the central east-west and north-south structures. There is a roughly parallel east-westerly line in the very south and another north-southerly line, the northern part of which runs just west of the map area; its southern part is shown on the map. These define the high, orthogonal blocks in the western part of the map.

The apparent difference in colours between the 50 and 10m values the minimum values are particularly misleading; the yellowish green colours in the north have values of 1m a. s. l.

The rock block configuration is a slight reminiscence to the northeast of the protruding half-sphere in Fig. 35 with lower land in the northeast and south-east. Most northwest structures do not reach the sea uninterrupted. A northeast trending belt occurs in the south-eastern quadrant and displays low rock blocks with an elongate northeast trend. The relatively high block east of Lake Götemaren receives a high range since it comes down to water level. The Laxemar blocks have relatively high mean, maximum and range values.

To facilitate the comparison between rock blocks on different scales Fig. 37 and 38 were compiled.

6 MODELLING & REMOVAL OF THE GRADIENT

Since the results, particularly from eastern Småland were so dominated by the regional topographic gradient. This gradient was modelled and removed to reveal the relative movements of possible late block-faulting.

6.1 Procedure

A residual trend-removal filtering was applied to the six different sets of digital elevation data. Since, in most cases, the regional topographical gradient is not a uniformly inclined planar structure, it cannot generally be expressed as a planar surface ($\check{z} = f(x,y) = A + Bx + Cy$) using the edge coordinate data for the data set.

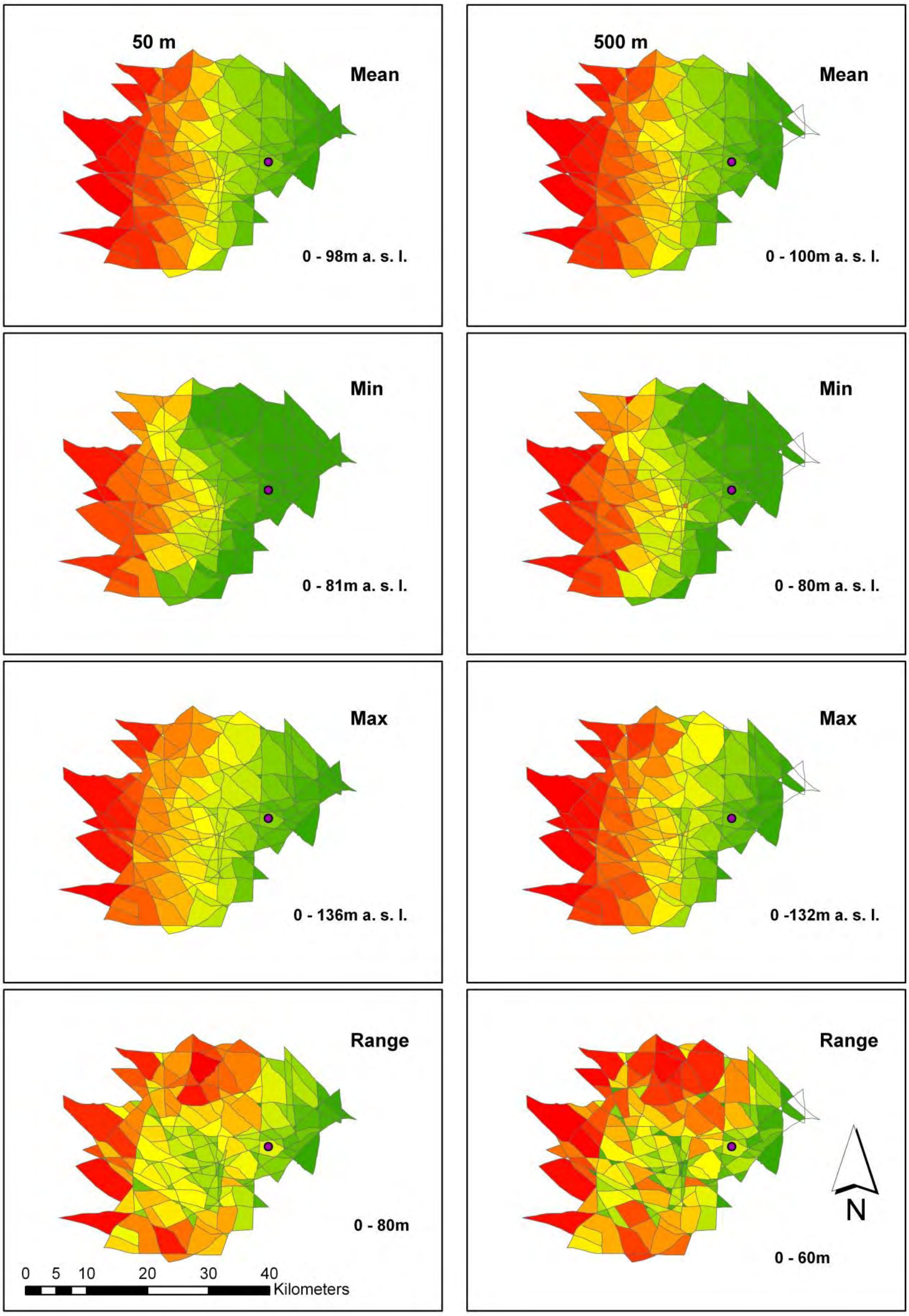


Figure 35. Polygons in eastern Småland - Semi-Regional Laxemar area, elevation data. Mean altitude, minimum, maximum and range values for semi-regional rock blocks based on the 50m and 500m grids. The colour palette has different values for each set of polygons. The span is given in metres for each map. Violet dot = the Laxemar SKB site.

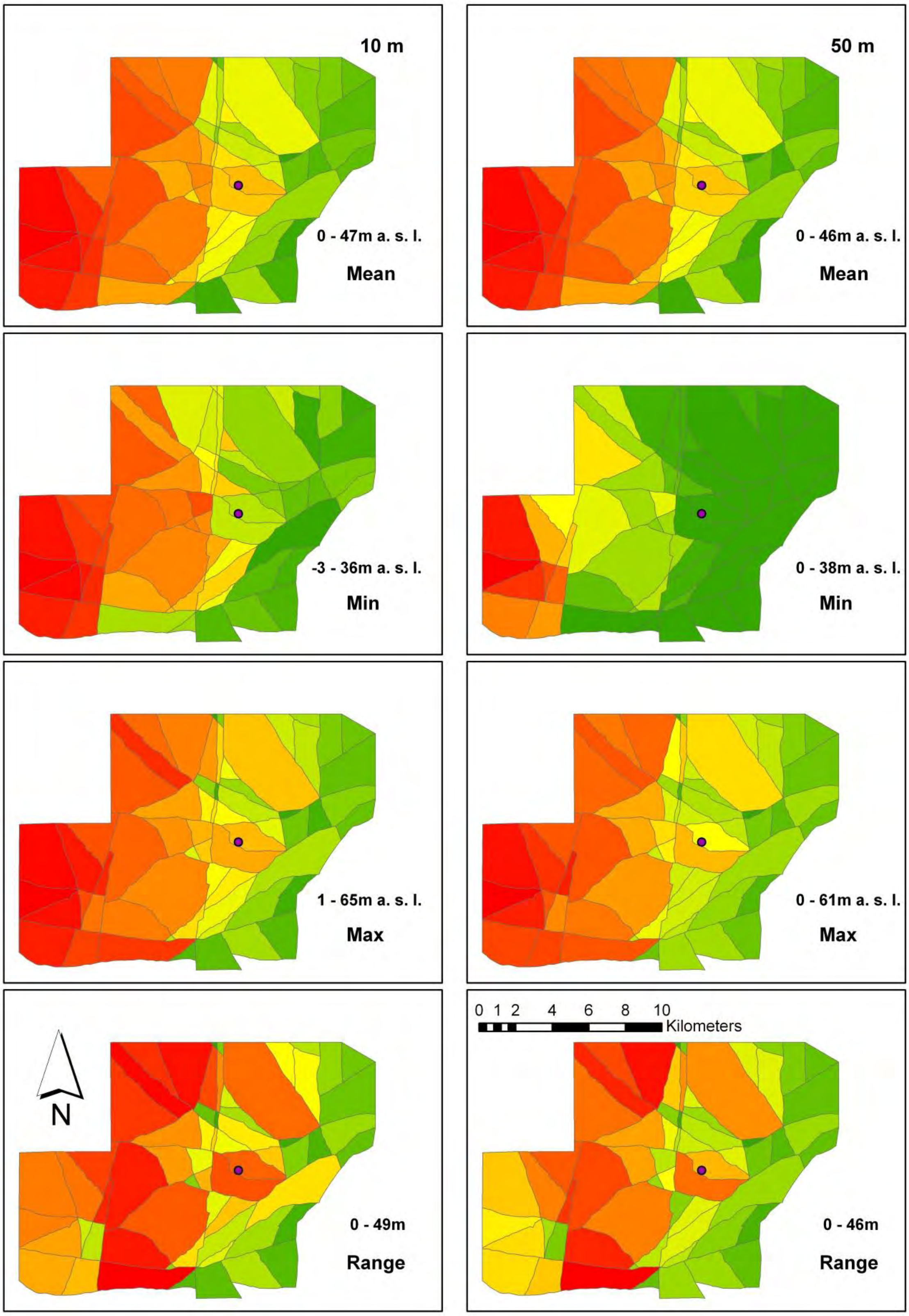


Figure 36. Polygons in the Local Laxemar area, elevation data. Mean altitude, minimum, maximum and range values for the local rock blocks based on the 10m and 50m grids. The colour palette has different values for each set of polygons. The span is given in metres for each map. Violet dot = the Laxemar SKB site.

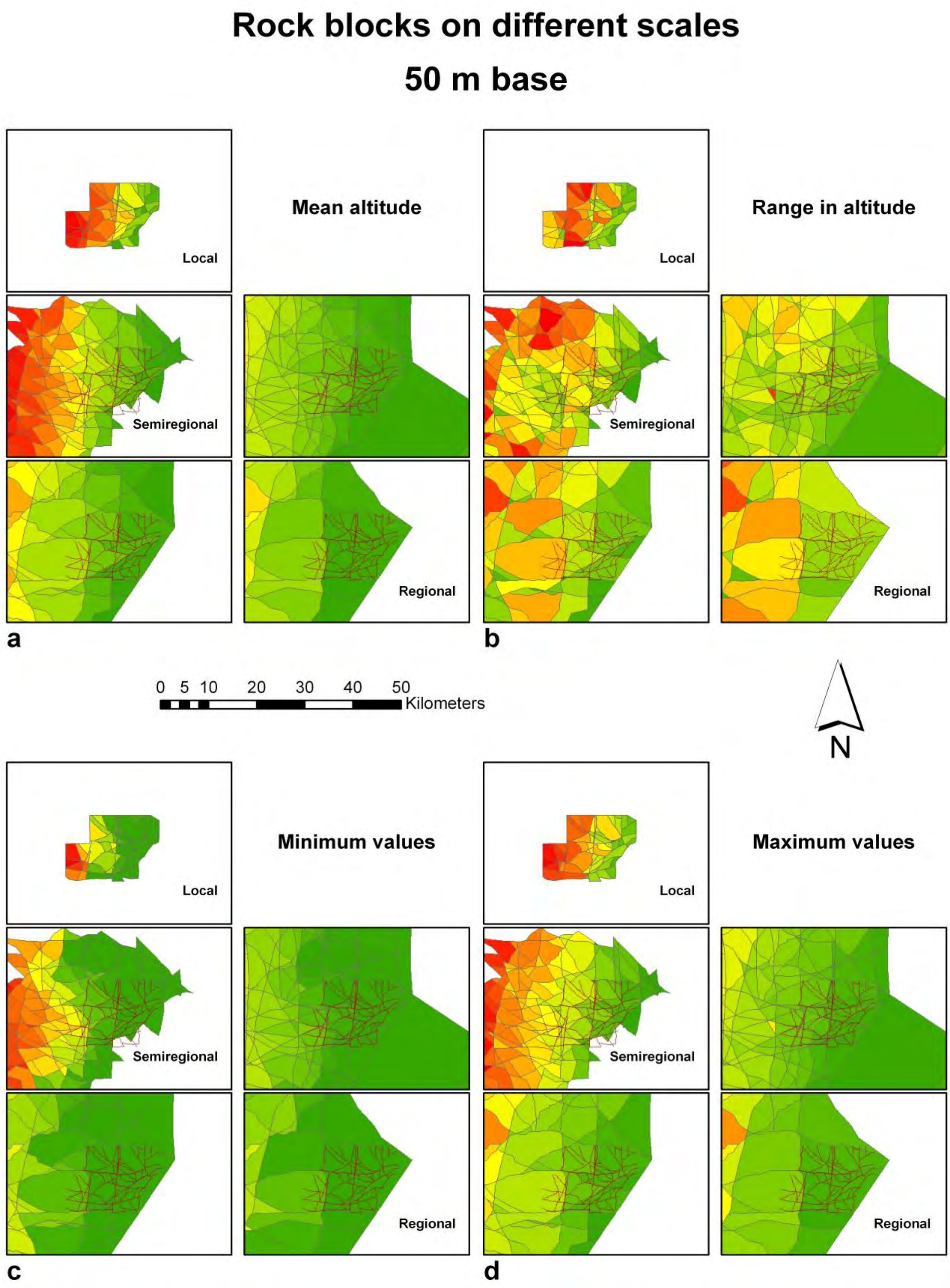


Figure 37. Compilation of elevation data, for the five sets of polygons within the Regional Laxemar area, successively larger rock blocks from local to regional scale, 50m grid. Relative colours cf. Figs. 32-36. a) Mean values, b) Range values, c) Minimum values, d) Maximum values.

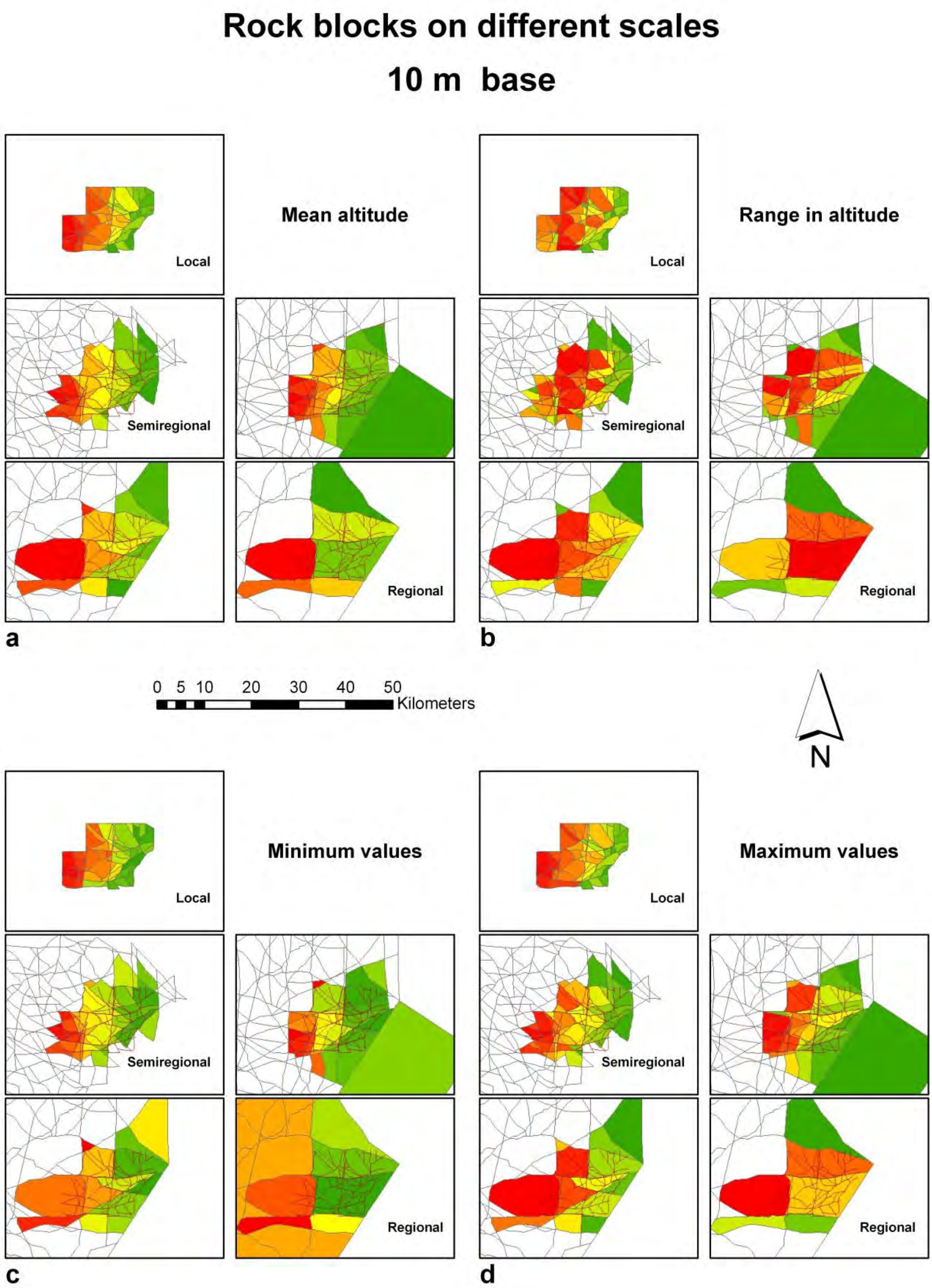
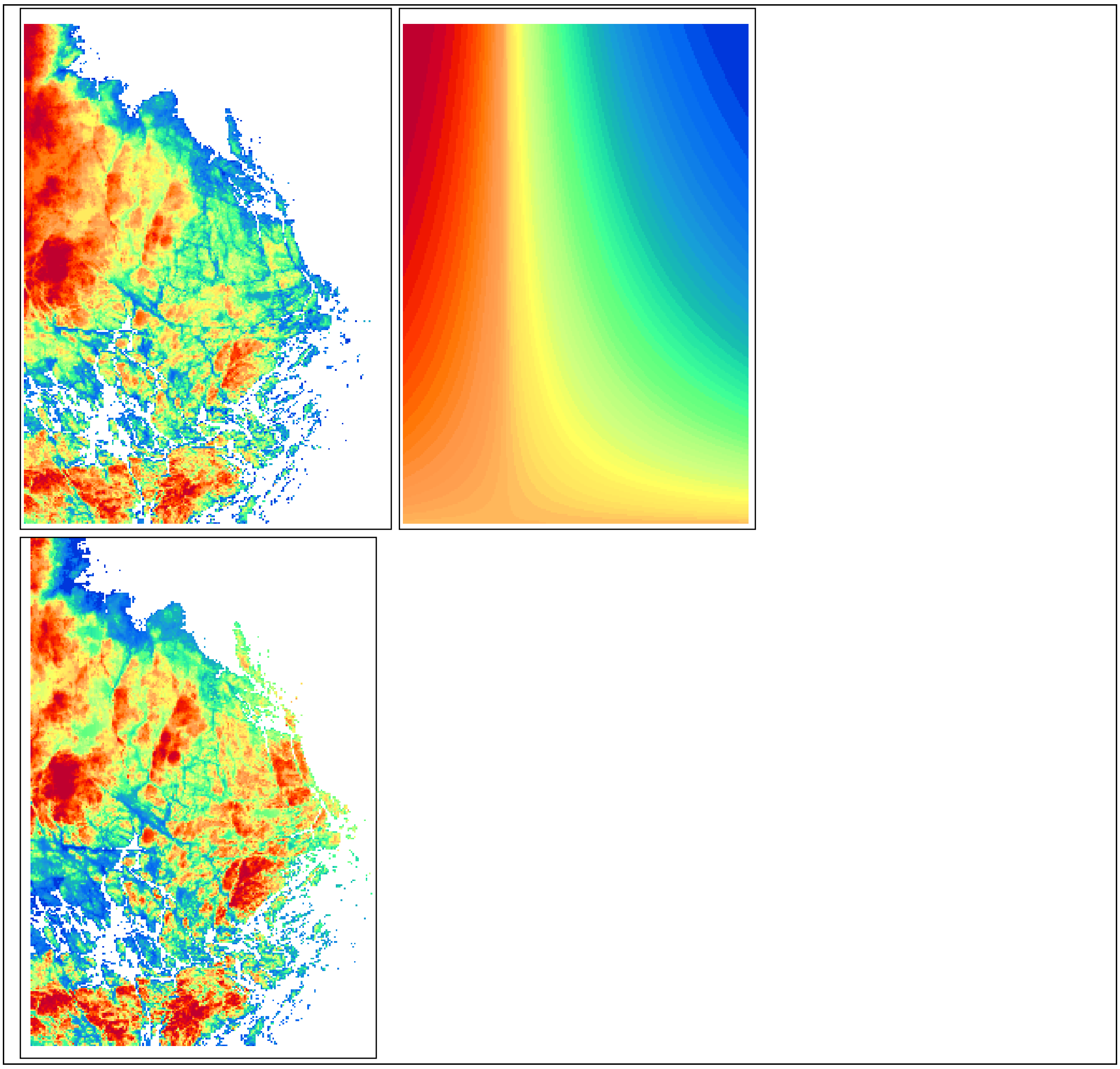


Figure 38. Compilation of elevation data, for the five sets of polygons within the Regional Laxemar area, successively larger rock blocks from local to regional scale, 10m grid. Relative colours cf. Fig. 36. a) Mean values, b) Range values, c) Minimum values, d) Maximum values.



a b c

Figure 39. Removal of the regional gradient, 500m grid of Uppland, a) Original data, b) Polynomial regression trend (2nd order), and c) Residual data.

The creation of trend data needs to incorporate the entire data set in order to take into account local rock-block characteristics. A polynomial regression algorithm was therefore considered. The polynomial regression gridding technique creates a grid which will try to fit to the equation

$$f(x,y) = A + Bx + Cy + Cx^2 + Dxy + Ey^2 + Fx^3 + Gx^2y + Gy^2x + Hy^3 + \ldots\ldots$$

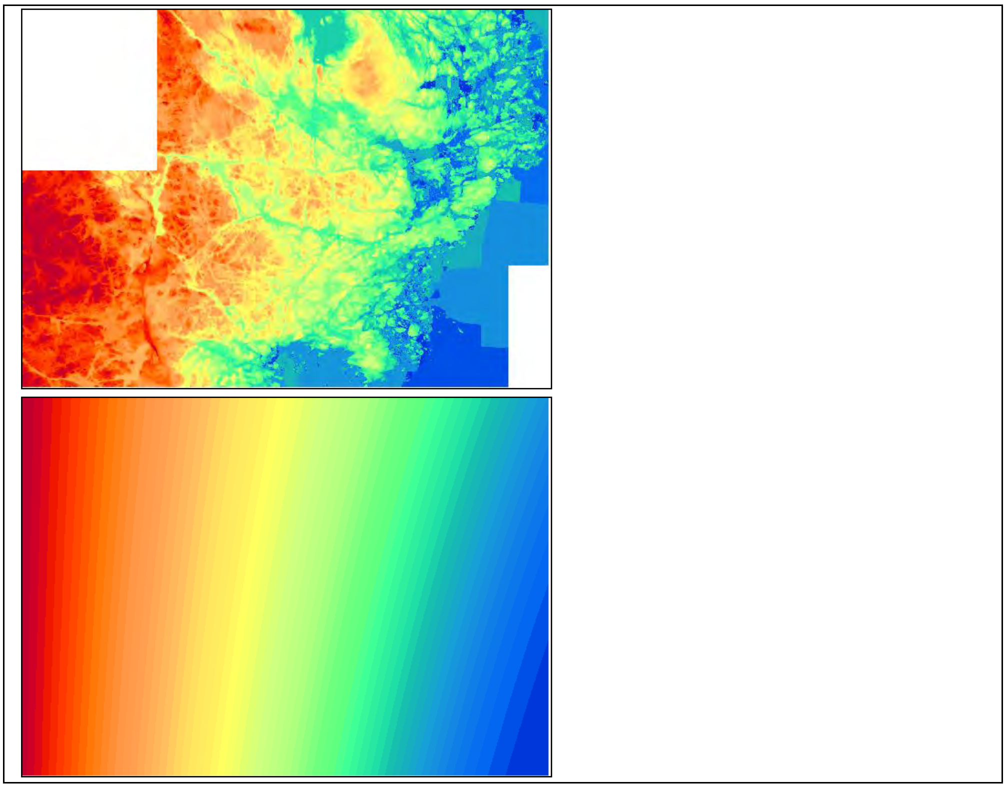
where the maximum power of the x and y coefficients can be chosen to adapt the data to a surface ranging from a simple planar surface to a user-defined surface of a higher power (Help tutorial Surfer 8.0 Golden Software 2006).

6.1.1 Workflow

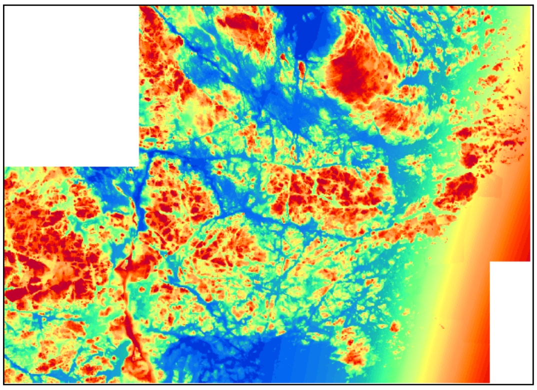
To be processed and fully displayed, the data had to be converted into Surfer and Geosoft/Oasis grid format. Polynomial regression gridding was performed using the Surfer software (Golden software 8.0) and a trend grid was created. The final residual grid was achieved by subtracting the trend grid from the original data set to obtain a residual data grid. The residual grid was eventually converted back to the ArcGIS environment to be used for further analysis.

Special care has to be taken through the conversion process between various grid formats. The ArcGIS Grid format differs from, e.g. the Surfer Grid format in terms of how a single pixel is spatially registered. An offset of half a pixel‟s size can be the result of such a conversion which needs to be corrected for.

Examples from the polynomial regression trend filtering are given in Fig. 39 and 40. The morphology of the Uppland 500m digital elevation grid exhibits a different trend direction in the northern part as compared to the southern part. This is obvious in the polynomial regression trend (Fig. 39a). The Laxemar 10m grid shows a simpler trend (Fig. 40).



a b



c

Figure 40. Removal of the regional gradient 10m grid of Laxemar, a) Original data, b) Polynomial regression trend (2nd order), and c) Residual data.

The original data sets and the residuals are shown in Fig. 41, Uppland, and Fig. 42, eastern Småland. The six sets of “gradient-removed” data were then analysed in the same way as were the original true elevation data.

6.2 Uppland - Removed Gradient

The higher mean altitude values for the calculated 500m data have a more scattered appearance than the true elevation data (Fig. 43, cf. Figs. 29 and 41, upper row); the dense concentration of higher rock blocks in the northeast is replaced by a vaguer alignment of high blocks north of the Örsundsbro line. The western part of the Mälaren basin is more obviously a lowland and the rectangle of northeast Stockholm also stands out in higher relief. The high minimum values remain while the low values along the coast are consistently elevated. The maximum values do not show any significant change; the northeast is consistently higher and the western Mälaren basin lower. The range, of course, is very similar. With the removal of a north-eastern gradient, the north-western components of structures are enhanced.

Fig. 44 compares the polygon results for the original 50m elevation data with the recalculated 50m base (cf. Fig. 41, middle row). The north-westerly backbone of high ground is enhanced and the polygons, north of Uppsala, have got relatively lower values. The minimum for the river values is more pronounced and the polygons close to the sea elevated. However, for the maximum values this eastern belt does not stand out but shows a rather balanced picture, as do the range values.

In Fig. 45, the recalculated 10m (cf. Figs. 31and 41, lower row) and 50m bases are compared for the Forsmark local polygons. In the mean and minimum values there is a clear north-north-westerly trend with a high-value nucleus in the southwest. In the lower 50m row Gräsö is revealed rather well. The mean, minimum and range values in the sea for the two sets are, however, false since the sea level is considered as the lowest value in the 50m base and close to in the 10m base while we know that water depth reaches 59m at its deepest reading on the sea charts

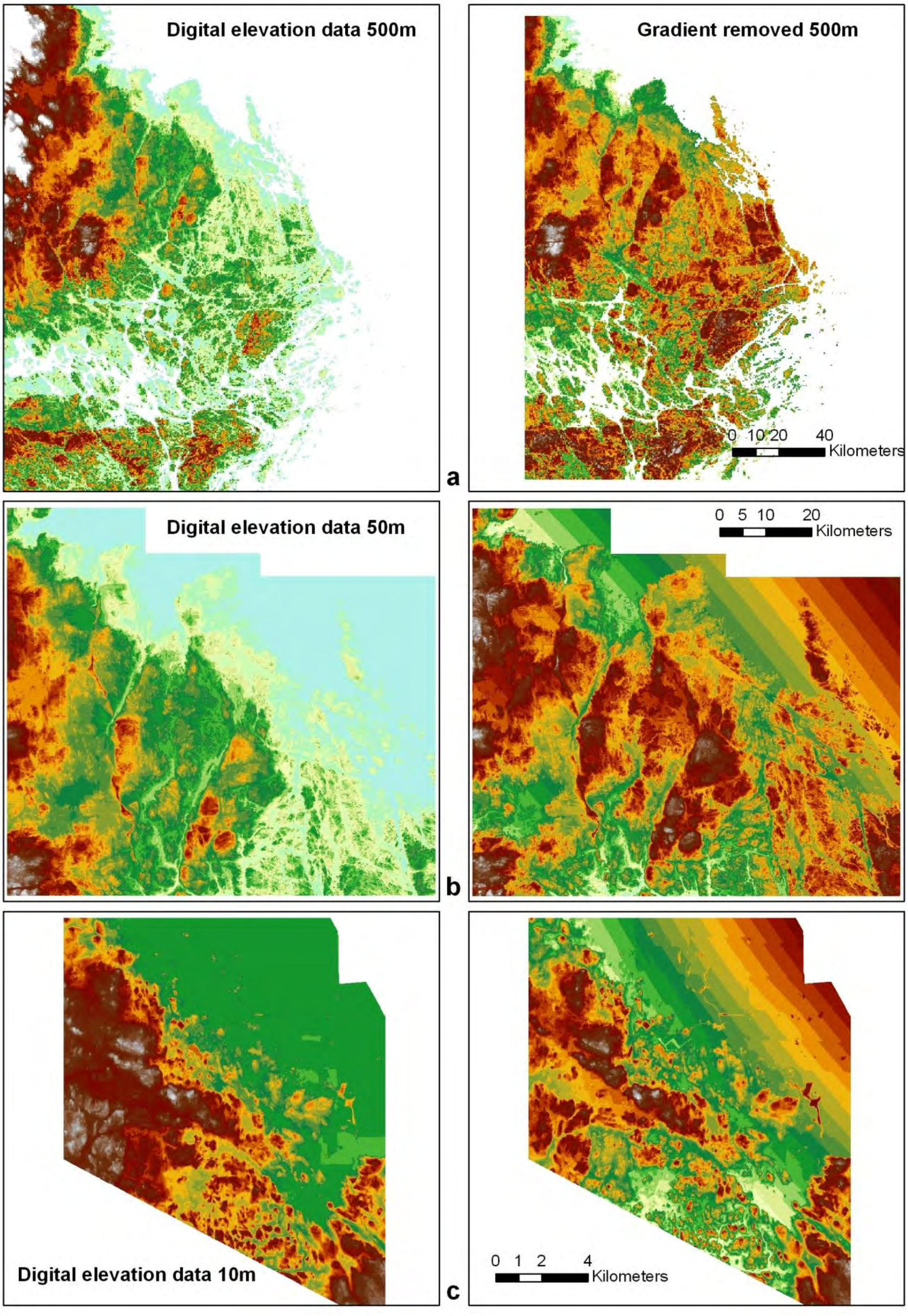


Figure 41. Digital elevation data, Uppland, a) the 500m, b) the 50m, and c) the 10m grids and the corresponding processed data sets after the removal of an estimated topographic gradient.

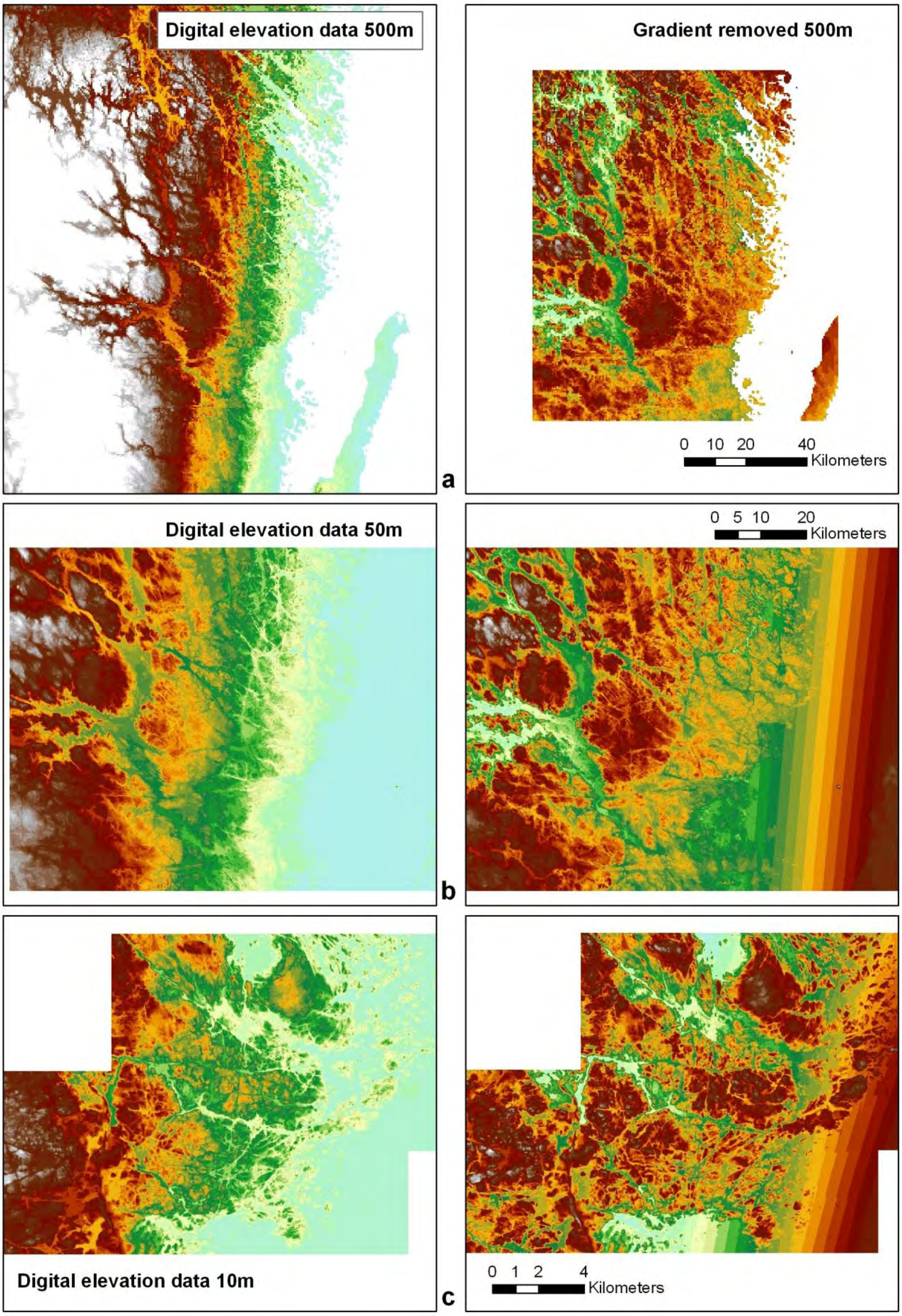


Figure 42. Digital elevation data, Småland, a) the 500m, b) the 50m, and c) the 10m grids and the corresponding processed data sets after the removal of an estimated topographic gradient.

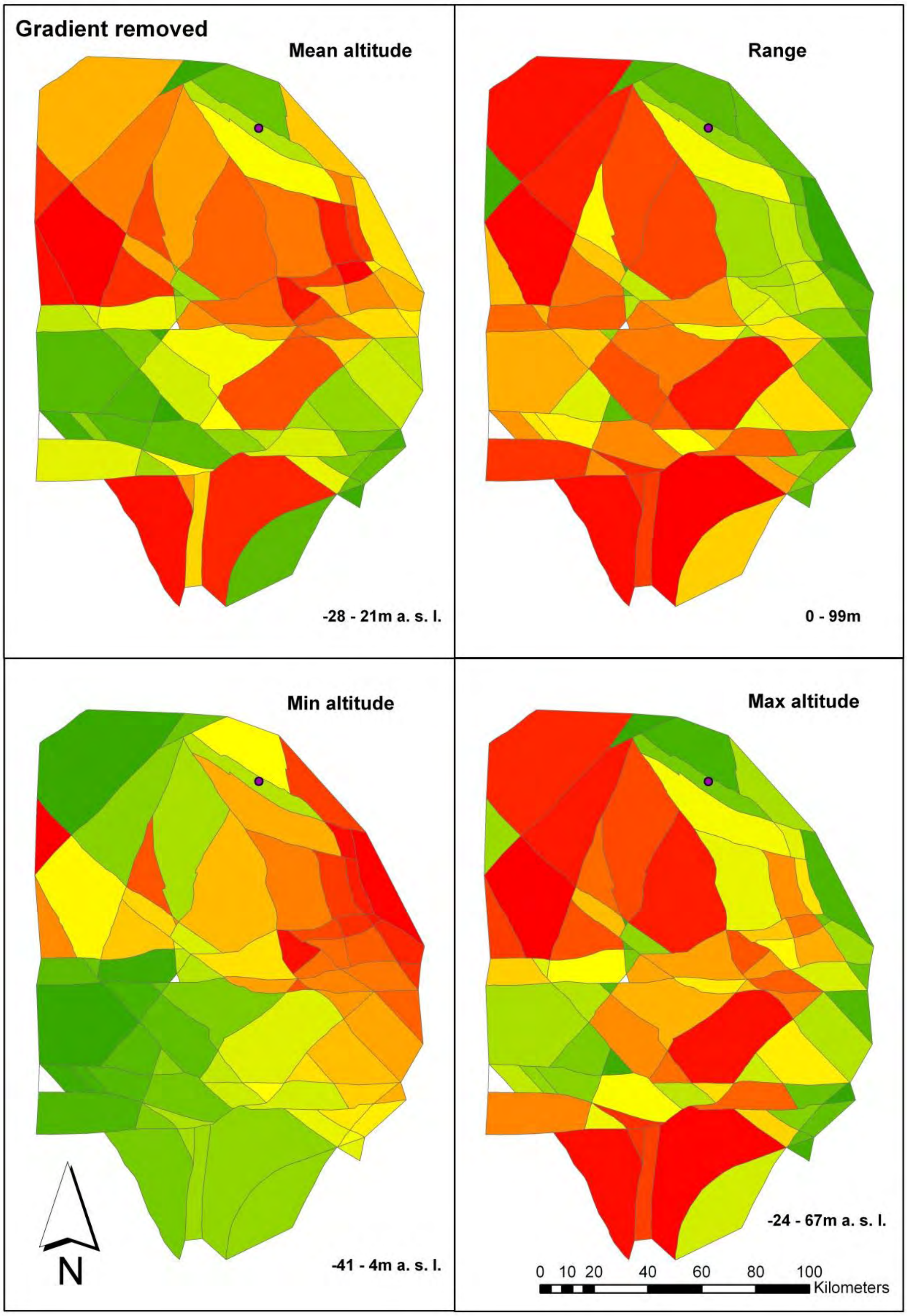


Figure 43. Polygons in Uppland – Regional Forsmark area, topographic gradient removed. Mean altitude, range, minimum and maximum values for the regional rock blocks based on a 500m grid. The colour palette has different values for each set of polygons. The span is given in metres for each map. Violet dot = the Forsmark SKB site.

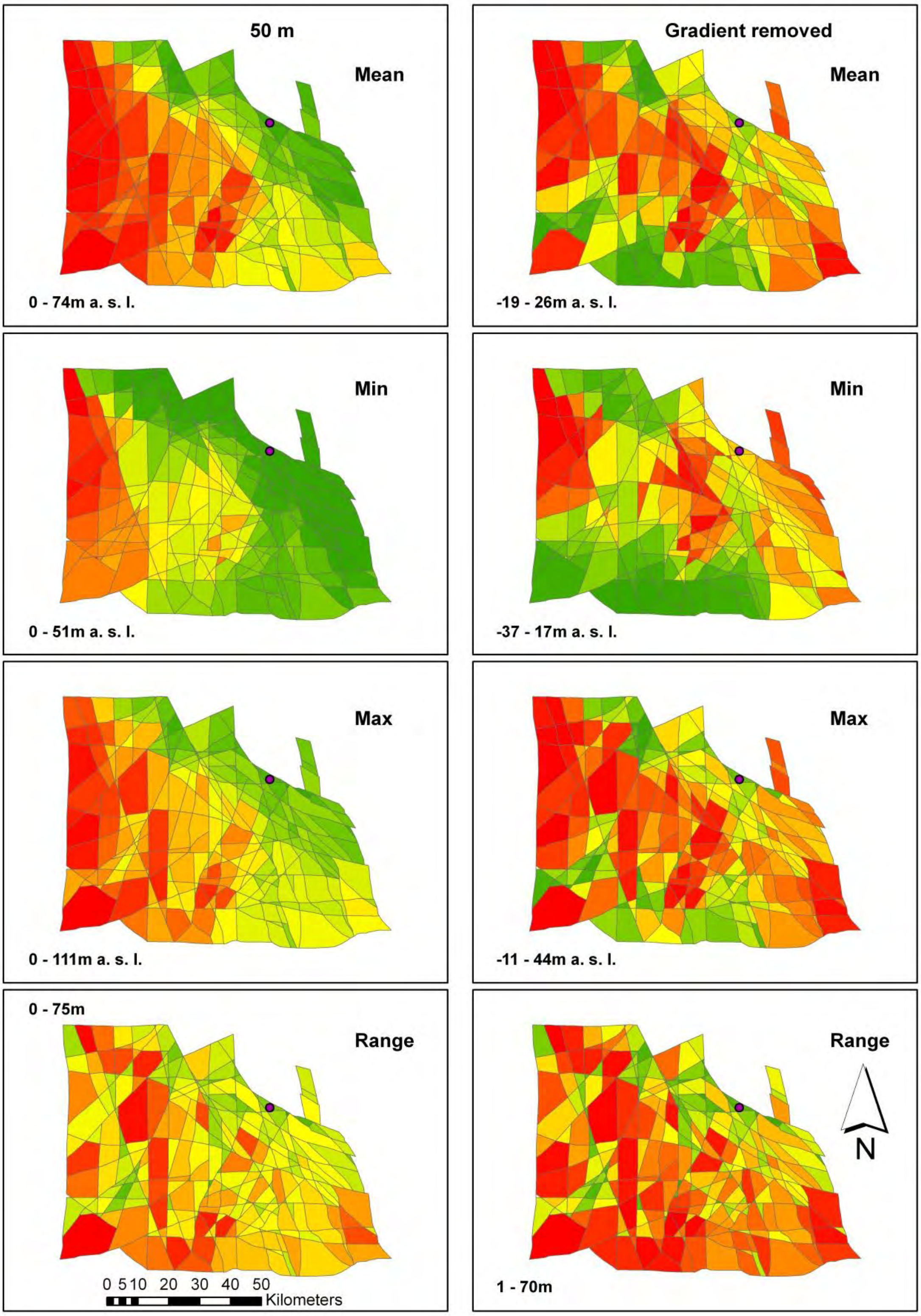


Figure 44. Polygons in Northern Uppland – Semi-Regional Forsmark area. Mean altitude, minimum, maximum and range values for the semi-regional rock blocks, true elevation data and the topographic gradient removed based on 50m grids. The colour palette has different values for each set of polygons. The span is given in metres for each map. Violet dot = the Forsmark SKB site.

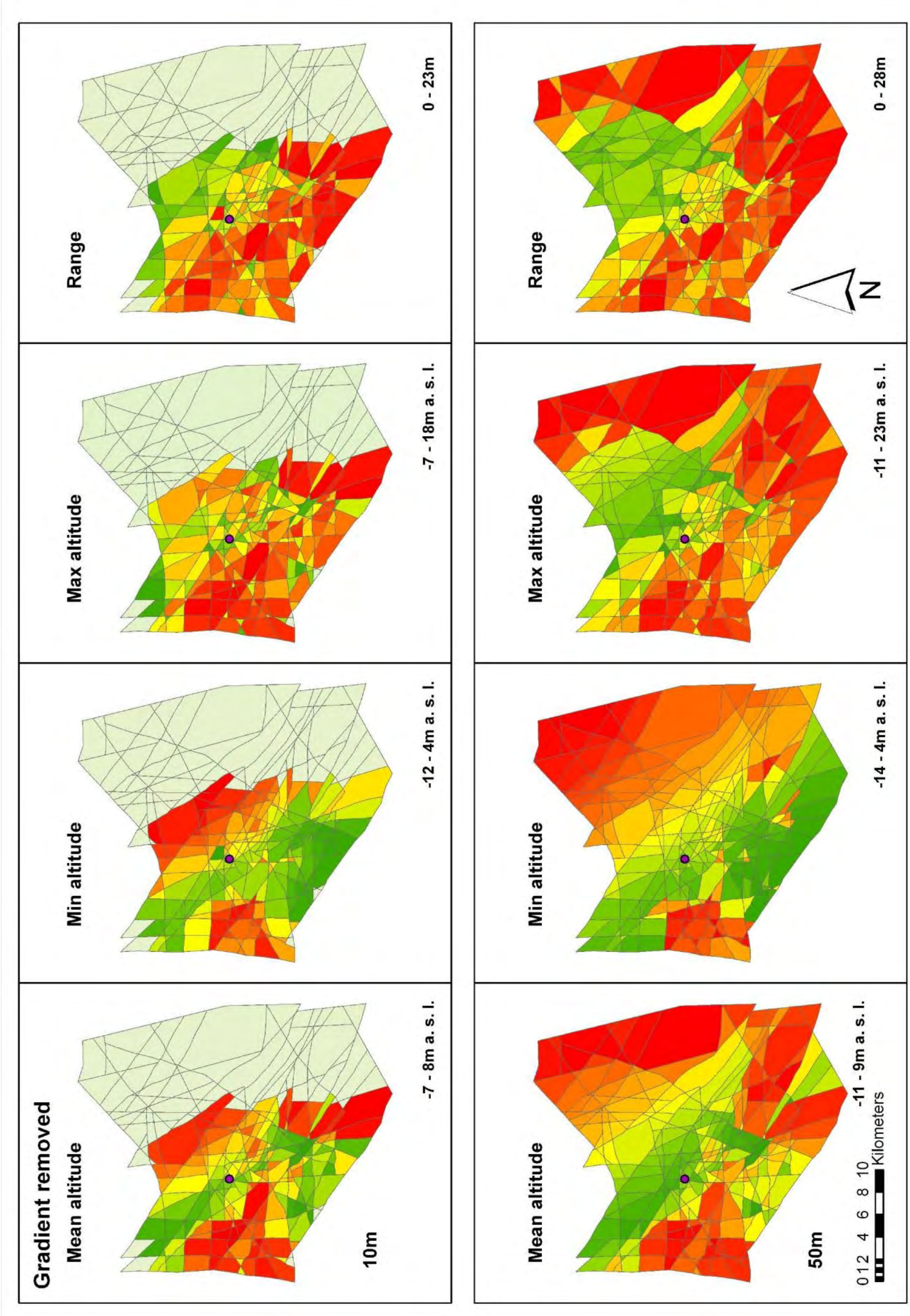


Figure 45. Polygons in the Local Forsmark area, topographic gradient removed. Mean altitude minimum, maximum and range values for the local rock blocks based on 10m and 50m grids. The colour palette has different values for each set of polygons. The span is given in metres for each map. Violet dot = the Forsmark SKB site.

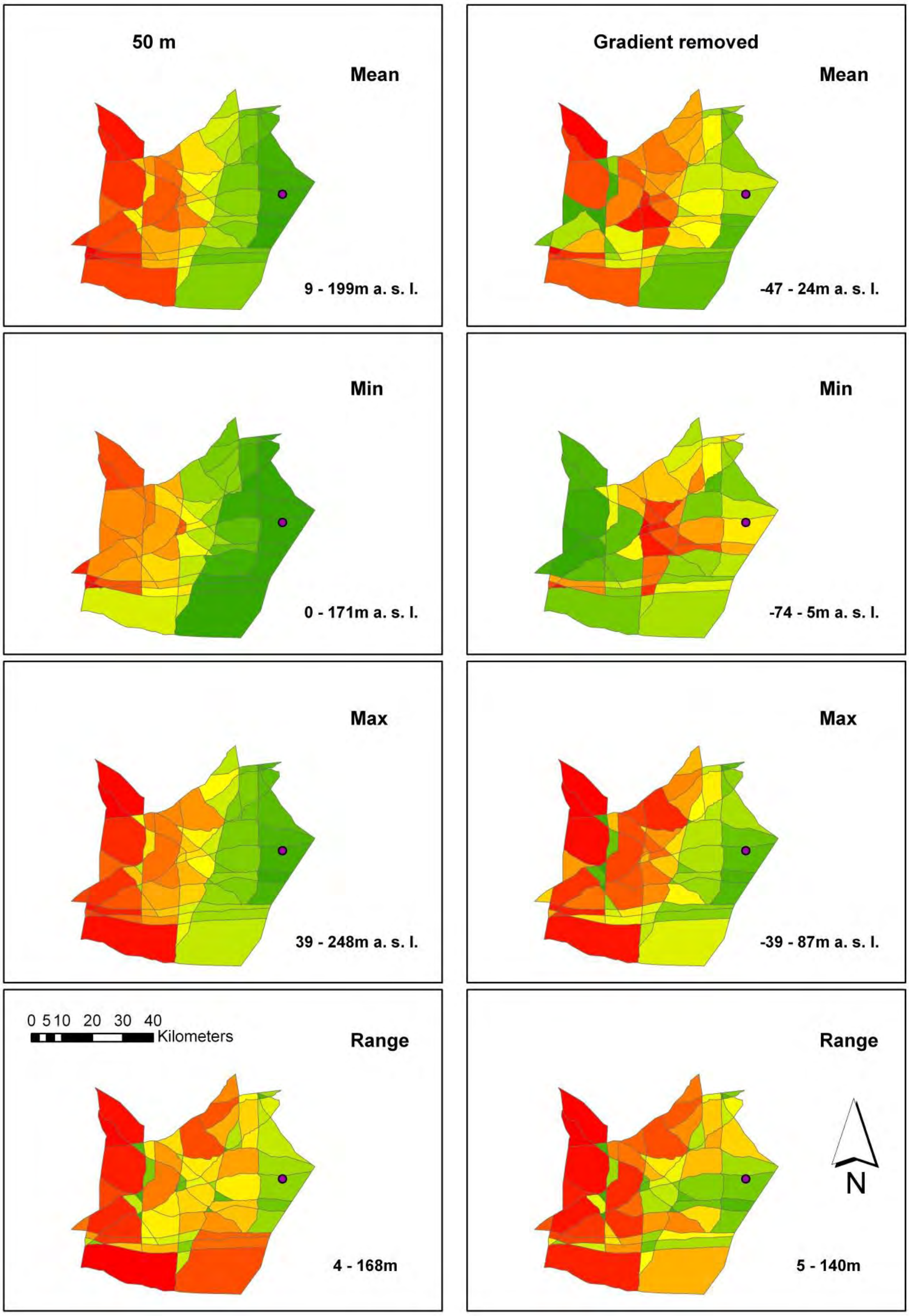


Figure 46. Polygons in eastern Småland - Regional Laxemar area. Mean altitude, minimum, maximum and range values for the largest regional rock blocks, true elevation data and the topographic gradient removed based on 50m grids. The colour palette has different values for each set of polygons. The span is given in metres for each map. Violet dot = the Laxemar SKB site.

6.3 Småland – Removed Gradient

With the pronounced gradient in eastern Småland removed the residual elevation gives a more varied picture in *the regional area* (Figs. 46-48, cf. Fig. 42, upper and middle rows). The coastal areas are still the lowest but several interesting features appear. The inland valley is more or less visible on all images. The south and north-western corner are high on all maps except the minimum values, along with parts (but not always the same polygons) of the lath in between the inner valley and the coast.

The minimum values for the western areas are distinctly low showing that these areas have been eroded to a relatively deeper level than the coastal areas. The maximum and range values pertain much of the earlier picture form the original values, while the mean values give low values in the inner valley and an emerging prominent west-northwest valley joining it in its southern part. Especially for the interpretation of smallest-regional-rock-blocks higher values occur in near shore areas.

For the *Semi-Regional area* (Fig. 49, cf. Fig. 42, middle row) the removal of the gradient all occurs within an east-sloping terrain. The mean values for the easternmost polygons achieve high values as do the ones along the western borderline. The central part, in general, has higher values to the south than further to the north(east) but for some outstanding exceptions. The minimum values have high values in the east and also reveal a higher nucleus in the central area widening westwards; low areas surrounding in the northwest, north and south. The maximum values show a more scattered picture but generally reproduce the low east and high west from the original values. Small green triangles define the rock-block boundaries of larger rock blocks. Finally, the range values show high values in the north, west and south with lower values in the south-centre, along a north-south structure and in small triangles in major structures, and close to the sea in the very east. The area with low range values in the south-centre has high minimum values.

For the *local Laxemar area* the removal of the gradient (Fig. 50, cf. Fig. 42, lower row) yields a varied picture for the mean and maximum values with red and green blocks alternating. The minimum values give low values especially in the central corridor bound by major north-south structures. High values are created along the coast and the very west. The range values get higher towards the west, the low values occurring close to the sea in the northeast and southeast and in triangular-rectangular odd blocks further west. The polygons containing the Laxemar and Simpevarp-(Ävrö) areas stand out as highs on all maps, as does the block between the sea and Lake Götemaren but for its minimum value.

To facilitate the comparison between rock blocks of different scale Fig. 51 and 52 were compiled.

7 COMPARISON WITH BEDROCK & EARTHQUAKE DATA

After completion of the polygon study the polygon lines were compared to the Fennoscandian Shield Map (2001), and the position of earthquake epicentre data (SNSN, Helsinki Catalogue) were put on top (cf. Figs. 56 and 57).

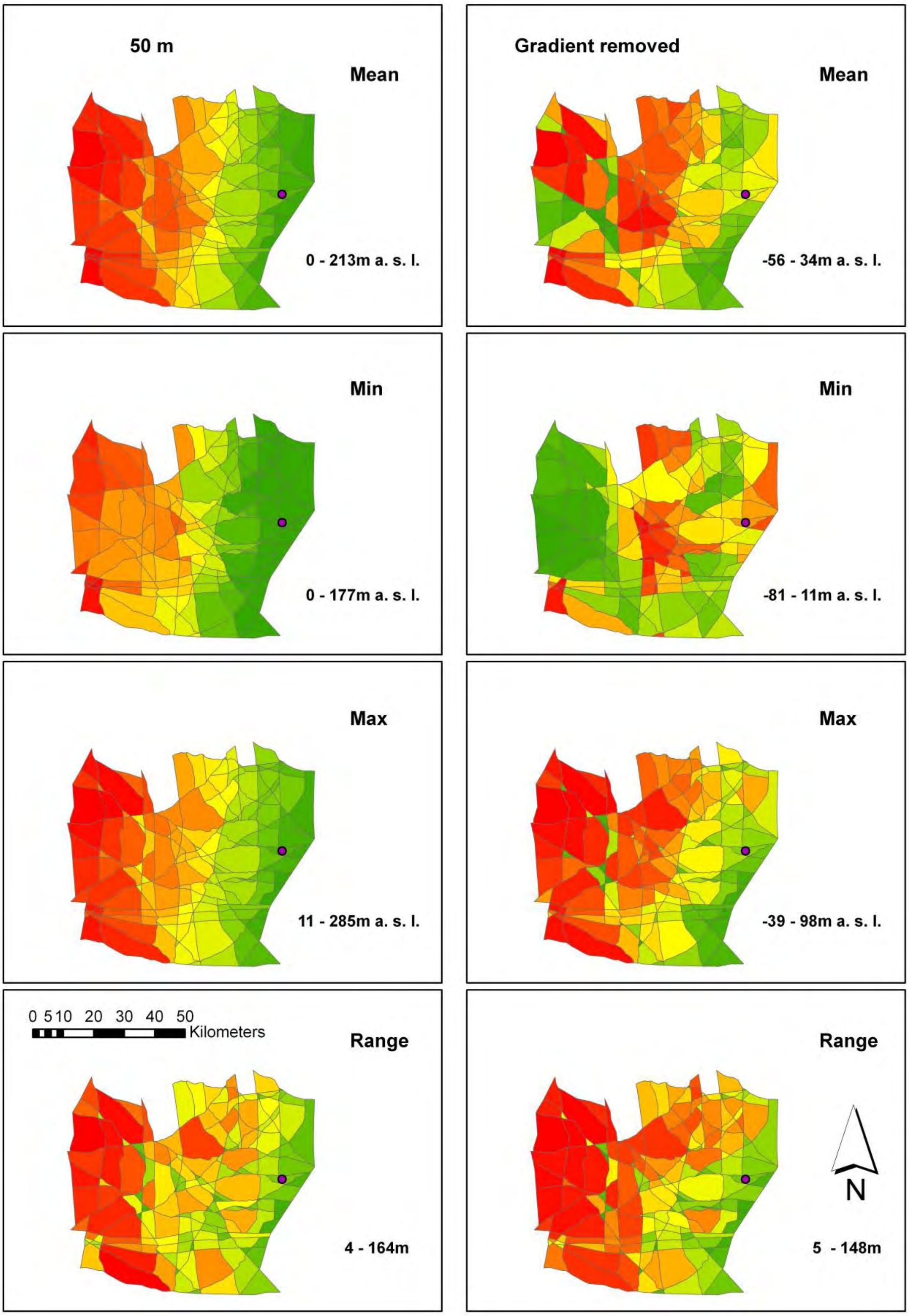


Figure 47. Polygons in eastern Småland - Regional Laxemar area. Mean altitude, minimum, maximum and range values for the second largest regional rock blocks, true elevation data and the topographic gradient removed based on 50m grids. The colour palette has different values for each set of polygons. The span is given in metres for each map. Violet dot = the Laxemar SKB site.

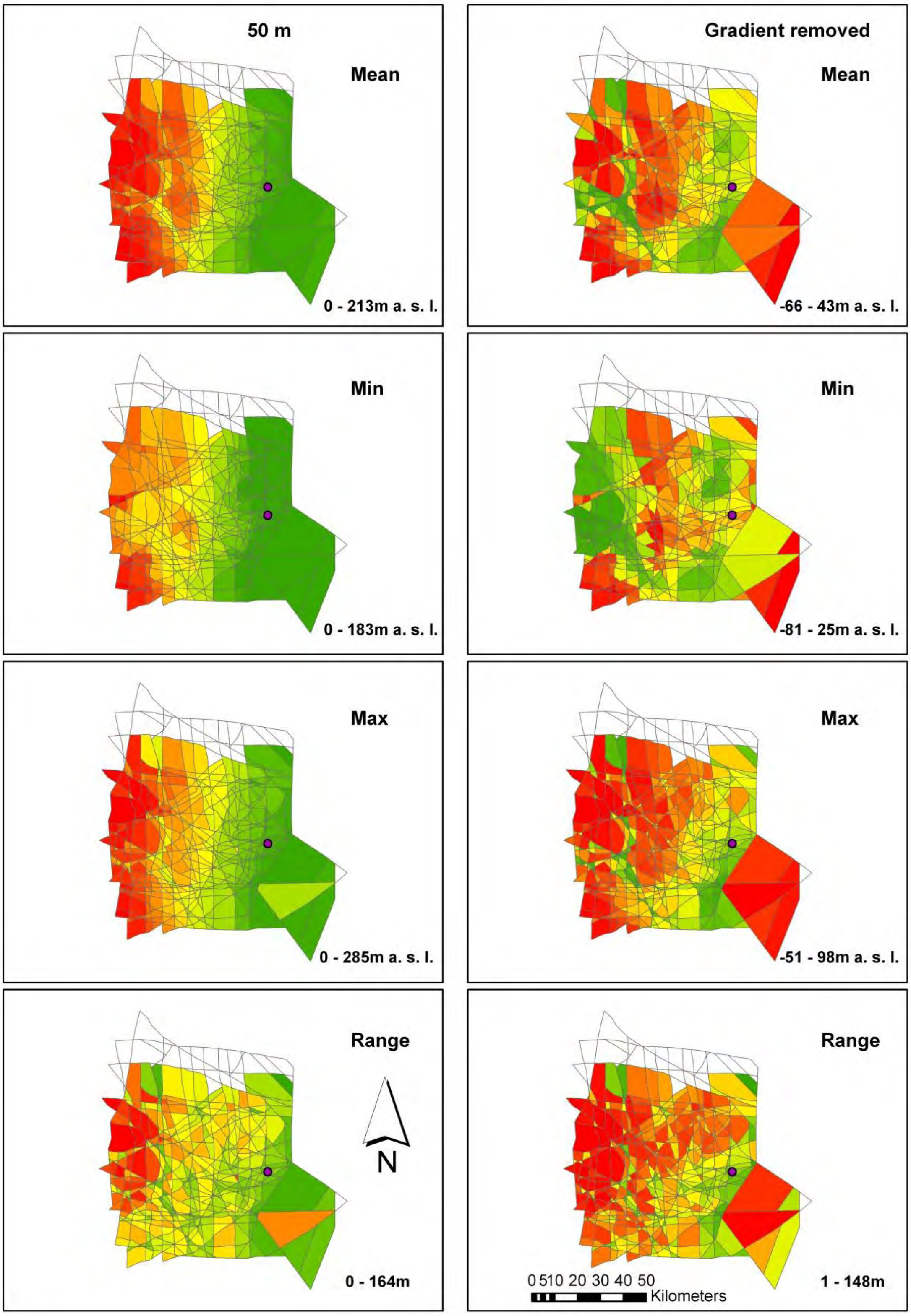


Figure 48. Polygons in eastern Småland - Regional Laxemar area. Mean altitude, minimum, maximum and range values for the regional rock blocks, true elevation data and the topographic gradient removed based on 50m grids. The colour palette has different values for each set of polygons. The span is given in metres for each map. Violet dot = the Laxemar SKB site.

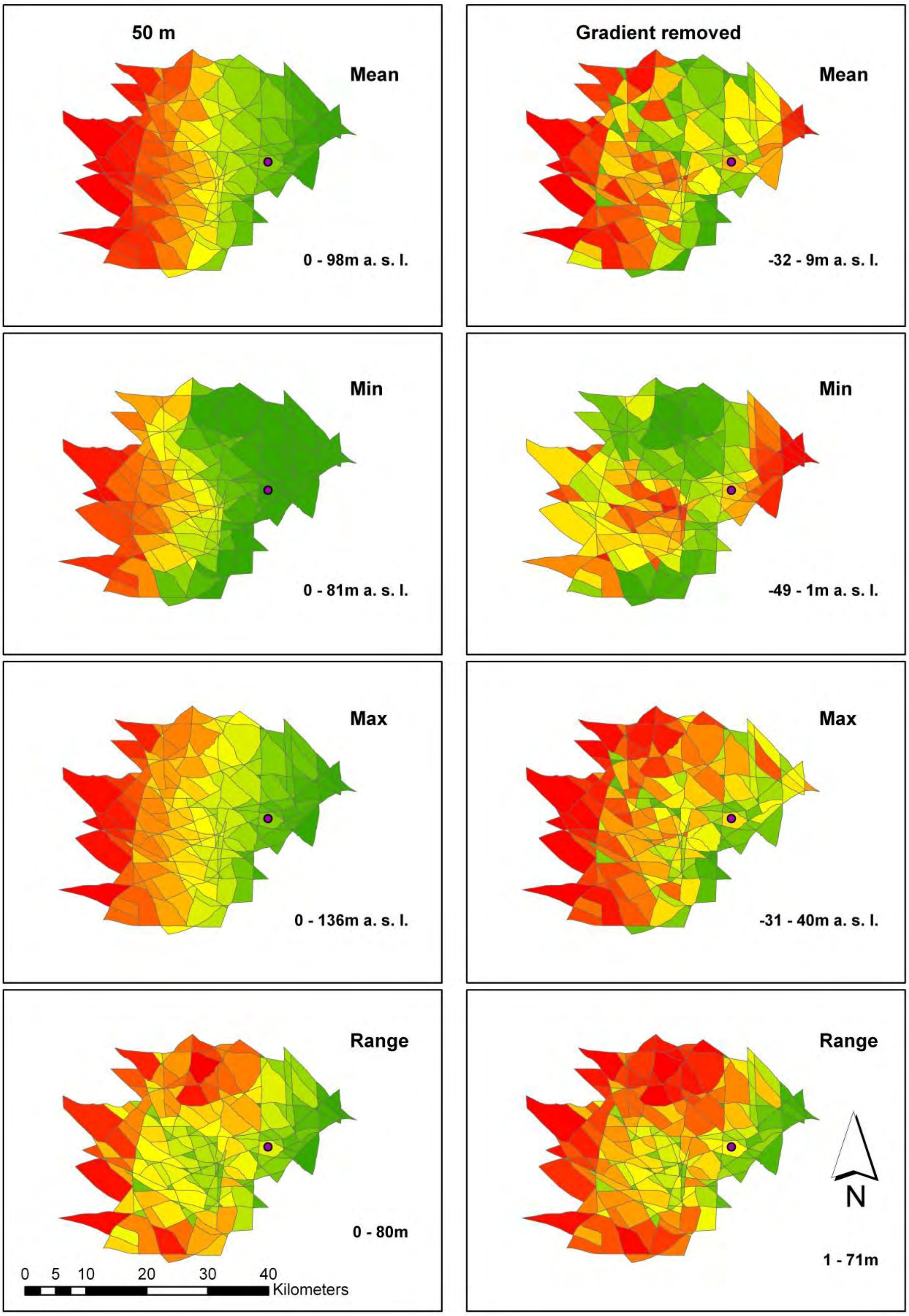


Figure 49. Polygons in eastern Småland – Semi-Regional Laxemar area. Mean altitude, minimum, maximum and range values for the semi-regional rock blocks, true elevation data and the topographic gradient removed based on 50m grids. The colour palette has different values for each set of polygons. The span is given in metres for each map. Violet dot = the Laxemar SKB site.

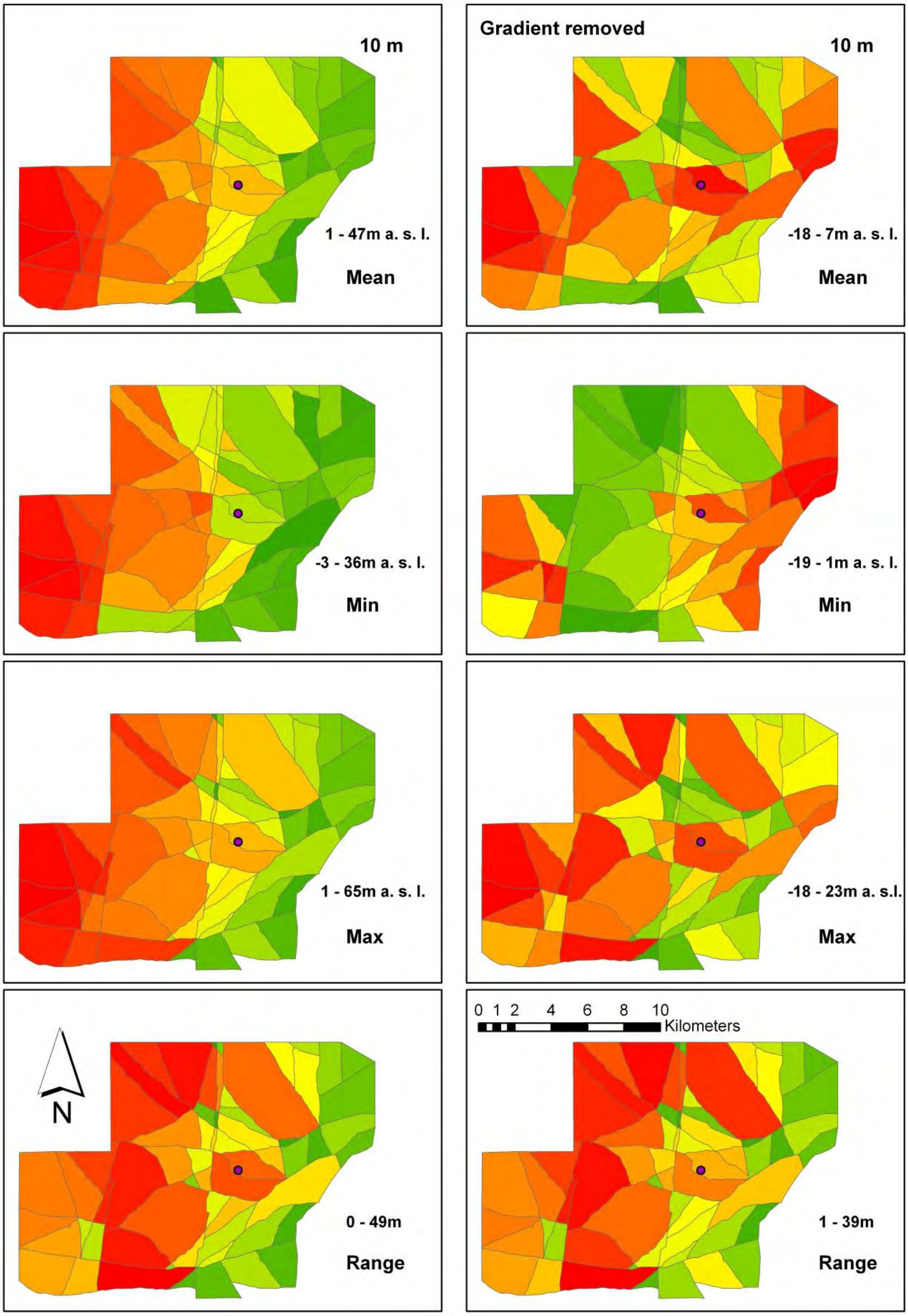


Figure 50. Polygons in the Local Laxemar area. Mean altitude, minimum, maximum and range values for the semi-regional rock blocks, true elevation data and the topographic gradient removed based on 10m grids. The colour palette has different values for each set of polygons. The span is given in metres for each map. Violet dot = the Laxemar SKB site.

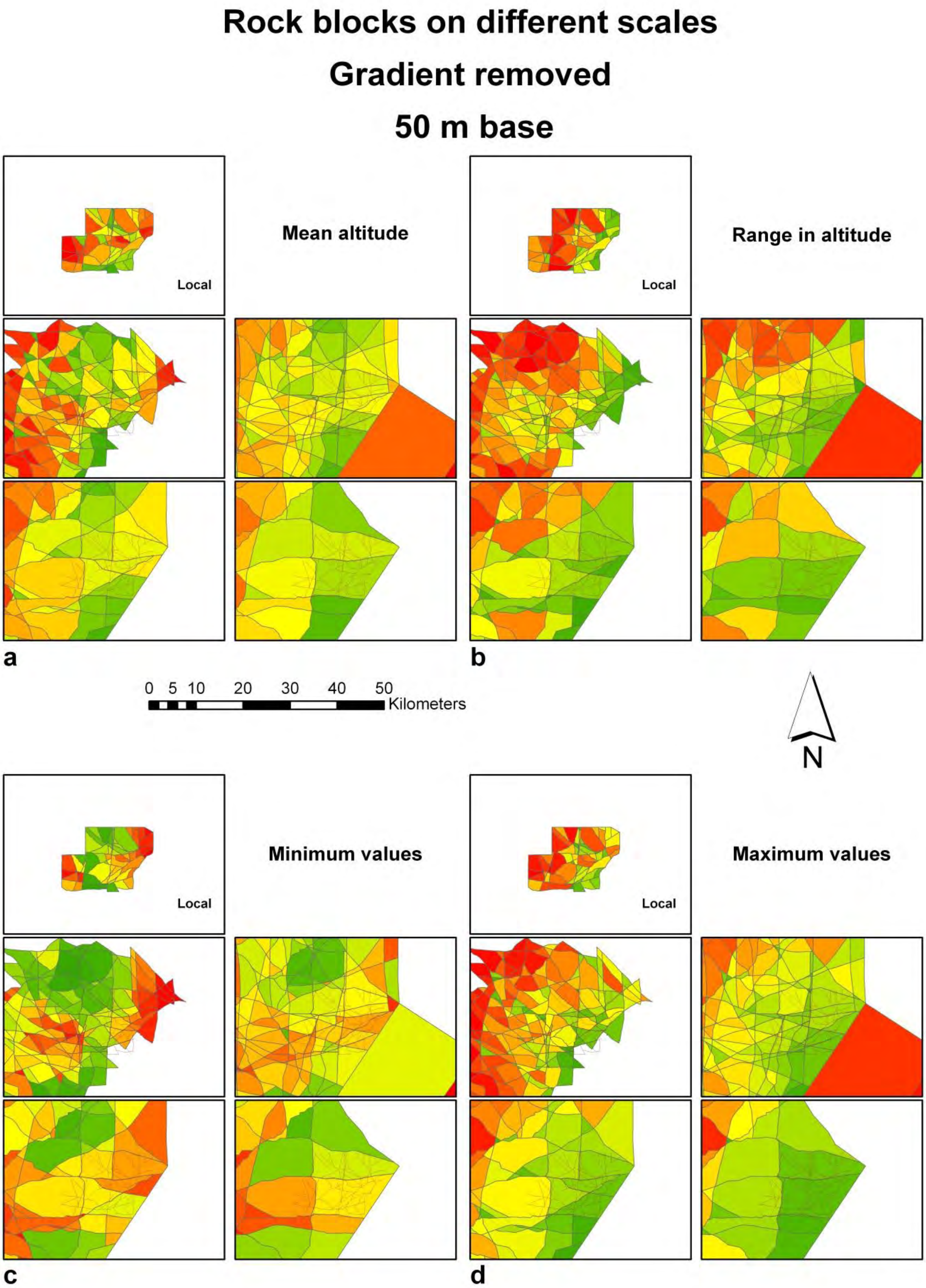


Figure 51. Compilation of the elevation data – gradient removed, mean values for the five sets of polygons in the Regional Laxemar area, 50m grid. Relative colours cf. Figs. 46-49. a) mean values, b) range values, c) minimum values, d) maximum values.

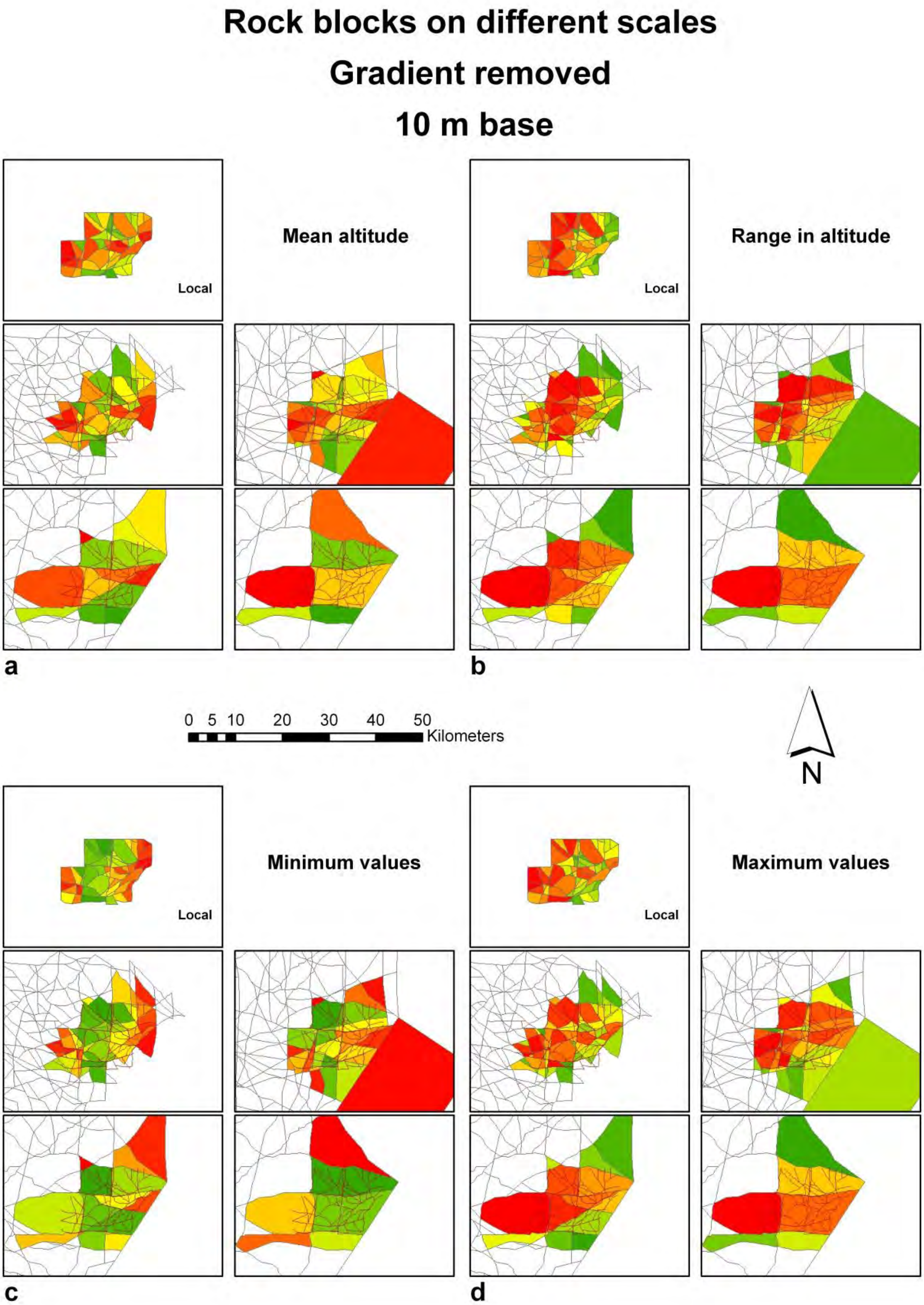


Figure 52. Compilation of the elevation data – gradient removed, minimum values for the five sets of polygons in the Regional Laxemar area, 50m grid. Relative colours cf. Fig. 50. a) mean values, b) range values, c) minimum values, d) maximum values.

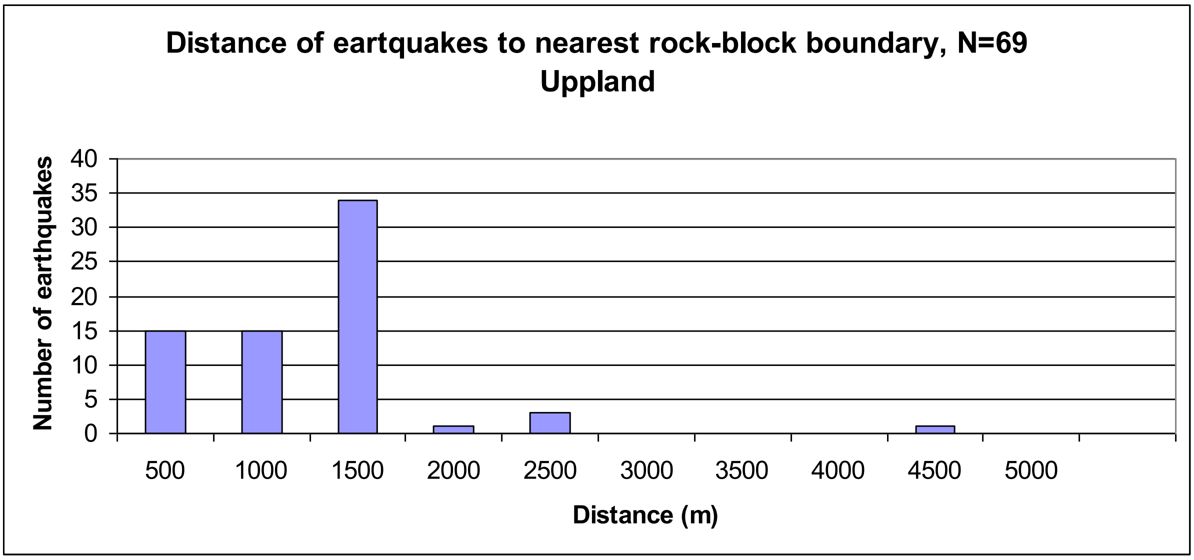


Figure 53. Distance between 69 recorded earthquakes and the closest rock-block boundary in Uppland.

The polygons were created from digital elevation data and were not compared to the geological map or the earthquake data until after the analyses of the relative elevation of rock blocks were made. Nevertheless there is very good agreement between the rock-block interpretations and the geological bedrock map which clearly indicates that the interpretations as well as earthquake activity reflect structures in the bedrock.

7.1 Earthquakes

The location of epicentres in the figures are the surface projections of the seismic events. Note that if a seismic event occurs at 5km depth on a surface (rock-block boundary) with a dip of 70°, the epicentre will be c. 2km away from the surface expression of the rock-block boundary.

To elucidate the relationship between rock-block boundaries and earthquake epicentres, 69 seismic events recorded within a rectangular area (100 000 x 75 000m; RAK coordinates 1565000-1655000, 665000-6725000) covering Uppland were analysed for their distance to a rock-block boundary (Fig. 53). Of these events 87% are located within a distance of one and a half kilometre from a rock-block boundary.

In the series of registered seismic events there are two clusters that stand out at Finnsjön and Dannemora. Finnsjön is a former SKB site and the twelve events from 1981 occurred at the same time as reflection seismic profiling was performed in that area. Dannemora is a relatively deep mine and thirty (out of 69) events occurred here during 1981 and 1982. When the earthquakes at these locations are subtracted from the bulk of events, there is a clear relationship between the location of earthquake epicentres and structures outlining rock-block boundaries; about 50 percent of all natural earthquakes are located closer than 400m from a regional structure in Uppland (Fig. 54).

In eastern Småland within a similar rectangle (82 000 x 70 800m; RAK coordinates 1483500-1565500, 6350000-6420800) 14 events have occurred (Fig. 55). Thirty percent of these earthquakes are located closer to a block boundary than 100m and 71 % closer than 1km.

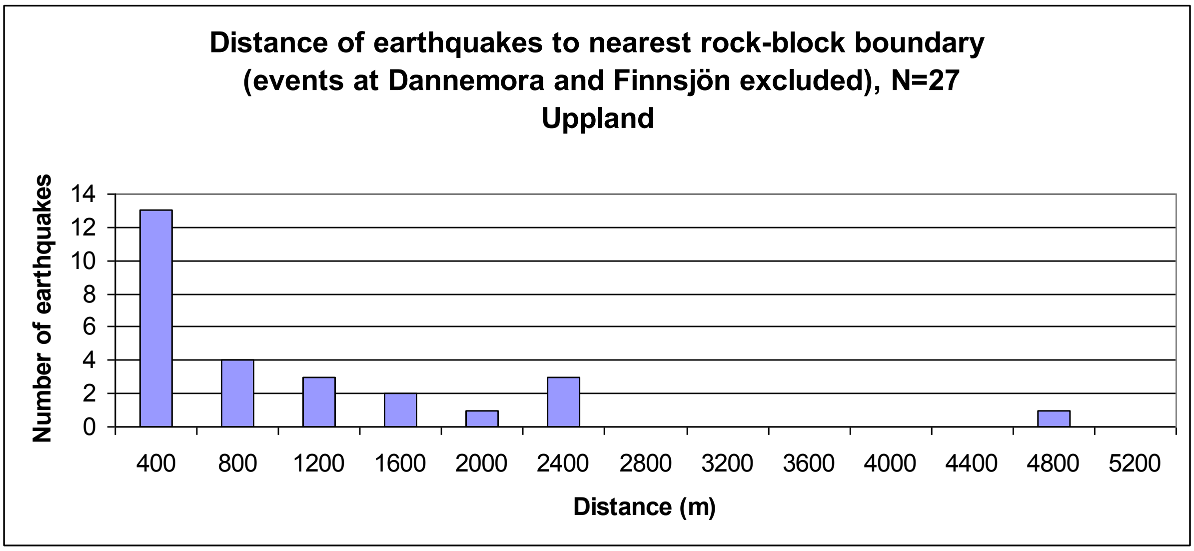


Figure 54. Distance between 27 recorded natural earthquakes and the closest rock-block boundary in Uppland. 12 events at Finnsjön and 30 at Dannemora have been excluded.

For magnitude estimates of the earthquakes cf. Fig. 9 and 12.

7.2 Uppland

The metasedimentary rocks (blue on Fig. 56) are confined almost completely to the south of the Örsundsbro line. Also granites (red and brown) are often bounded by major structures while volcanites (yellow) both occur within certain blocks and along major structures.

The regional Forsmark area has an average uplift of 6mm/year (SKB 2005, p. 100). It has a low earthquake frequency but, yet, it is higher than in south-eastern Sweden. The greatest earthquake magnitude registered during the last three hundred years is M3.7 (1990, south of Heby, Catalogue of earthquakes in Northern Europe since 1375).

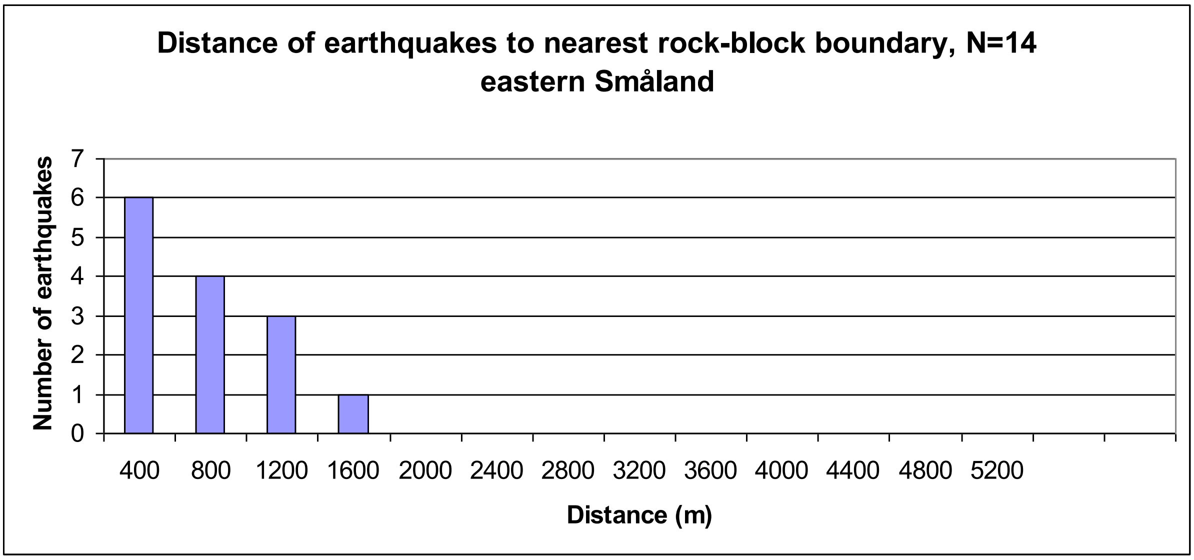


Figure 55. Distance between 14 recorded natural earthquakes and the closest rock-block boundary in eastern Småland.

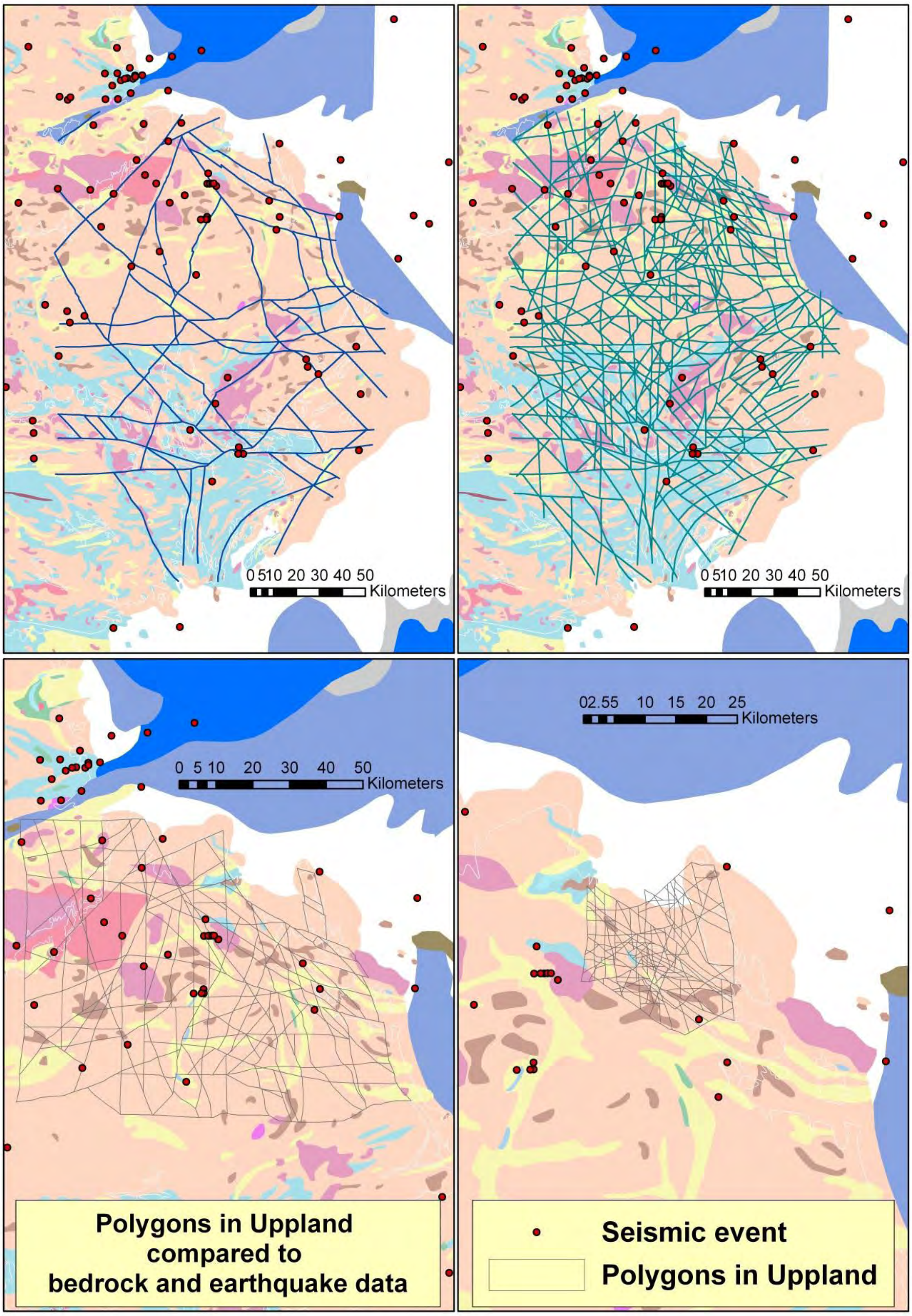


Figure 56. The different sets of polygons in Uppland compared to the bedrock lithologies of the Swedish part of the Fennoscandian Shield map (2001), and earthquake data from (SNSN) and the Helsinki Catalogue of earthquakes in Northern Europe since 1375.

The distribution pattern of earthquake epicentres shows distinct features:

a. Most epicentres are located on block boundaries while slightly fewer are located close to block boundaries and few are located inside rock blocks.

b. There is an absence of earthquake registrations in an up to 60km wide northeast-southwest trending belt across Uppland which coincides with topographically low areas; from western and central Mälaren and north-eastwards towards Åland.

The range in earthquake magnitude northwest of this belt has a large spread with lower magnitudes as compared to the area to the southeast where the earthquake magnitude is generally higher and more uniform (M2.0-3.1). The frequency of earthquakes is higher in the northwest than in the southeast. The structural pattern in the "non-seismic" belt is not uniform; Mälaren, located along the northern side of the east-west trending Sörmland horst, is characterized by a regular large-scale pattern outlined by northwest trending fractures, while the north-eastward continuation of the belt is more dominated by the northerly grain.

In north-eastern Uppland, earthquakes appear along block boundaries with a north-westerly trend while in the central and western parts they occur, preferentially, along north-south block boundaries and, sub-dominantly, along north-east boundaries.

Time sequences of separate series of seismic events indicate movements along specific structures, e.g. along lineaments oriented north-south (west of Åland) and east-northeast (at Gävlebukten). These are faults that demarcate down-faulted blocks with Jotnian sandstones (Fig. 56) that constitute topographically low blocks also today.

In the vicinity of Forsmark, according to SNSN data, an event of magnitude 0.54 occurred in 2004, 16km southeast of Forsmark just north of Östhammar, and in the same structural belt, c. 9km further south between Östhammar and Hargshamn, a 1.90 event occurred in 2000, and a 1.30 event in 1982 at Hargshamn. In 2002, a -0.35 event occurred 20km northeast of Forsmark just east of northern Gräsö.

In the Forsmark local area, the maximum horizontal stress (σ_H) has a north-westerly trend, sub parallel to ridge-push and regional deformation zones (SKB 2005, p. 292).

The earthquake epicentres show a clear correlation with the rock block pattern and lithological boundaries. Correlation may be even better if depth to hypocentra and dip of faults were taken into consideration. Interesting is, that some of the points not lying in direct contact with the interpreted lines lie in the prolongation of a line, an indication of that a structure is not fully appropriate for non-seismic slip.

7.3 Småland

Interpreted structures often conform to lithological boundaries (Fig. 57). The Oskarshamn lines agree well as do the major northwest-trending and other east-west structures. Northeast structures often delineate different domains.

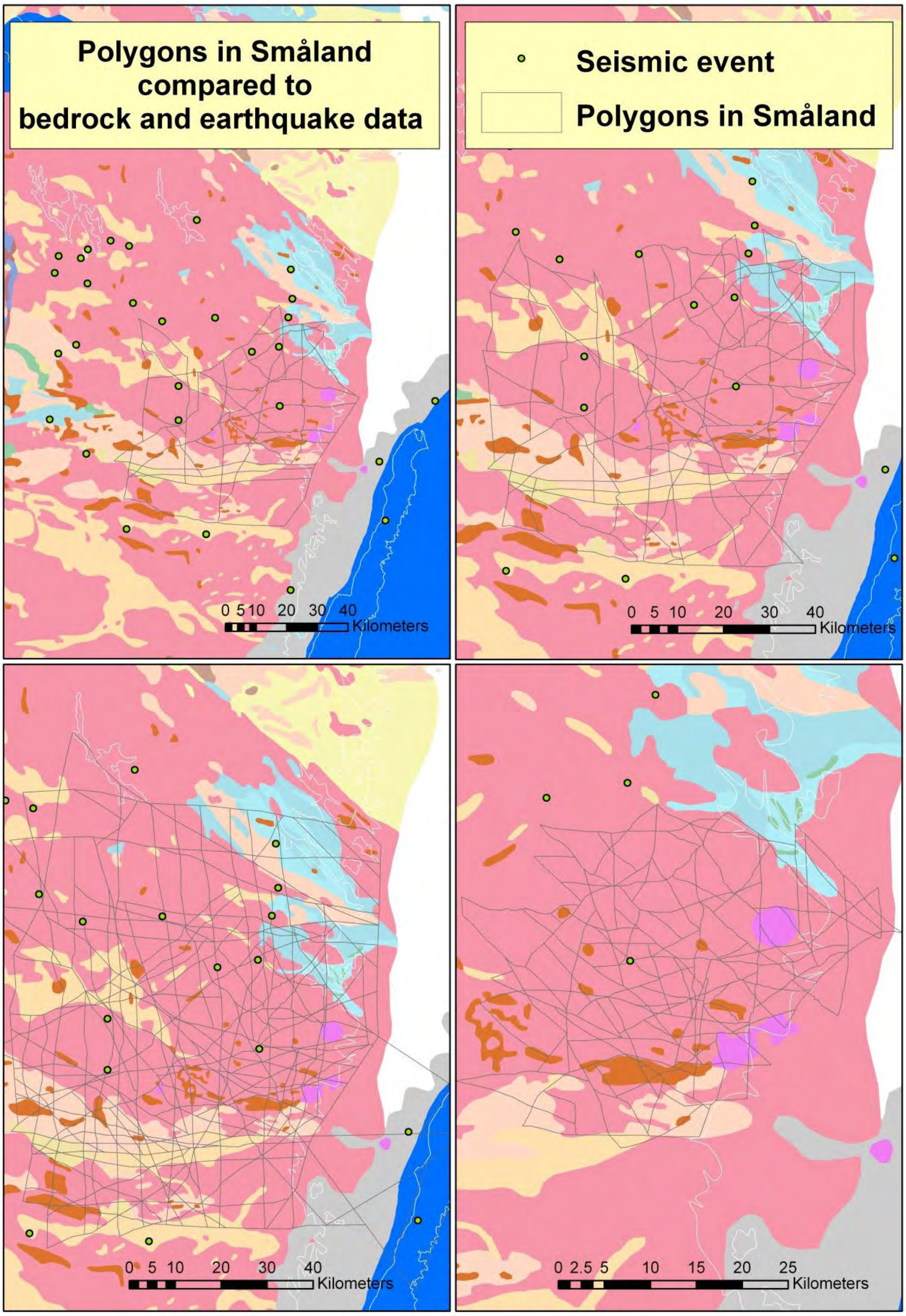


Figure 57. The different sets of polygons in eastern Småland compared to the bedrock lithologies of the Swedish part of the Fennoscandian Shield map (2001), and earthquake data from (SNSN and the Helsinki Catalogue of earthquakes in Northern Europe since 1375.

In eastern Småland, earthquake epicentres occur preferentially near north-south trending block boundaries or in their close extension and especially at their junction with other structures oriented in east-west, northwest and subordinately in north-east.

The uplift rate in the Laxemar regional area is 1mm/year (Ekman, 1996). Earthquakes are relatively sparse in south-eastern Sweden and none has been registered within the Laxemar local area. The closest recorded earthquake occurred in 1996 and was located at the east-west trending Mederhult zone approximately 13.5km west of the SKB “Laxemar sub-area” (magnitude 2.0L, Catalogue of earthquakes in Northern Europe since 1375). The three closest earthquakes recorded by SNSN, with magnitudes between 0.34 and 1.07 during the period 2003 to spring 2007 were located at distances between 20 and 40km from the “Laxemar subarea”.

Earthquake epicentres are less abundant and, as for Uppland, show a very good correlation with the finest network of the regional area.

8 DISCUSSION

What is the purpose of treating bedrock as rock blocks, except for the fact that they give patterns that resemble a structural pattern that can easily be seen in most outcrops? When rock deforms plastically, the entire rock yields to the stress put on it. At lower temperatures the deformation is more and more confined to discrete deformation zones. However, while large displacements occur along major deformation zones, deformation may also be taken up by minor displacements along multiple, smaller suitable structures, together adding up to considerable total values.

8.1.1 Geological structures that may generate lineaments and rock-block boundaries

What structures are likely to act as rock-block boundaries? What structures are extensive in an igneous or metamorphic terrain and may form relatively regular patterns?

Lithological banding, contacts and foliation often do not appear as extensive and linear structures in this type of geological terrain. Dykes with properties different from the surrounding bedrock may stand out. Late dykes are known to appear as extensive linear features. In Småland, late north-south trending mafic dykes c. 1 Ga occur but are more frequent further to the west of our areas; older mafic dykes, 1.4 to 1.8 Ga, are generally oriented north-northwest to the north of the east-west lines through Oskarshamn, and northeast south of this belt. The mafic rocks in Gävlebukten, c. 1.3 to 1.4 Ga, have an east-northeast trend (Gorbatschev et al. 1987).

Rock-block boundaries in the present study agree well with brittle deformation zones outlined on geological maps (cf. Lundegårdh et al. 1985, Antal et al. 1998 a-d). The Uppland presentations are very similar while the Småland ones show some discrepancies; the largest disagreement occurs for extensive structures with an open topographical expression.

8.1.2 What is the character of structures that appears as linear topographical features, lineaments, here interpreted as rock-block boundaries?

They have a topographical signature, are valleys or other landform breaks, with a change in the gradient or a minimum (maxima although they may be arranged in a line are usually not treated as lineaments; the lineament is drawn on either side, or both). The structure may be caused by brittle deformation with increase in porosity and alteration. This may result in either softening or strengthening of the rock due to recrystallization and formation of, e.g. free quartz formed by the alteration. Sealed deformation zones may be more resistive to weathering and stiffer as compared to the host rock. Extensive formation of clay minerals during retrogressive alteration can make the rock tighter. Alteration zones may also become softer and such zones are less resistant to erosion than the host rock. Deep grus weathering is found in Småland (Lidmar-Bergström et al. 1999) and Uppland (Ekolsund). Such weathering increases the porosity in the zone and it can easily be eroded. Brittle deformation along a zone may increase the porosity drastically and an open fracture zone can relatively easy be affected by erosion.

8.1.3 Depth, width, length and orientation of valleys

The depth of a valley shows that the structure has potential for being eroded, has an increased porosity and/or is softened by alteration. It may reflect the base of erosion. The real depth however, is often concealed, hidden below a sequence of sediments. The occurrence of bedrock canyons, e.g. Moredalen (cf. Olvmo 1989, Tirén et al 2001) and Strupdjupet (Tirén et al 1996), indicates that the true depth of bedrock valleys can be considerable (30 to 50m deep). Thus the true depth to bedrock in valleys may be much greater than what is revealed by the elevation data.

The width of a valley is not a simple indicator for the importance of a structure as it is also related to the orientation of the feature and the time it has been subject of erosion. In flat areas the surface expression of gently inclined brittle-deformation zones often becomes vague. Besides the gradient, flow of water is directed by suitable watercourses, zones of weakness, and may give information on the character of the zones.

The dominating orientation for watercourses in eastern Småland is in northwest-southeast and north-south with the addition of some in east-west. Very few run in a north-easterly direction. The general topographic gradient is east-west and this suggests that the water paths are older than the present surface attitude. The northwest-south-easterly valleys had a favourable orientation in relation to the ice-movement and glacial drainage for being deepened, widened and filled.

In Uppland there are two populations in the arrangement of watercourses with the extensive west-northwest lineament through Uppsala as a dividing line. North of the dividing line streams run both north and south in north-northwest – south-south-easterly directions, and along long east-of-north courses. South of the dividing line the parallel west-north-westerly – east-southeast direction is dominant.

Thin hairline lineaments may be extensive and overprint wider topographical lineaments. These are however, generally not included as block boundaries as they have no major topographic impact; the ground surfaces on either side are uniform.

The orientation and length of rock-block boundaries are useful tools for the characterization of lineaments, better than the number of linked lineaments as these are rather a matter of the definition of the term lineament than that they give an adequate value for characterization of rock-block boundaries. Important is however, that the irregularity of a rock-block boundary may influence the possibility of a structure to reactivate, or to form precursors or nuclei of "new" fractures.

8.1.4 What does the ground surface represent?

The investigated areas lie close to the sub-Cambrian peneplain. This is shown by the flat surfaces that in rare cases may hold sandstone dykes and, outside the investigated areas, provide the basement for Lower Palaeozoic sedimentary rocks. The sub-Cambrian peneplain was very level and its flat sub-horizontal surfaces occurring at different altitude testify to movements of the rock blocks holding these surfaces.

The ground surface of some rock blocks also has less relief than the surrounding rock-block surfaces. This implies that the sedimentary cover was removed more recently than for their neighbours. This in its turn suggests that this block at some time had a lower position relative to the neighbours. According to Lidmar-Bergström (1994) southern Sweden had an extensive Mesozoic cover above the Palaeozoic rocks. These cover rocks were removed mainly during the Tertiary, triggered by the main phases of uplift in the Palaeogene (sea-floor-spreading related) and especially (the formation of the South Swedish Dome, Lidmar-Bergström and Näslund 2002, Japsen et al 2002) in the Neogene and Quaternary (Pliocene-Pleistocene), cf. Table 4.

8.1.5 Time of movements

Bedrock in the studied areas was mainly formed during the Palaeoproterozoic at greater depth than where it occurs today. Plastic deformation involving major parts of the rock volume gave way for more localized brittle deformation as the rock cooled. During the last one and a half billion years bedrock has responded to the applied stresses and changes in the relations and directions of the axis in the strain ellipsoid. Major events influencing these are listed in Table 4.

8.1.6 Earthquakes and block boundaries

The present deformation of Fennoscandia is mainly attributed to the isostatic adjustments during and after melting of the Weichselian ice sheet. Although the models fit fairly well the data are sparse and of varying quality. Yet, it has been argued that there is also a tectonic component to the Scandinavian uplift (Mörner 1979, Fjeldskaar et al. 2000). Fjeldskaar et al. show a tilting of the Scandinavian Peninsula with an excess uplift of Norway parallel the coast and a deficit in the expected uplift along the Swedish Bothnian east coast. These are also zones with increased seismicity. The southernmost part of the Bothnian anomaly coincides with the sedimentary basin in Gävlebukten and the north-western earthquake domain commented on in 7.2 above. They also show a minor area of negative expected uplift south of the Oskarshamn lines but here with low seismicity. Many of the recorded Småland earthquakes may have a connection with east-west trending rock-block boundaries.

However, not all uplift is related to seismic activity. The iso-lines for the post-glacial uplift in southern Sweden show a symmetric pattern, while the eastern half suffers a much lower seismicity.

Many earthquakes are located close to block boundaries. Others are located in the prolongation of interpreted rock-block boundaries that are not drawn, yet discernible or they may define a line along a vague change in topography. Some occur at junctions, often of oblique structures.

8.1.7 Distortion of the rock-block pattern

In Uppland, the northeast pattern in the west is overruled by the north-northwest to northwest pattern along the coast that in its turn yields to a west-northwest pattern in the northeast. East-west lines provide a somewhat wavy lensoid pattern. The east-west structures make two major belts, the northern, Örsundsbro, widens up in the east, while the southern south of Mälaren, widens in the west. North-south lines are uncommon in the regional interpretation but are dominant in the western part of the northern-Uppland interpretation where they step or terminate against northwest and northeast lines.

In Småland, northwest structures do not reach the coast uninterrupted. They bifurcate eastwards and often decrease in importance at east-west or northerly structures. North-north-westerly lines display en-echelon occurrence. East-west fairly straight lines occur in clusters while others, more undulating, link northwards or are not through-going. The expression of northeast structures varies in intensity along strike. Northerly structures occur in two families, one winding with wider valleys and another with fairly regular spacing of straighter through-going lines.

8.1.8 Size and shape

Small rock blocks, often of triangular shape, occur in the crossing of several structures. Small elongate blocks also appear in corridors. Small blocks may cover too small an area to receive a value due to the position in relation to the pixel (this may also have bearing on the detection of maximum and minimum values). Some areas also got a “no value” because of water coverage.

Large blocks may appear in the periphery and display disproportionate size because of their peripheral importance for the study.

8.1.9 The shoreline

The shoreline with the lack of values or different ways of representing them is problematic. What does the coastline represent? Is it just a matter of the location of the water line on a gently sloping surface or is it a steep to vertical rock-block boundary? A good natural port is usually connected with the occurrence of a major rock-block boundary with either a deeply eroded valley or a down-faulted block on one side.

8.1.10 Rock blocks and groundwater flow

The minimum altitude value for many rock blocks is zero. How does this affect the groundwater flow?

The observation of different gradients in the valleys versus rock blocks may have significance for the regional and local components of groundwater flow. The valleys act as a base level for the regional flow system. Since the gradient there is lower it may mean that the forces driving regional flow are reduced relative to those driving local flow. The deeper valleys inland will tend to reduce the heads that can be transmitted from the rock blocks to drive the regional flow system at depth. This tends to limit the regional gradient and reduce the importance of regional versus local flow cells. The local flow systems may be more three-dimensional inland (i.e. flowing from the middle of rock blocks toward valleys on either side as well as coastward) and then become more two-dimensional (more purely coastward) closer to the coast. A repository, thus, could be in "regional discharge" zones but for relatively smaller "regional" systems.

Table 4. Summary of possible episodes causing movements in studied areas

Time	**Geological event**	**Movement**	**Lithology**
Palaeoproterozoic	Svecokarelian, Gothian	Bulk formation of bedrock	Lithosphere building
Mesoproterozoic	Sub-Jotnian	Intrusion Faulting	Rapakivi granites
Mesoproterozoic	Jotnian	Block faulting	Sandstone deposition
Mesoproterozoic	Post-Jotnian	Intrusion of dykes	Dolerites
Mesoproterozoic	Sveconorvegian	Orogenesis in Western Scandinavia	Lithosphere building
Neoproterozoic	Continental break-	Block move-	Sedimentary

	up	ments	loading
Neoproterozoic	Glaciations	Block move-ments	Clastic dykes
Ordovician		Subduction (?) in the west	
Silurian	Caledonides	Orogenesis in Western Scan-dinavia and Southern Baltic Sea	Lithosphere building
Devonian	Isostatic compen-sation	Block move-ments	Molasse
Upper Palaeozoic	Hercynian	Orogenesis in the south and far east	
Upper Palaeozoic-Mesozoic	Prolonged open-ing of Atlantic	Block move-ments Grabens	Grabens Dykes
Palaeogene	Sea-floor spread-ing in North At-lantic	Block move-ments Uplift, Tilting	
Palaeogene-Neogene	Alpine-Himalayan	Orogenesis in the far south	
Neogene	Formation of the South Swedish Dome	Block move-ments Uplift, Tilting Erosion	Uncovering of sub-Cambrian peneplain
Pleistocene	Glaciations	Block move-ments	Till, glacioflu-vial deposits

8.1.11 Removal of the gradient

The removal of the gradient enhanced the structural relationships. The maps have a better balance in colour representation which made it easier to evaluate the entire map area at the same time.

In Uppland the shift from north-north-easterly to north-north-westerly trends is better revealed and the higher eastern triangle in the Mälaren segment stands out more clearly. In northern Uppland the block character is more obvious. And in the local Forsmark area the north-south structures are better revealed on the gradient-removed map as are rectangular blocks (east-west, north-south).

Especially in eastern Småland the detailed structures become clear over the entire map area when the strong east-west striping is removed. The relative depth of the inner valley is highlighted and its northerly slope enhanced. For the 50m grid, again the picture becomes clearer, especially in the near-coast areas; the way north-southerly structures swing westwards in the vicinity of the Oskarshamn belt.

In general the two types of maps, original data and gradient-removed, complement each other. This holds true also for the analyses made on the six original sets and the six sets with the gradient removed. The maps of mean values for polygons with removed gradient, in general, show a balanced picture with high and low values spread over the picture.

The polynomial regression trend for Uppland is more complicated than that for Småland and Uppland has lower relief than Småland. Småland has a relatively uniform gradient and the removal of the gradient gives a reduction of the span and enhances the resolution. This is mirrored in the following statistics:

The removal of the regional gradient affected the spread in mean values which were reduced to a half, 47%, for Småland, and 78% for Uppland, as a mean. Mean values for the reduction for minimum and maximum values were higher, 61% and 62% for Småland and 93% and 76% for Uppland of the original values. For the range values the reduction was 86% for Småland and 90% for Uppland.

For the polygons-with-removed-gradient in northern Uppland and Forsmark, NNW lines and segments are verified. In Småland, especially the minimum values are interesting. For the larger regional rock-block interpretations the trend of the gradient is reversed for minimum values with a culmination in the central ribbon. In the detailed regional interpretation, small rectangular blocks comprise a north-easterly narrow belt of higher blocks in the north-western part of the map which is cut by a similar east-west belt. In the local area the minimum values give a low corridor west of the central north-south line. On the range map for the detailed regional interpretation there is an east-north-easterly broad belt of higher blocks across the map north of the Oskarshamn lines.

The general impression gives that for mean and minimum values the local Laxemar area is situated on an elevated segment centred on the Mederhult line while the local Forsmark area, in general, is located in a topographical low.

9 SUMMARY

To get an overall impression of the character of the landscape, a remote study of bedrock structures should include studies of the geomorphology at various scales. Thematic maps improve the general understanding of an area. The size of the regional area that needs to be studied for understanding the structural setting of a site should be related to the character of the structural terrain within which the site is located. Rock-block maps, especially when covering areas with a datum surface − in this case the sub-Cambrian peneplain − improve the understanding of late deformation as it reveals where the peneplain is offset along and across structures. The originally flat landscape and the relatively thin cover of Quaternary sediments in the two regional areas show minor changes in the relative altitude and relief of the peneplain. Deformation zones with an increased porosity (less resistant to erosion) appear as a network of valleys. This outline of weathered valleys indicates structures that are softer than the bedrock in general and may form larger-scale transport paths for groundwater in the bedrock. A rock-block map may also show how regional structures can be intricately linked together during reactivation.

9.1.1 Similarities in Uppland - the Forsmark and Eastern Småland – the Laxemar regional areas

Both are flat areas with low altitudes and low relief. Their present ground-surfaces are close to the sub-Cambrian peneplain. Both are situated in areas of Precambrian bedrock with present maximum horizontal stress (σ_H) oriented in northwest-southeast; the frequency of earthquakes is low. Both are located within one distance of the diameter of a late granite of rapakivi type. Both face the Baltic Sea to their east in the form of bulb-like peninsulas. Both areas lie below the highest shore line.

9.1.2 Differences

The Forsmark area is situated within a metamorphic terrain while the Laxemar area rests on low-metamorphic igneous rocks. In the Laxemar area, the rate of uplift is lower but the relief is higher, the frequency of earthquakes is lower, and the rock block pattern is more uniform than in the Forsmark area And although the frequency of earthquakes is relatively low in the studied areas, it is found that most earthquakes can be related to structures that demarcate rock blocks. Many earthquakes occur at the intersections of major lineaments i.e. at rock blocks corners.

9.1.3 Topographical characteristics in Uppland

The structural pattern in Uppland is an interplay and interference between different sets of lineaments; the east-west division, and north-northeast, north-northwest and west-northwest sets. The early structures and distribution of lithologies govern the major division into domains, particularly the occurrence of volcanites and granite bodies.

As shown in the polynomial regression, the gradient is not simple in Uppland. The relief of Uppland is very low and the erosion base is close to sea level. The drainage pattern clearly divides into two structural domains, southwest of the west-northwest line through Uppsala and northeast of there. The north-northwest belt along the coast is a low. Still much of the low areas northeast of Uppsala are drained to the south.

The very north-eastern part around Forsmark is a complex of subsided triangular bodies of varying order, demarcated by north-of-west, west-northwest, north-northwest and north-south block boundaries.

9.1.4 Topographical characteristics in Eastern Småland

Eastern Småland has a regional easterly gradient where land rises westwards in steps along north-south rock-block boundaries. A wide segment with moderate elevation separates the low coastland from the hilly inland. North-south structures have a regular spacing.

The Oskarshamn belt is a composite structure with both elevated and subsided blocks within the belt. The area to the south has a smoother gradient. Structures north of the belt swing westwards into the belt and rock-block parameters are displaced westwards south of the belt. The bedrock exposure is higher north of the Oskarshamn belt and even higher north of the Mederhult zone.

There are several pronounced valleys in the northwest direction that may have suffered glacial erosion and cleaning before being filled with clay bottoms; some are deeply cut (Strupdjupet, excess of 50m).

The Local Laxemar rock block stands out as a relative high.

9.1.5. Seismicity

Epicentres are located in association with interpreted rock-block boundaries. The rock-block boundaries are structures that have potential for movements to occur. The earthquakes in Gävlebukten are registered in an area with a deficit in post-glacial uplift as compared to uplift models. In connection with this area of "lower" uplift are two major sedimentary basins with Jotnian sandstone and Lower Palaeozoic cover. In the eastern basin, east of Singö, seismic events occurred in 2006 at two locations along the western border. In 1979 there were three relatively strong earthquakes in connection with the western margin of the north-northwest belt along the Roslagen coast.

The seismicity in eastern Småland is lower than in Uppland.

REFERENCES

ArcGIS 9.2, 2007: ESRI, www.esri-sgroup.se/templates/AreaPage.aspx?id=1100

ArcGIS Spatial Analyst, 2007: ESRI, www.esri-sgroup.se/templates/Page.aspx?id=273

Antal, I., Bergman, T, Gierup, J., Rudmark, L., Thunholm, B., Wahlgren, C.-H., Stephens, M., and Johansson, R., 1998a: Översiktsstudie av Kalmar län, geologiska förutsättningar. Swedish Nuclear Fuel and Waste Management Co (SKB), P-98-24, 48pp, Svensk Kärnbränslehantering AB, Stockholm.

Antal, I., Bergman, T., Persson, C., Stephens, M., Thunholm, B., Åsman, M., and Johansson, R., 1998b: Översiktsstudie av Sörmlands län, geologiska förutsättningar. Swedish Nuclear Fuel and Waste Management Co (SKB), P-98-28, 49pp, Svensk Kärnbränslehantering AB, Stockholm.

Antal, I., Bergman, T., Persson, C., Stephens, M., Thunholm, B., Åsman, M., and Johansson, R., 1998c: Översiktsstudie av Stockholms län, geologiska förutsättningar. Swedish Nuclear Fuel and Waste Management Co (SKB), P-98-30, 47pp, Svensk Kärnbränslehantering AB, Stockholm.

Antal, I., Bergman, S., Gierup, J., Persson, C., Thunholm, B., Stephens, M., and Johansson, R., 1998d: Översiktsstudie av Upplands län, geologiska förutsättningar. Swedish Nuclear Fuel and Waste Management Co (SKB), P-98-32, 49pp, Svensk Kärnbränslehantering AB, Stockholm.

Asklund, B., 1923: "Űbersicht der geologischen Stellung der Bruckspaltung Südostschwedens". Geologiska Föreningens i Stockholm Förhandlingar (GFF), 45, 249-285.

Axberg, S., 1980: Seismic stratigraphy and bedrock geology of the Bothnian Sea, northern Baltic. Stockholm Contributions in Geology, 36, 3, 153-213.

Beunk, F.F. and Page, L.M., 2001: Structural evolution of the accretional continental margin of the Paleoproterozoic Svecofennian orogen in southern Sweden. Tectonophysics 339, 67-92.

De Geer, S., 1910: Karta över mellersta Sveriges Landformer. Sveriges geologiska undersökning, Ba 7.

De Geer, S., 1913: Karta över södra Sveriges Landformer. Sveriges geologiska undersökning, Ba 9.

Ekman, M., 1996: A consistent map of the postglacial uplift of Fennoscandia. Terra-Nova 8/2, 158–165.

Excel 2003: Microsoft Office Excel.

Fennoscandian Shield map, 2001: *Eds*. Koistinen, T., Stephens, M.B., Bogatchev, V., Nordgulen, Ø., Wennerström, M. & Korhonen, J., Geological Map of the Fennoscandian Shield, Scale 1:2 000 000. Geological surveys of Finland, Norway and Sweden and the North-West Department of Natural Resources of Russia.

Fjeldskaar, W., Lindholm, C., Dehls, F.F. and Fjeldskaar, I., 2000: Postglacial uplift, neotectonics and seismicity in Fennoscandia. Quaternary Science Reviews, 19, 1413-1422.

Flodén, T., 1977: Tectonic lineaments in the Baltic from Gävle to Simrishamn. KBS Teknisk rapport 59, 56pp. Kärnbränslesäkerhet, Stockholm

Gorbatschev, R., Lindh, A., Solyom, Z., Laitakari, I., Aro. K., Lobach-Zhucheko, S.B., Markov, M.S., Ivliev, A.I., and Bryhni, I., 1987: Mafic dyke swarms of the Baltic Shield. *in* H. C. Halls and W. F. Fahrig (*eds*.), Mafic dyke swarms. Publication No. 0120 of the International Lithosphere Program, 361-372.

GSD, Land survey of Sweden, Gävle, www.geolex.lm.se

Gyoobum, K. (2004). Lineament analysis (Version ArcView 3.x) [Avenue]: ESRI. Retrieved May 12, 2005, from the World Wide Web: www.arcscripts.esri.com/details.asp?dbid=13579

Help tutorial Surfer 8.0 Golden Software 2006: www.goldensoftware.com

Helsinki Catalog of earthquakes in Northern Europe since 1375, www.seismo.helsinki.fi/english/stations/index.htm

Hobbs, W.H., 1903: Lineaments of the Atlantic border region. Geological Society of AmericaBulletin 15, 483–506.

Hobbs, W.H., 1912: Earth features and their meaning. Macmillan, New York, 506pp.

Japsen, P., Bidstrup, T. and Lidmar-Bergström, K., 2002. Neogene uplift and erosion of southern Scandinavia induced by the rise of the South Swedish Dome. *in* Doré, A.G., Cartwright, J.A., Stoker, M.S., Turner, J.P. and White, N.(*eds*.) Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration. Geological Society of London Special Publications, 196, 183-207.

Lidmar-Bergström, K., 1994: Morphology of the bedrock surface. *in* Curt Fredén (*ed*.) 1994, Geology. National Atlas of Sweden. Almquist & Wiksell International, Stockholm, 44-54.

Lidmar-Bergström, K., Olsson, S. and Roaldset, E., 1999: Relief features and palaeoweathering remnants in formerly glaciated Scandinavian Basement areas. Spec. Publs Int. Ass. Sediment, 27, 275-301.

Lidmar-Bergström, K. and Näslund, J. O., 2002: Landforms and uplift in Scandinavia. *in* Doré, A.G., Cartwright, J.A., Stoker, M.S., Turner, J.P. and White, N.(eds.) Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration. Geological Society of London Special Publications, 196, 103-116.

Land Survey of Sweden, www.lm.se, in Swedish www.lantmateriet.se/templates/LMV_Page.aspx?id=1009 and in English www.lantmateriet.se/templates/LMV_Page.aspx?id=1009&lang=EN

Lundegårdh, P., Bruun, Å. and Wikström, A., 1985: Provisoriska översiktliga Bergrundskartan Oskarshamn. Sveriges geologiska undersökning, Ser. Ba. 34. Provisoriska översiktliga berggrundskartan Oskarshamn. Sveriges geologiska undersökning, Ba. 34.

Lundqvist G., 1961: Karta över landisens avsmältning och högsta kustlinjen i Sverige. Sveriges geologiska undersökning, Ba 18.

Muir-Wood, R., 1993: A review of the seismotectonics of Sweden. Swedish Nuclear Fuel and Waste Management Co (SKB), TR-93-13, 225pp.

Mörner, N.A., 1979: The Fennoscandian uplift and Late Cenozoic geodynamics: geological evidence. Geo Journal 33, 287-318.

Olvmo, M., 1989: Meltwater Canyons in Sweden. A study of the kurso, skura- and grave-type. PhD thesis, Guni report 27, 134pp, Dept. of PHYSICAL geography, University of Göteborg.

Påsse, T., 2004: The amount of glacial erosion of the bedrock. . Swedish Nuclear Fuel and Waste Management Co (SKB), TR-04-25, 39pp, Svensk Kärnbränslehantering AB, Stockholm.

Rudberg, S., 1954: Västerbottens berggrundsmorfologi – ett försök till rekonstruktion av preglaciala erosionsgenerationer i Sverige. Geographica, Skrifter från Upsala Universitets Geografiska Institution, 25, 257pp, Uppsala.

Rämö, O.T., 2005: Rapakivi granites *in* Rämö, O.T., Halla, J., Nironen, M., Lauri, L.S.,
Kurhila, M.I., Käpysho, A., Sorjonen-Ward. P., and Aikes, O., EUROGRANITES 3005 –
Proterozoic and Archean Granites and Related Rocks of the Finnish Precambrian.
Eogranites 2005 Field Conference, September 11-17 September, 2005. Publications of the
Department of Geology A1, 130pp.

SKB, 2005: Preliminary site description, Forsmark area – version 1.2. Swedish Nuclear Fuel and Waste Management Co (SKB), R-05-18, 752pp. Svensk Kärnbränslehantering AB, Stockholm.

SKB, 2006: Preliminary site description, Laxemar subarea – version 1.2. Swedish Nuclear Fuel and Waste Management Co (SKB), R-06-10, 656pp. Svensk Kärnbränslehantering AB, Stockholm.

SNA, 1994: Geology. (*ed*. C. Fredén). National Atlas of Sweden. SNA Publishing, department of Human Geography, Stockholm University. Almquist & Wiksell International, 205pp, Stockholm.

Suominen, V., 1991: The Chronostratigraphy of Southwestern Finland with Special Reference to the Postjotnian and Subjotnian Diabases. Geological Survey of Finland, Bulletin 356, 100pp, Espoo.

Surfer software 8.0 (Golden software), 2002: www.goldensoftware.com

Svedmark, E., 1887: Orografiska studier i Roslagen. Geologiska Föreningens i Stockholm Förhandlingar (GFF), 9, 188-210.

Swedish National Seismic Net (SNSN), www.geofys.uu.se/snsn

Swedish part of the Fennoscandian Shield map, digital version, 2005: Fennoscandian Shield map, 2001: *in* Koistinen, T., Stephens, M.B., Bogatchev, V., Nordgulen, Ø., Wennerström, M. & Korhonen, J. (*eds*.), Geological Map of the Fennoscandian Shield, Scale 1:2 000 000. Geological surveys of Finland, Norway and Sweden and the North-West Department of Natural Resources of Russia, 051107_0816.

Söderlund, U., Patchett, P.J., Vervoort, J.D., and Isachsen, C.E., 2004. The 176Lu decay
constant determined by Lu-Hf and U-Pb isotope systematics of Precambrian mafic intrusions. Earth and Planetary Science Letters 219, 311–324.

Tchoukanski, Ianko, 2007: ET GeoWizards 9.6 for ArcGIS 9.2, www.ian-ko.com

Tirén, S.A., Beckholmen, M., Voss, C. and Askling, P., 1996: Development of a Geological and a Structural Model of Äspö, south-eastern Sweden. Swedish Nuclear Power Inspection (SKI), SKI report 96:16, 198pp.

Tirén, S.A., Wänstedt, T. and Sträng, T., 2001: Moredalen - a canyon I the Fennoscandian Shield and its implication on site selection for radioactive waste disposal in south-eastern Sweden. Engineering Geology, 61, 99-118.

2010:40

The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 270 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

Strålsäkerhetsmyndigheten
Swedish Radiation Safety Authority

SE-171 16 Stockholm
Solna strandväg 96

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

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