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Rock-block configuration in Uppland and the Ålands-hav basin, the regional surroundings of the SKB site in Forsmark, Sea and land areas, eastern Sweden

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

SSM Perspective

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

Background

The topography in Uppland is more broken in the sea area east and northeast of Forsmark than it is on land. The major structure in the Ålands-hav basin is a west-north-westerly line that passes southwest of Åland, with a very steep gradient from the Åland archipelago down to an exceptionally low sea-floor valley. On its southern side it rises in steps to a low flat basin divided into a deeper western half and a somewhat shallower eastern half.

The Swedish Nuclear fuel and Waste management Co (SKB) has investigated the Forsmark site, which lies at the west-northwest trending shoreline in northern Uppland, sheltered from the sea by one of the larger islands in the Uppland archipelago, Gräsö. To assess the structures around Forsmark also in the sea area, the bottom structures of the Ålands-hav basin were investigated by means of depth-readings from sea charts. Two rock-block maps with rock blocks at different scales were constructed and analysed for their top surface elevation.

Purpose

The purpose of the current project is to evaluate data in SKB's early site descriptive models and discuss alternative structural geological models. In this work available marine geological data in the Baltic Sea outside Forsmark will be used. The interpretation of the sea data will contribute to the understanding of the late geological history of the area in the mainland as well as in the sea.

Results

Inspection of sea charts revealed the occurrence of a major topographic structure between Forsmark and Gräsö. Two seismic events in 2006 on a major north-south structure just outside the archipelago to the east, in the Ålands-hav basin, revealed the importance of the major down-faulted occurrence of Jotnian meta-sediments, one out of two in the Baltic Sea where water depth reaches beneath 200m. To address these issues an attempt was made to assess the bottom structure of the Ålands-hav basin to elucidate the structure also north and east of the regional Forsmark area.

Effects on SSM supervisory and regulatory task

The result of this study will give SSM new knowledge of structures in the sea outside Forsmark that might be important also for the modelled site area at the mainland.

Project information

SKI reference: SKI 14.9-040255/200409071 and
SKI 2005/741/200509030
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

The Forsmark SKB site lies at the west-northwest trending shoreline in northern Uppland, sheltered from the sea by one of the larger islands in the Uppland archipelago, Gräsö. To assess the structures around Forsmark also in the sea area, the bottom structures of the Ålands-hav basin were investigated by means of depth-readings from sea charts. Two rock-block maps with rock blocks at different scales were constructed and analysed for their top surface elevation.

The topography in Uppland is more broken in the sea area east and northeast of Forsmark than it is on land. The major structure in the Ålands-hav basin is a west-north-westerly line that passes southwest of Åland, with a very steep gradient from the Åland archipelago down to an exceptionally low sea-floor valley. On its southern side it rises in steps to a low flat basin divided into a deeper western half and a somewhat shallower eastern half.

The deep west-north-westerly zone can be traced on-land past Öregrund and Forsmark. West of Öregrund however, the main trough swings into a north-north-westerly direction, just west of Gräsö. The southern border south of Öregrund and Forsmark, shows a major drop in elevation northern side down. Forsmark thus lies on a ribbon with lower ground on both its southern and northern boundaries.

This west-north-westerly belt is cut in two by a major north-south lineament that cuts through the archipelago between Åland and Gräsö with a very deep canyon. This structure was seismically active in June 2006. The southern part of this line constitutes the western border of the low basin and has a steep gradient on its western side up to the Uppland mainland.

The deep basin is filled with Jotnian metasediments.

South of this basin, the Uppland mainland continues under water towards the east. South of Åland an east-north-easterly ridge separates the low basin to the north from an east-west trending trough which is the eastern continuation of a major on-land structure, the Örsundsbro line north of Norrtälje.

Keywords: elevation data, sea charts, block-faulting, structures, lineament, rock-block surface, polygons, earthquake distribution, Uppland, Ålands hav, Jotnian metasediments. Permission to use sea charts 535, 536 and 719 was provided by the Swedish Maritime Administration, © Sjöfartsverket tillstånd nr 08-01367.
The digital elevation data were published with the permission of the National Land Survey of Sweden (I 2007/1092).

1 INTRODUCTION

When constructing rock-block polygons, from topographic data for the regional areas around the SKB sites in Forsmark, Uppland, and Laxemar, eastern Småland (Beckholmen and Tirén 2010), the fact that these areas lie near the coast (and thus close to the spatial limits for the databases) was a major problem, especially considering that the water line was treated differently by different data sets.

The location of a site at one of the boundaries of the interpretation confines the knowledge of the surroundings by half.

Inspection of sea charts revealed the occurrence of a major topographic structure between Forsmark and Gräsö which was not included in the digital elevation data sets for the Forsmark area.

Two seismic events in 2006 on a major north-south structure just outside the archipelago to the east in the Ålands-hav basin, revealed the importance of the major down-faulted occurrence of Jotnian meta-sediments, one out of two in the Baltic Sea where water depth reaches beneath 200m.

To address these issues an attempt was made to assess the bottom structure of the Ålands-hav basin to elucidate the structure also north and east of the Regional Forsmark area.

2 METHOD

Depth-readings from sea charts (Swedish Maritime Administration 535 1975, 536 1996 and 719 2002) were converted to digital format and represented by a colour palette in the same manner as topographic data on land, and lineament and rock-block interpretations of the topography were made. From these two polygon nets were constructed in the same way as for the areas on land. The polygon net for the larger rock blocks on land is essentially the same as the one presented for the Forsmark regional area in the main report. The outer boundaries of the fringe blocks have been modified to actually represent block boundaries and not just a closure of the blocks at the map frame or data occurrence. The finer network is based on a selection of lines from the intermediate rock-block boundaries in Uppland (lineament digital elevation data in Figure 9 in Beckholmen and Tirén 2010). The sea areas are newly constructed.

Since the coupled topography data for these polygon sets were separate databases of very different character, a table was compiled manually for the polygons with the Mean, Minimum, Maximum and Range values from the two data sets. The land data is the 500m grid of Sweden and covers the land surface while the sea bottom areas are only covered by spot checks on sea charts (cf. Fig. 2a). These point readings were also converted into a raster-file by inverse distance interpolation and was analysed for mean values and used in Figures 1 and 2b-d. The maximum and minimum values were taken directly from the sea charts, and the range values were calculated from these.

In the archipelago that fringes the mainland there are data from both sets. Here, the maximum, minimum and range values may be fairly correct while the given mean values may be deceptive since they stem from either of two truncated data sets, the land or sea data set with a zero level at +0m and they do not represent true integrated mean values for the block. Minimum values in the sea south of the area of data coverage, as displayed in Figure 2a, have a false value of 0m a. s. l. For max values on Åland elevation readings were taken from topographical maps of Åland (cf. http://kansalaisen.karttapaikka.fi).

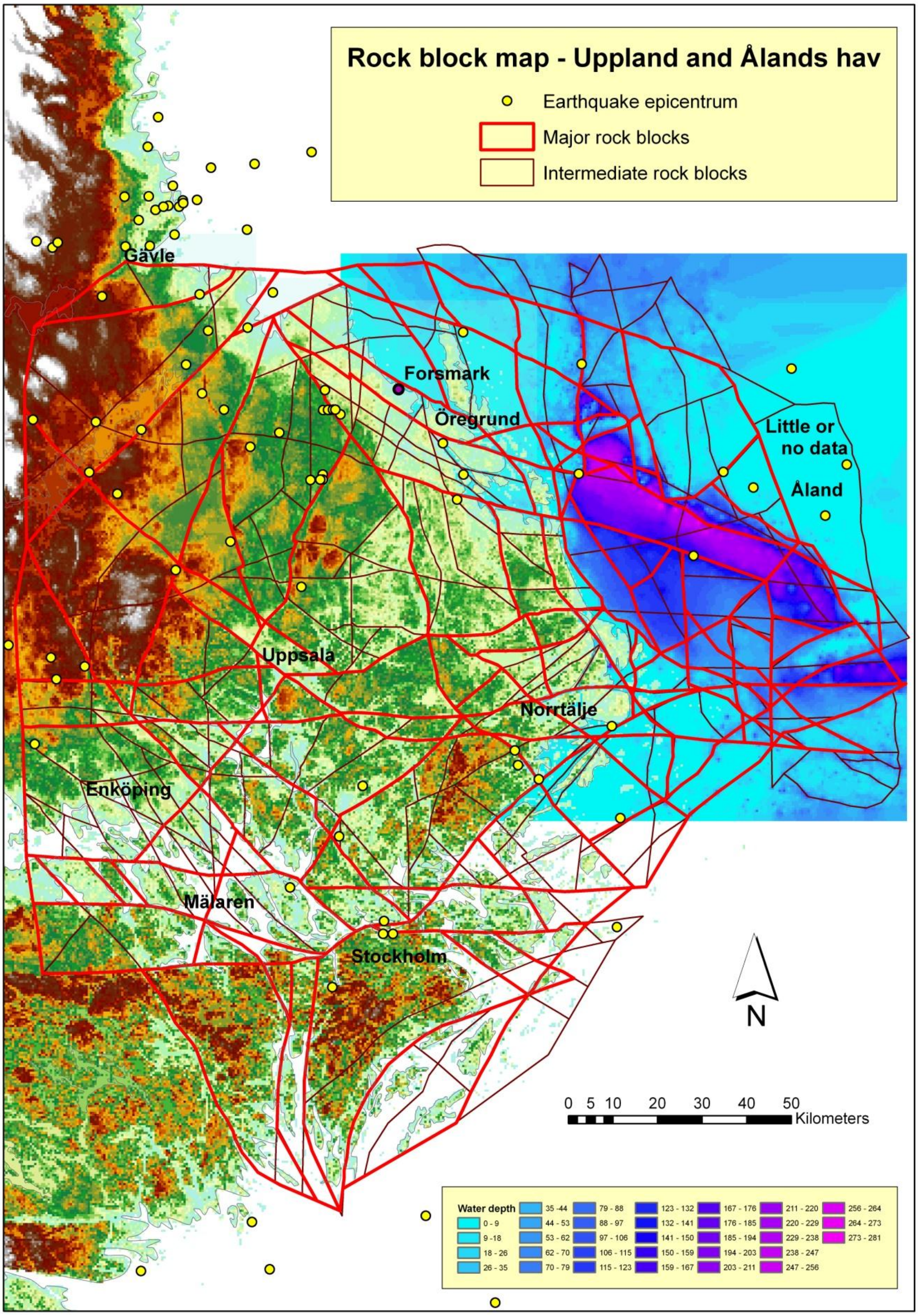


Figure 1. Rock block map of the Uppland – Ålands-hav area. Elevation displayed on land by the 500m grid with the exclusion of altitudes above 115m and the transparent 50m grid and in sea-covered areas by an inverse distance weighted interpolation grid (ESRI, ArcGIS 9.2) based on spot checks from sea charts. Earthquake data from (SNSN) and the Helsinki Catalog of earthquakes in Northern Europe since 1375.

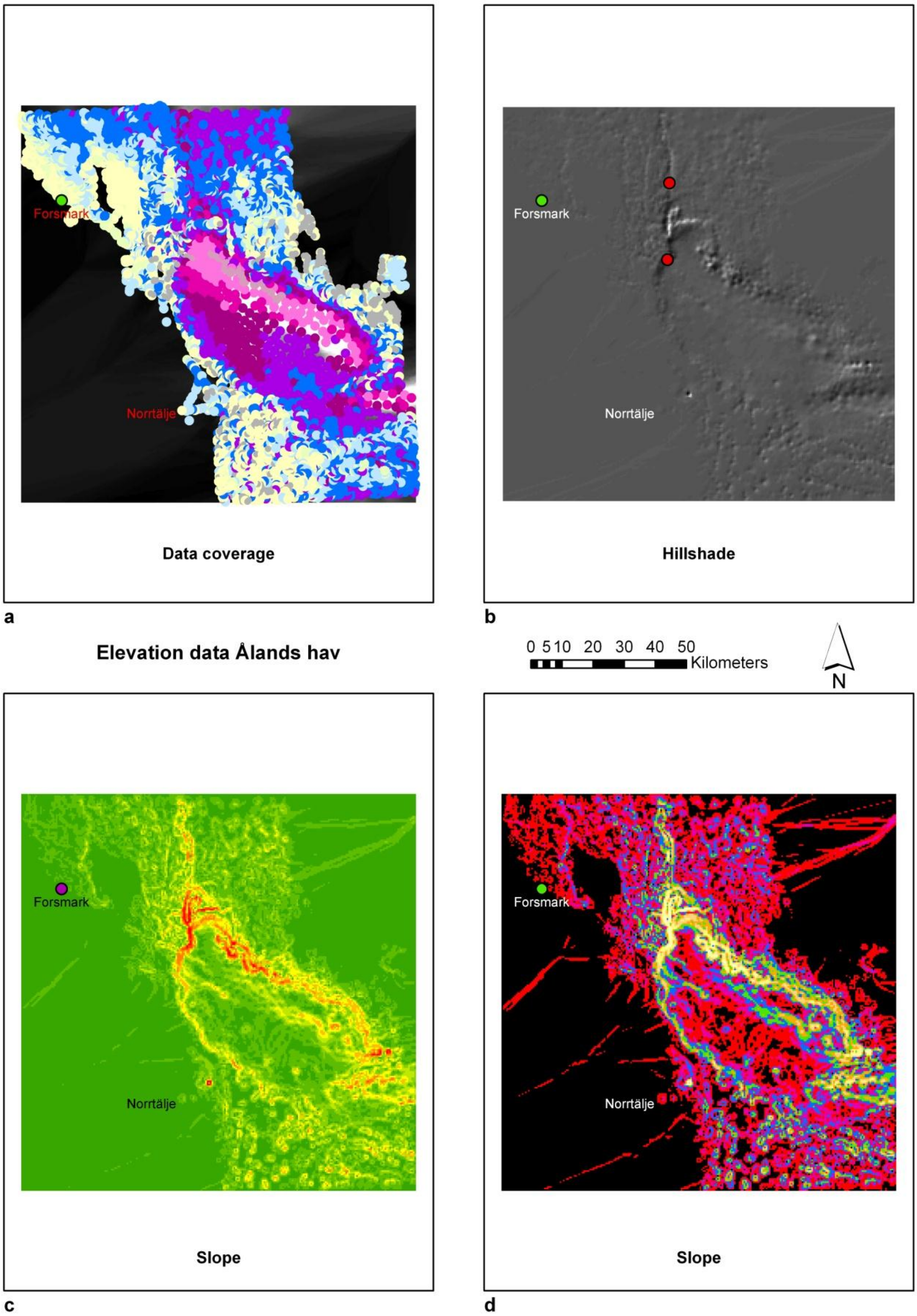


Figure 2. Sea chart readings, a) Classed individual readings showing the extent of the covered area, b) Hillshade map made from the inverse distance weighted interpolation grid with the location of two 2006 earthquake epicentra, c and d) Slope maps made from the inverse distance weighted interpolation grid, different colour palettes.

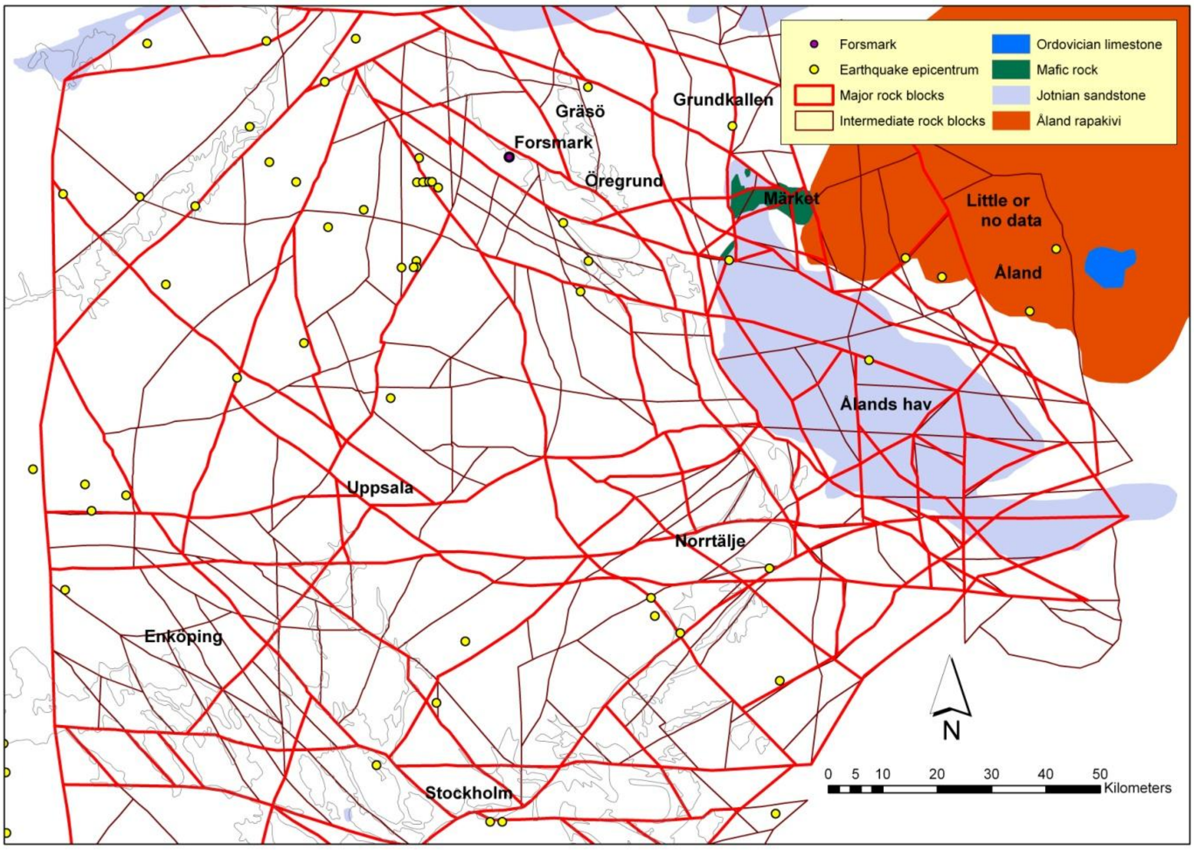


Figure 3. Rock block map of the Uppland – Ålands-hav area. Bedrock geology from the Fennoscandian Shield Map2001, Flodén 1977 and Rämö 2005. Earthquake data from (SNSN), and the Helsinki Catalog of earthquakes in Northern Europe since 1375.

3 MORPHOLOGY

The most prominent feature is the very deep north-northeast sloping segment just southwest of Åland where water depth reaches 285m b. s. l. (Fig. 1); the gradient up to the Åland land surface is steep (cf. also Fig. 2c and d). Another conspicuous structure is the winding north-south line with the two 2006 seismic events (cf. especially Fig. 2b). Both these features are related to the occurrence of the Jotnian sandstone that forms the floor of most of the Ålands-hav basin (Fig. 3). Also the south-western boundary of the basin has a steep gradient. Parallel to the long axis of the basin there are nested lines (Figure 2c) with a west-northwest trend pointing towards the Forsmark shoreline.

In the south the Norrtälje (Örsundsbro) line can clearly be seen to continue across the sea. Slightly north of this line there is a ridge towards the Åland high. East and southeast of Norrtälje the sea is shallow with occasional deeps. Gräsö Island is the dry south-western part of a flat with a steep gradient on its western side in Öregrundsgrepen northwest of Öregrund (cf. Fig. 2c).

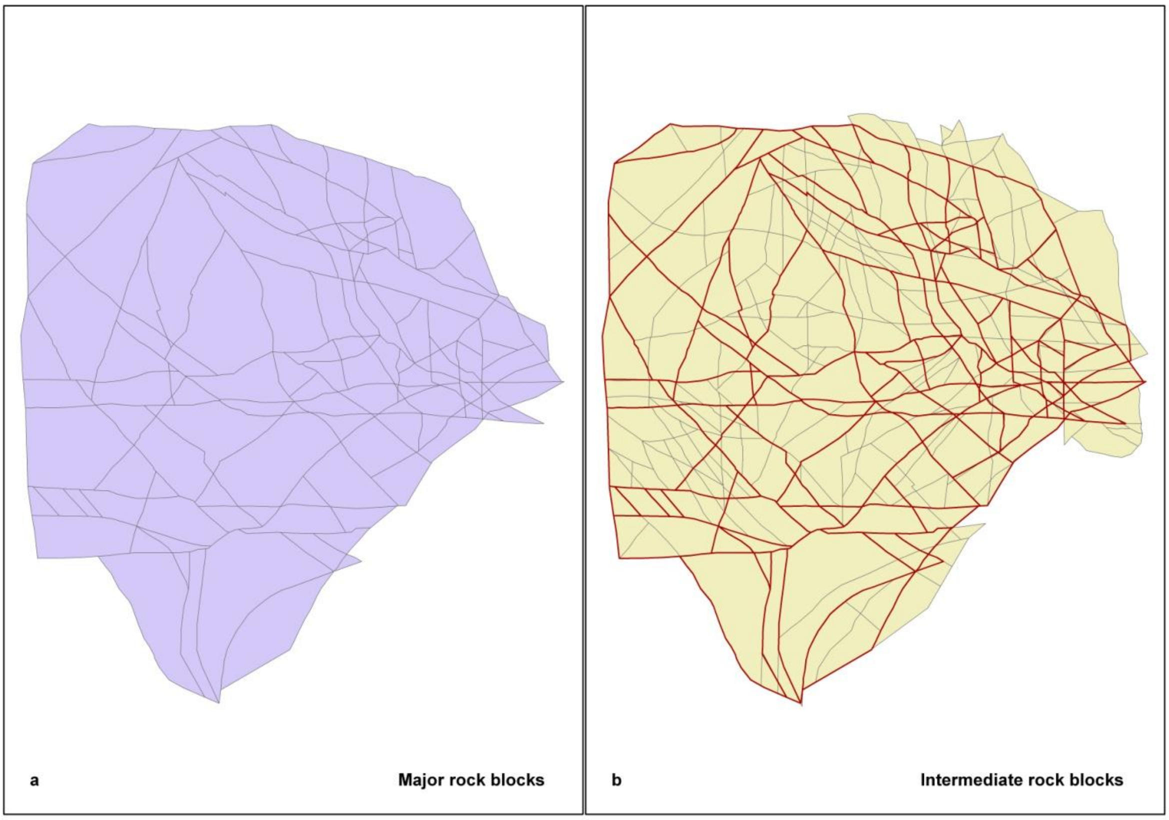


Figure 4. Polygons for the Uppland – Ålands-hav area, a) Rock-block interpretation at regional scale, b) Rock-block interpretation at regional scale stacked on an intermediate rock-block interpretation, colours showing the areas covered by the rock blocks interpreted for a given grid.

The Jotnian sandstone (Fig. 3) is cut in its northern part by mafic rocks which morphologically stand out as a ridge, (the Märket high, cf. Fig. 2b). West of the north-south trench, with the 2006 seismic events, there is an elevated rib, the Grundkallen highs.

4 ROCK BLOCKS

As in the main study (Beckholmen and Tirén 2008), the subdivision 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.

Polygons were constructed from major and intermediate lineaments interpreted from the topographic data sets. The resulting networks are presented in Fig. 4 and displayed in Fig. 1 and for the major part of the investigated area in Fig. 3. From Fig. 3 it is also possible to see how a regional smooth line in the more detailed version is split up into en echelon structures with a more northerly trend (cf. Fig. 3, eastern part).

Table 1. Arithmetical mean length (m/number of block boundaries) for every 10 degrees interval. Values from the main report added for comparison.

Intervals	Uppland – Ålands hav Largest	Uppland – Ålands hav Smaller
Mean all	11653	7460
270-280	9636	6162
280-290	12381	7220
290-300	9077	7024
300-310	13648	7161
310-320	9885	7387
320-330	13865	8583
330-340	13799	9262
340-350	15169	8551
350-360	11481	6981
00-10	8790	6914
10-20	9516	6440
20-30	16558	8969
30-40	9104	9866
40-50	16830	9037
50-60	8626	8460
60-70	11768	6141
70-80	10070	6319
80-90	11398	7268
Max	16830	9866
Min	8626	6141

4.1.1 Major rock blocks

The threefold north-south division of the investigated area by east-west lines still hold true. The structure defining the northern limit of the Mälaren basin continues eastwards into the sea and the northeast lines along the southeast coast are paralleled in the east.

The north-western part of the map is dominated by the interplay of northeast- and northwest- trending lines and north-northwest trending lines of the belt along the coast. The deep basin is characterized by west-northwest blocks that continue on land in northern Uppland. In the sea area there is also a northerly trend in the areas north and south of the deepest segment.

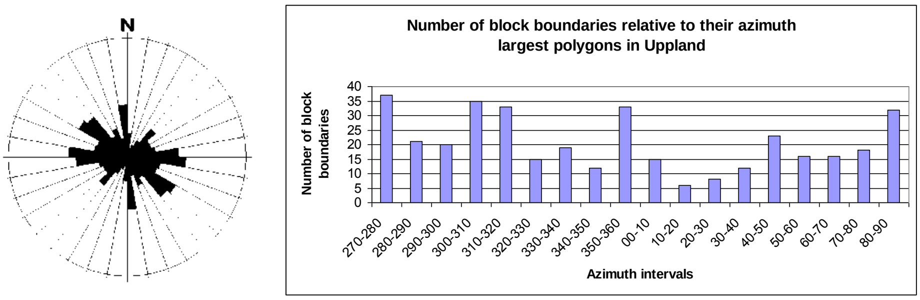
4.1.2 Intermediate rock blocks

Adding of finer structures reveals clusters of structures with north-westerly and north-easterly trends, while north-south and east-west structures often come in singles.

5 LINEAMENTS - ROCK-BLOCK BOUNDARIES

The orientation and length of rock-block boundaries are presented in rose diagrams (Figs. 5 and 6). The mean lengths for every 10° interval are given in Table 1.

Large polygons in Uppland and Ålands hav



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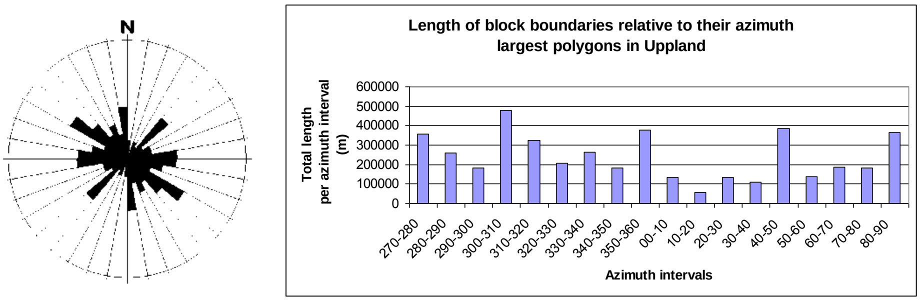
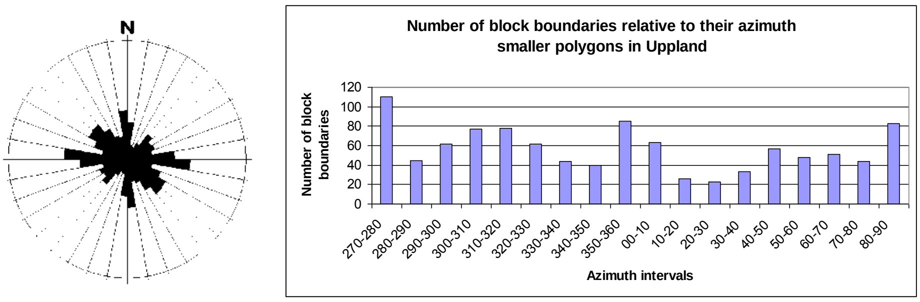


b

Figure 5. Orientation of major rock-block boundaries in the Uppland – Ålands-hav area displayed by rose diagrams (outer circle 10%) and histograms, a) Number of lineaments for 10° intervals, N=371, and b) Length of lineaments within 10° sectors, total length 4 323093m.

Intermediate polygons in Uppland and Ålands hav



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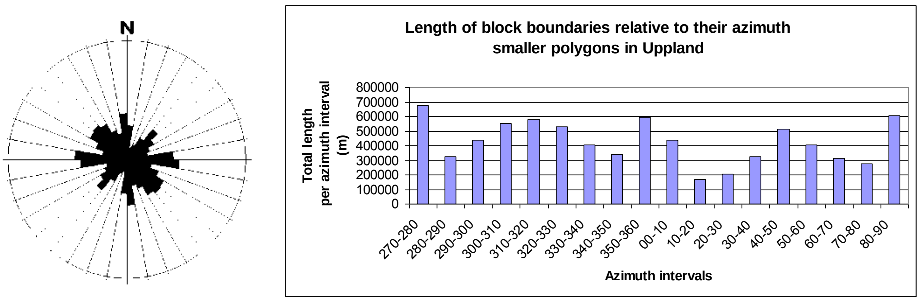


b

Figure 6. Orientation of intermediate rock-block boundaries in the Uppland – Ålands-hav area displayed by rose diagrams (outer circle 10%) and histograms, a) Number of lineaments for 10° intervals, N=1031, and b) Length of lineaments within 10° sectors, total length 7 691377m.

Table 2. Parameters for rock blocks in Uppland and Ålands hav (for comparison included also the Regional Uppland area in Beckholmen and Tirén 2008).

Base map	Elevation data grid (xm*xm)	Size of map area/tot. rock block area (x109m2)	Number of rock blocks	Mean size of rock blocks (x106m2)	Standard deviation (x106m2)	Total length of rock block boundaries (x106m)	Density of rock-block boundaries (m/m2)
Uppland and Ålands-hav Largest polygons	50 500 Nautical charts	27.82	147	189.27	260.74	4.323	0.00336
Uppland and Ålands-hav Large polygons	50 500 Nautical charts	30.02.	418	71.82	93.93	7.691	0.00256
Uppland Regional area	500	17. 86	79	226.09	309.27	2.8361	0.00016

5.1.1 Major rock blocks

Rock-block boundaries occur in most directions with peaks around east-west, northwest, just west of north and northeast. There are very few boundaries in the N10-20E. Northeast structures are comparatively long as are the west-northwest ones.

5.1.2 Rock-block boundaries of intermediate rock blocks

Further division of rock blocks gives many east-west orientated rock-block boundaries. A broad peak occurs in northwest and other peaks around north-south and northeast. The east-west lines are relatively shorter and the northeast ones longer.

6 ANALYSES OF ELEVATION DATA FOR INDIVIDUAL POLYGONS

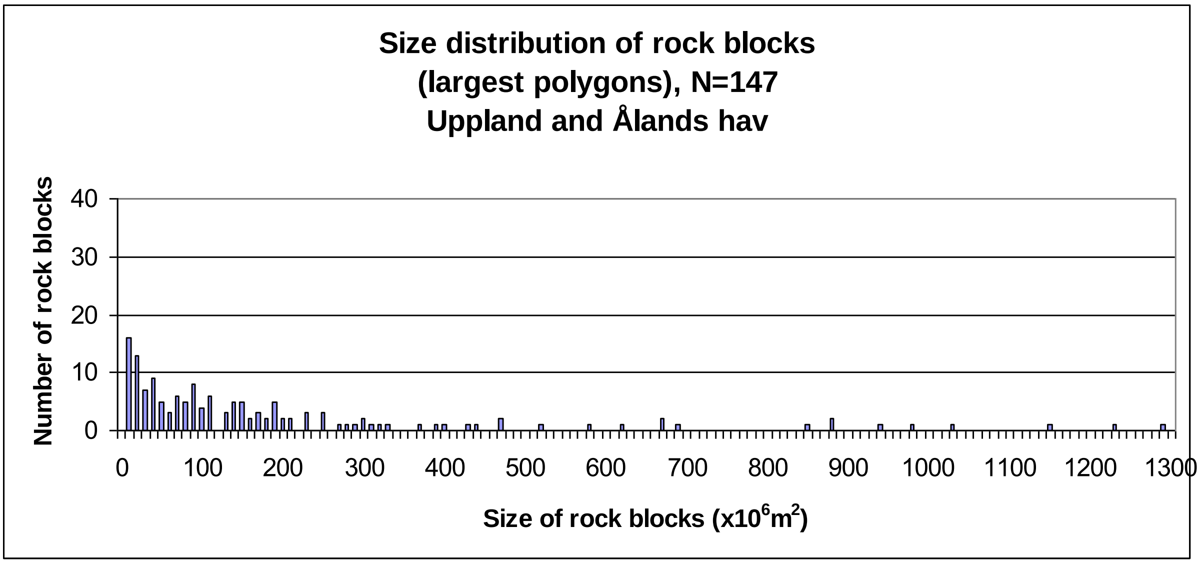
6.1 STATISTICS ON THE ROCK BLOCKS

The individual polygons were analysed for their topographic characteristics and mean, maximum, minimum and range values. Size is shown in Table 2 and in Figure 7. Maximum versus minimum values are displayed in Figure 8 and in maps in Figures 9-12.

6.1.1 Size of rock blocks

Histograms displaying the size of the area for individual polygons are shown in Figures 7 and the statistics are given in Table 2.

There is a decrease in number with increasing block size. Several isolated values for large rock blocks in the very right of the diagrams are due to marginal blocks.



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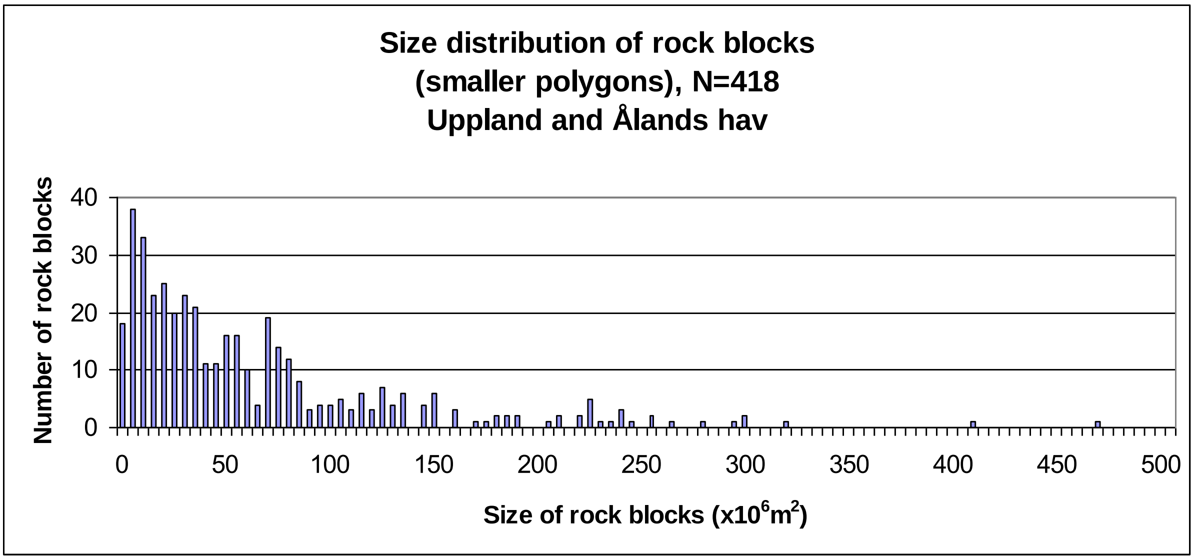

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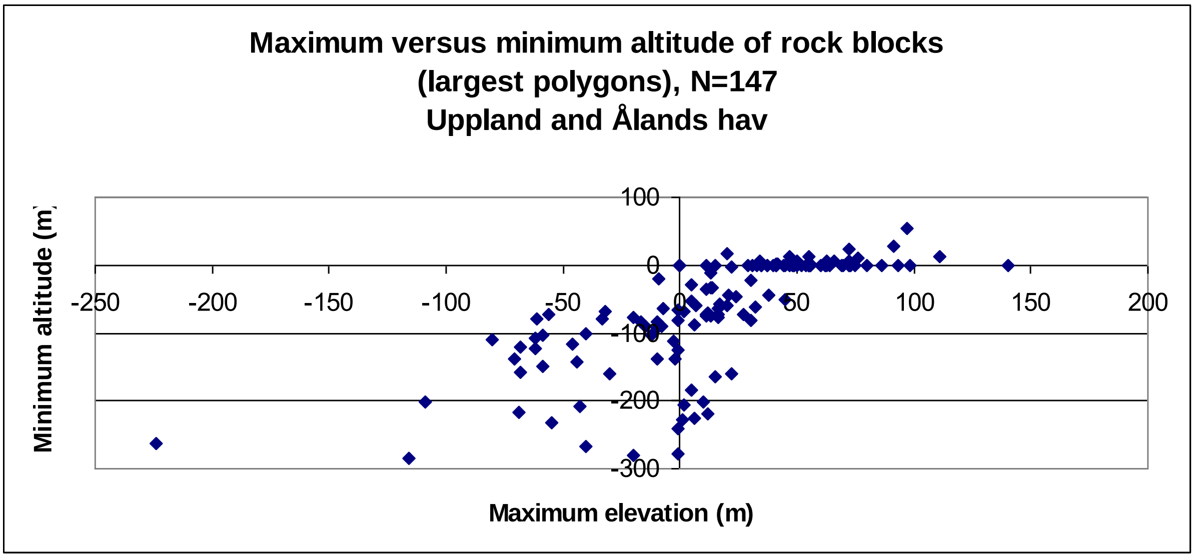
Figure 7. The distribution of size for rock blocks in the Uppland – Ålands-hav area, a) Major rock blocks, 147 blocks, and b) Intermediate rock blocks, 418 blocks, five rock blocks are larger than 500x106m2, not included in the Figure.

6.1.2 Maximum and minimum values for rock blocks

For the smaller rock blocks there is a vague trend similar to the ones recorded in Småland and on land in Uppland (Fig. 8, cf. Beckholmen and Tirén 2008). The zero level – sea level – comprises an anomaly. The values from the sea charts have a much larger spread.

6.1.3 Major rock blocks

In Figure 9 the mean, range, minimum and maximum values are presented in relative colours for the major rock blocks.



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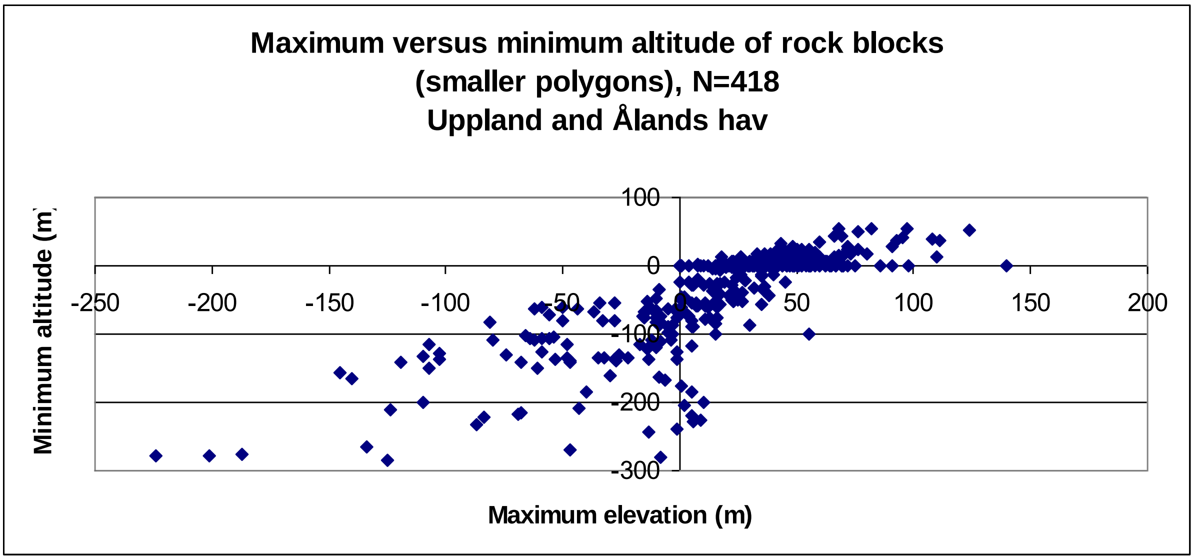

B

Figure 8. The relationship between maximum and minimum elevation of rock blocks (500m grid and readings from sea charts).

The Ålands-hav basin stands out very clearly on the mean, minimum and maximum maps with west-northwest and north-south trends. The mainland and the archipelagos outside Norrtälje and north of Forsmark show up as one entity. The thin rib south of Forsmark has a slightly higher minimum elevation and lower relative range values. The range values especially, reveal the west-northwest features. The range values are high in the deep basin because of the way the polygons were constructed with the block boundary in the deep part including the steep gradient within the rock blocks.

6.1.4 Intermediate rock blocks

The picture for the intermediate rock blocks is very similar to that of the major rock blocks (Fig. 10). The rock block in the sea outside Forsmark has low values along with the archipelago east of Norrtälje. The steep gradient in the deep basin shows up as high range values.

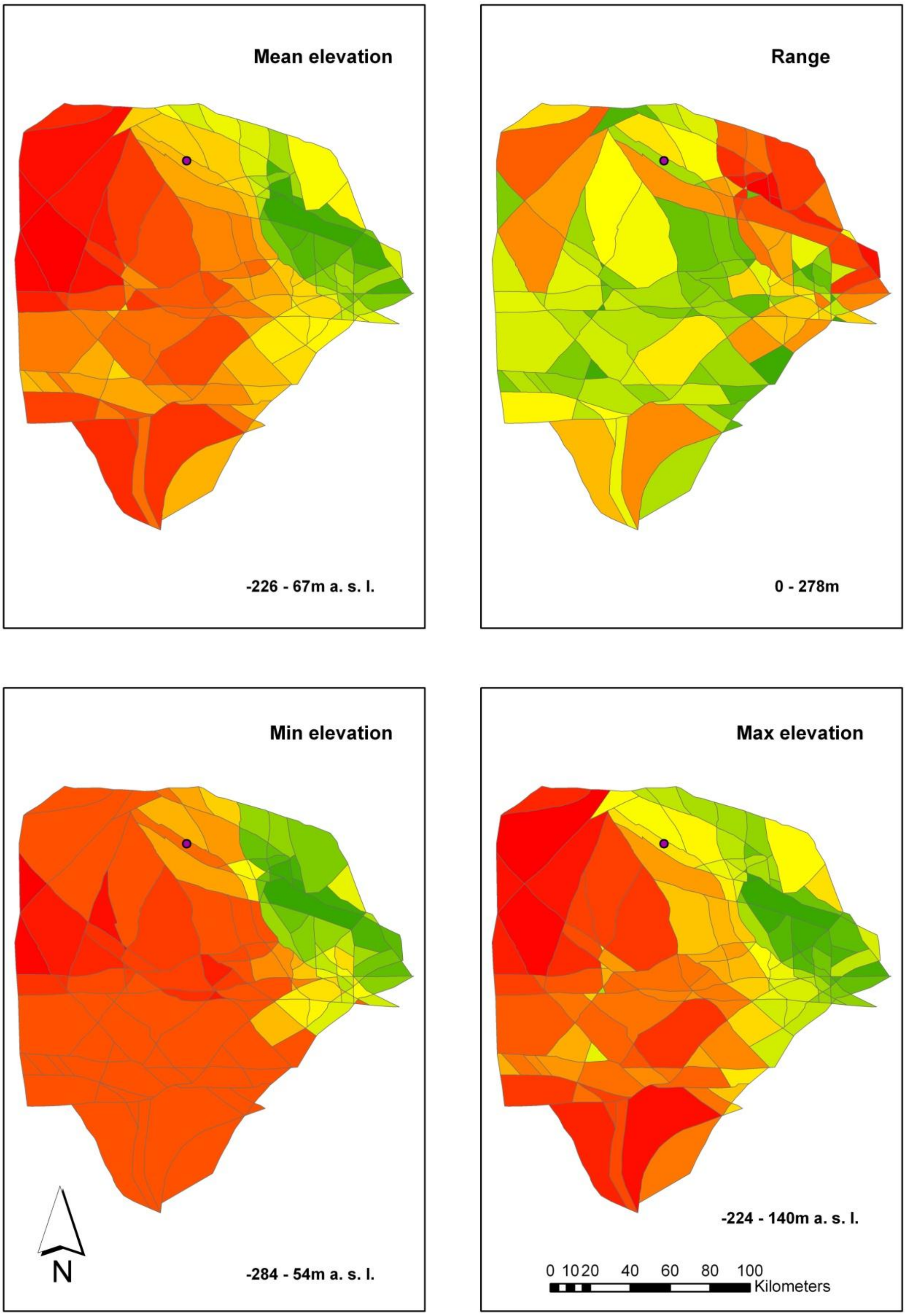

Figure 9. Polygons in the Uppland – Ålands-hav area, major rock blocks, elevation data. Mean altitude, range, minimum and maximum values for the regional rock blocks based on the 500m grid and sea charts readings. Note that the colour palette shows relative colours spanning the range of values and thus has different values for each set of polygons. The span is given in metres for each map. Violet dot = the Forsmark SKB site.

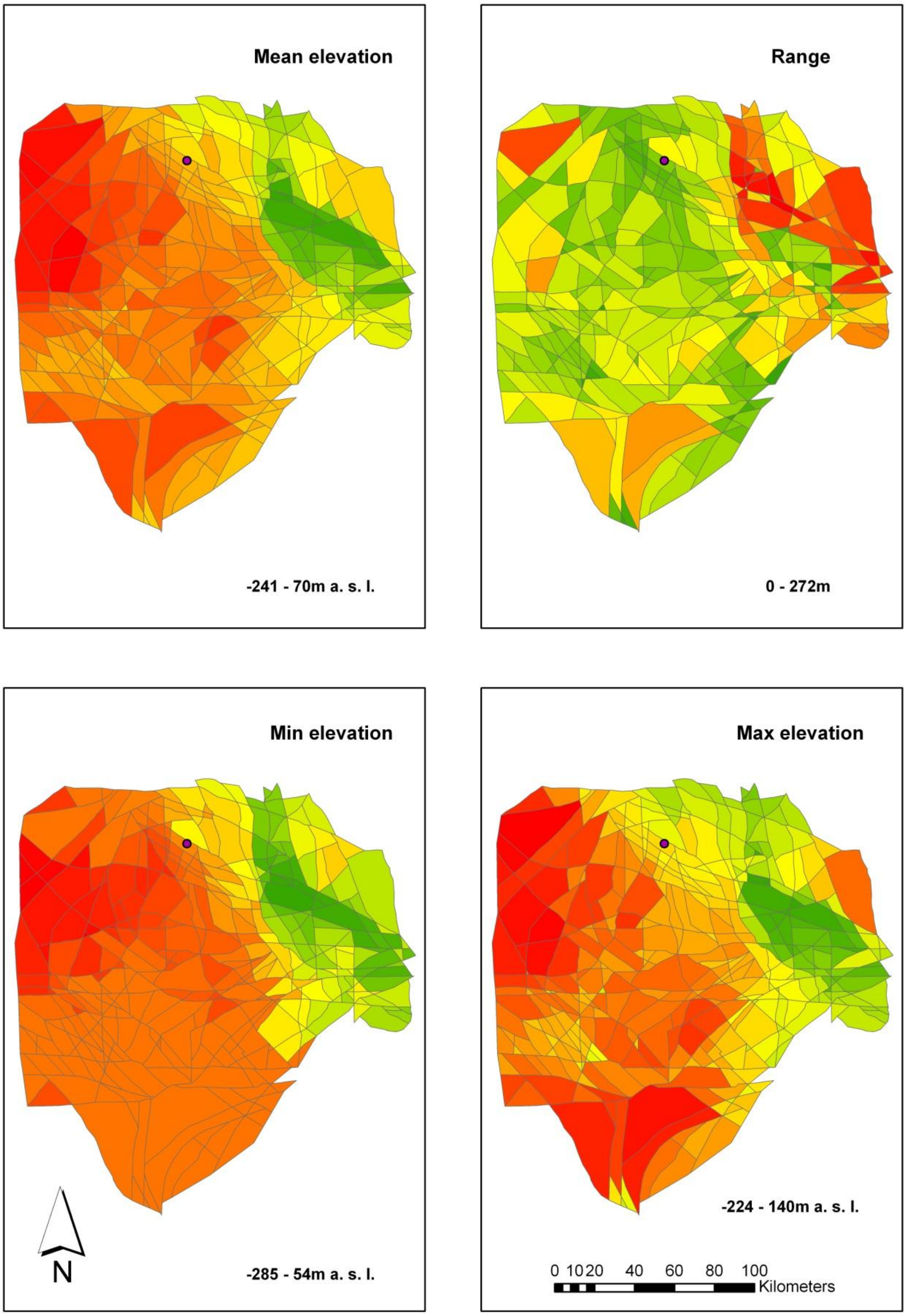

Figure 10. Polygons in the Uppland – Ålands-hav area, intermediate rock blocks, elevation data. Mean altitude, range, minimum and maximum values for the regional rock blocks based on the 500m grid and sea charts readings. Note that the colour palette shows relative colours spanning the range of values 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.

6.1.5 Data displayed on maps with fixed values

To shed some light on the true elevation relation, a fixed interval colour palette was used for both polygon sets (Figs. 11 and 12).

Again, the two sets are very similar but with a higher resolution in the more detailed version. The structure of the basin is better revealed by the fixed interval palette. The very steep gradient outside western Åland shows up on the range map of the finer net (Fig. D) as do the deep areas on the minimum and maximum maps. Note the low very tiny triangular block north of the mafic ridge at Märket.

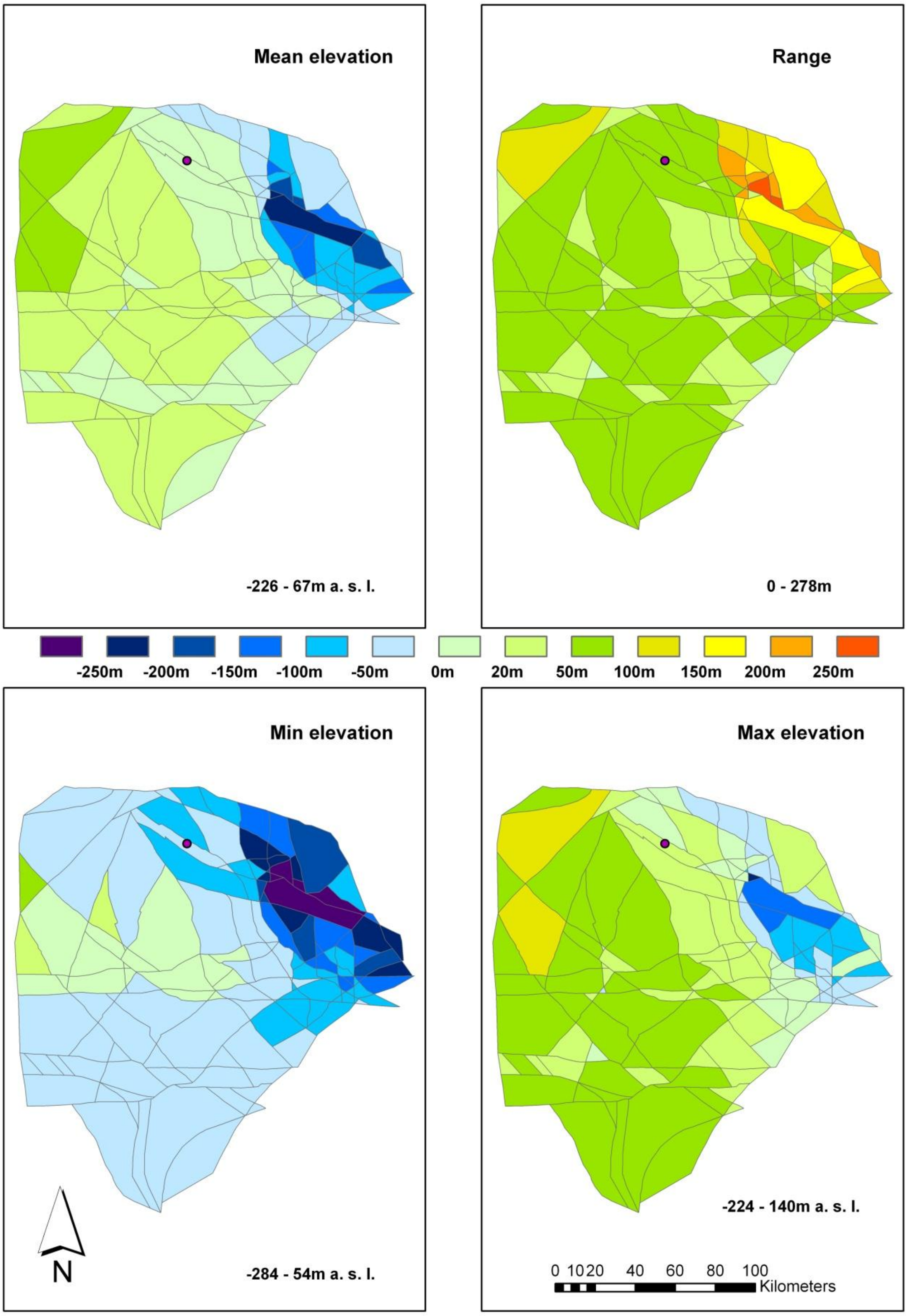

Figure 11. Polygons in the Uppland – Ålands hav area, major rock blocks, elevation data. Mean altitude, range, minimum and maximum values for the regional rock blocks based on the 500m grid and sea charts readings. The altitude is shown with a fixed colour palette. The span is given in metres for each map. Violet dot = the Forsmark SKB site.

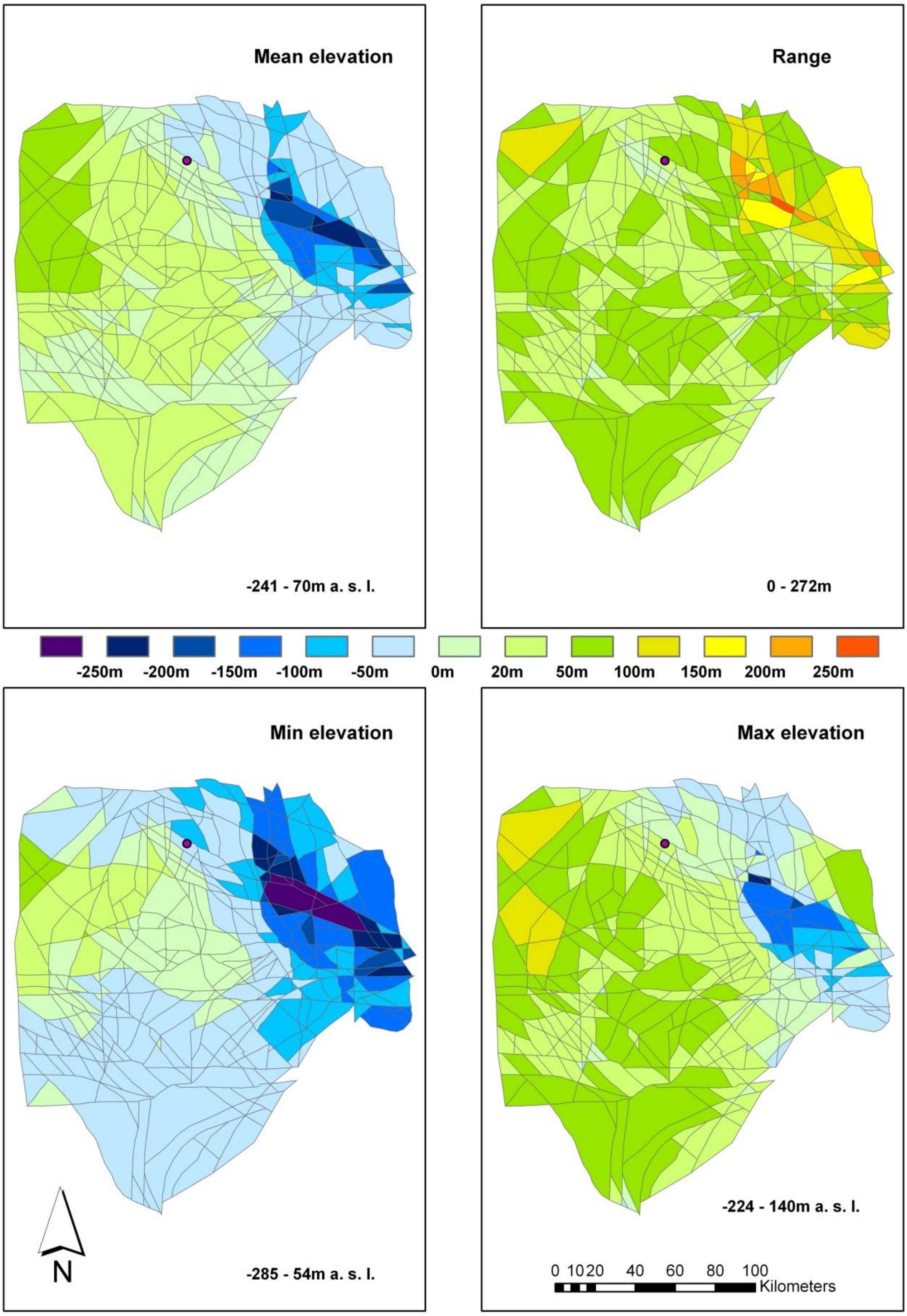

Figure 12. Polygons in the Uppland – Ålands hav area, intermediate rock blocks, elevation data. Mean altitude, range, minimum and maximum values for the regional rock blocks based on the 500m grid and sea charts readings. The altitude is shown with a fixed colour palette. The span is given in metres for each map. Violet dot = the Forsmark SKB site.

7 EARTHQUAKES

The locations of epicentres 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.

There is a deficit in the computed values of expected post-glacial uplift (Fjeldskaar et al 2000) in the Ålands-hav basin and Gävle Bay, i.e. in areas connected to the Jotnian sedimentary basins.

The enlarged Uppland area does not essentially change the picture from the on-land study. In the sea the two 2006 seismic events, M2.02 and M0.16, that triggered this investigation lie in close affinity to a major north-south lineament. A 2003, M0.35 event lies on the southern side of the northward sloping deep basin which is the continuation to the east of a major topographic break and rock-block boundary on land. An 1846 M2.8 event lies at the land-sea break where the isolines make a 90 degrees twist. This 1846 event, together with two of the remaining ones of magnitudes M0.26 (2003) and M3 (1882), lie at the edge of the Åland rapakivi massif or perhaps rather the shoreline, where this makes abrupt changes in orientation.

8 SUMMARY AND CONCLUSIONS

The topography is more broken in the sea area east and northeast of Forsmark than on land. The deepest structure in the sea between Forsmark and the island of Gräsö is not described in the SKB descriptions (SKB 2005). Gräsö is the high north-south rib on the western side of a major rock block, and, like the north-north-easterly blocks on land to the southwest, the western side has a much steeper gradient and is bordered by lower ground to the west. Structures in the Forsmark area can be followed eastwards where they comprise major rock block boundaries. There are two major trends crossing in the Ålands-hav basin, one west-north-westerly and one north-north-westerly to north-southerly. The north-north-westerly trend is parallel to the deep west of Gräsö. South of Forsmark the west-north-westerly continuation of a major structure causes an apparent northerly drop in elevation as in the sea. Forsmark lies on a ribbon with lower ground on its southern and northern boundaries. There is major block-faulting along the south-western boundary of the Åland rapakivi massif.

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2010:41

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