R-08-06

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Site descriptive modelling
SDM-Site Laxemar

Helena Nyman, SWECO Position

Gustav Sohlenius, Geological Survey of Sweden

Mårten Strömgren, Lars Brydsten, Umeå University

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Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 250, SE-101 24 Stockholm
Tel +46 8 459 84 00

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Summary

At the Laxemar-Simpevarp site, numerical and descriptive modelling are performed both for the deep bedrock and for the surface systems. The surface geology and regolith depth are important parameters for e.g. hydrogeological and geochemical modelling and for the over all understanding of the area. Regolith refers to all the unconsolidated deposits overlying the bedrock. The regolith depth model (RDM) presented here visualizes the stratigraphical distribution of the regolith as well as the elevation of the bedrock surface. The model covers 280 km^2 including both terrestrial and marine areas. In the model the stratigraphy is represented by six layers (Z1–Z6) that corresponds to different types of regolith. The model is geometric and the properties of the layers are assigned by the user according to the purpose. The GeoModel program, which is an ArcGIS extension, was used for modelling the regolith depths.

A detailed topographical Digital Elevation Model (DEM) and a map of Quaternary deposits were used as input to the model. Altogether 319 boreholes and 440 other stratigraphical observations were also used. Furthermore a large number of depth data interpreted from geophysical investigations were used; refraction seismic measurements from 51 profiles, 11,000 observation points from resistivity measurements and almost 140,000 points from seismic and sediment echo sounding data. The results from the refraction seismic and resistivity measurements give information about the total regolith depths, whereas most other data also give information about the stratigraphy of the regolith. Some of the used observations did not reach the bedrock surface. They do, however, describe the minimum regolith depth at each location and were therefore used where the regolith depth would have been thinner without using the observation point. A large proportion of the modelled area has a low data density and the area was therefore divided into nine domains. These domains were defined based on the geographical distribution of Quaternary deposits. The average regolith depth in each domain was calculated by the use of available data. These average depths were used together with measured depths to interpolate the regolith depths in the model area. The six layers (Z1–Z6) were modelled in the same way.

The six layers represent different types of regolith. The uppermost layer, Z1, is influenced by the impact from surface processes, e.g. roots and biological activity. The next layer (Z2) consists of peat. After that follows layer Z3, which is characterised by clay gyttja, followed by layer Z4 that consist of sand/gravel, glaciofluvial sediment or artificial fill. Layer Z5 correspond to glacial clay and the bottom layer Z6 correspond to till, which is resting directly upon the bedrock surface.

The resulting model clearly shows the valleys with thick regolith depths, surrounded by higher areas with thin layers of regolith and bedrock outcrops. The glaciofluvial esker (The Tuna esker) is distinctly shown as north-south band with a thick layer of regolith in the western part of the model area. The maximum depth of regolith in the model is about 48 m, and the average depth in this area is 2.2 m with bedrock outcrops included and 3.7 m with outcrops excluded.

Sammanfattning

I Laxemar-Simpevarp utförs numerisk och beskrivande modellering både för det djupa berget och för ytsystemen. Fördelningen av jord- och bergarter på ytan och djupet är viktiga parametrar till exempel för hydrogeologisk och geokemisk modellering samt för den övergripande förståelsen av platsen. Denna rapport beskriver det modellerade regolitdjupet i ett område som är något modifierat från Laxemar-Simpevarps regionala modellområde. Med regolit avses alla lösa avlagringar som överlagrar berget. Jorddjupsmodellen som presenteras här visualiserar de lösa avlagringarnas stratigrafi samt nivån för bergets överyta. Modellen omfattar en 280 km^2 stor yta som inkluderar både land- och havsområden. I modellen representeras stratigrafin av sex lager (Z1–Z6) vilka motsvarar olika typer av regolit. Användaren kan tillskriva dessa lager olika egenskaper. Modellverktyget som använts vid modelleringen av jorddjup är GeoModel som är ett tillägg till ArcGIS.

En detaljerad topografisk DEM (digital höjdmodell) och en jordartskarta har använts som input till modellen. Dessutom har data från 319 borrhål och 440 andra stratigrafiska observationer använts. Dessutom har också ett stort antal värden tolkade från geofysiska undersökningar använts; refraktionsseismiska mätningar fördelade på 51 profiler, 11 000 punkter från resisitivitetsmätningar och närmare 140 000 punkter från maringeologiska undersökningar. Några av de observationspunkter som använts når inte ner till bergets överyta. Dessa observationer har ändå använts för att säkerställa ett minsta djup till berg i de fall där jorddjupet hade blivit tunnare om observationen inte använts. Vissa delarna av modellområdet har en lägre datadensitet än övriga delar och området har därför delats in i nio domäner. Dessa domäner definierades med utgångspunkt från den geografiska fördelningen av jordarter. De genomsnittliga jorddjupen för domänerna räknades ut med de data som finns tillgängliga. Dessa medeljorddjup användes tillsammans med uppmätta jorddjup för att interpolera jorddjupen i hela modellområdet. De sex lagren (Z1–Z6) modellerades på samma sätt.

De sex lagren representerar olika typer av regolit. Det översta lagret, Z1, är påverkat av ytliga processer, t ex rötter och biologisk aktivitet. Nästa lager, Z2, utgör ett torvlager. Därefter följer Z3 som karaktäriseras av postglacial lergyttja, följt av Z4 som består av sand/grus, isälvsavlagringar eller fyllnadsmaterial. Z5 utgörs av glacial lera och det understa lagret, Z6, karakteriseras av morän som ligger direkt på bergets överyta. Alla lager kan ha mäktigheten noll.

Den resulterande modellen visar tydligt de för området karaktäristiska dalgångarna med stora jorddjup, omgivna av områden med mindre eller inget jorddjup. Likaså är isälvsavlagringen vid Fårbo (Tunaåsen) tydligt markerad som ett nord-sydligt stråk med stora jorddjup i den sydvästra delen av området. Det största jorddjupet i modellen är ca 48 m, och medelvärdet för jorddjupet i området är 2,2 m med hällar inkluderade och 3,7 m beräknat utan hällar.

Contents

1 Introduction

SKB has performed site investigations for localisation of a deep repository for high level radioactive waste. The site investigations were performed at two sites, Forsmark in the Östhammar municipality and Laxemar-Simpevarp in the Oskarshamn municipality, see Figure 1-1.

At the Laxemar-Simpevarp site, numerical and descriptive modelling are performed both for the deep bedrock and for the surface systems. The surface geology and regolith depth are important parameters for e.g. hydrogeological and geochemical modelling and for the overall understanding of the area. The here presented regolith depth model (RDM) will be used in e.g. hydrological and transport modelling of the area. The RDM visualize the spatial distribution of the regolith as well as the elevation of the bedrock surface. By compiling all available information regarding depth of regolith and elevation of the bedrock surface, the model also identifies areas with a low density of data.

The use of the term regolith is based on the need of a concept where all unconsolidated deposits overlying the bedrock are included, regardless of its origin. This means that Quaternary deposits of all kinds, such as till, clay and peat, together with artificial filling material are included in the regolith. All known regolith in the Laxemar Simpevarp regional model area was formed during the Quaternary period. Therefore, the term Quaternary deposits (QD) is often used for the regolith in the Laxemar Simpevarp area. In terrestrial areas, the upper c. 0.5 metre of the regolith is referred to as the soil. Soils are formed during the interaction of the parent material, climate, hydrology and biota. Different types of soils are characterised by horizons with special chemical and physical properties.

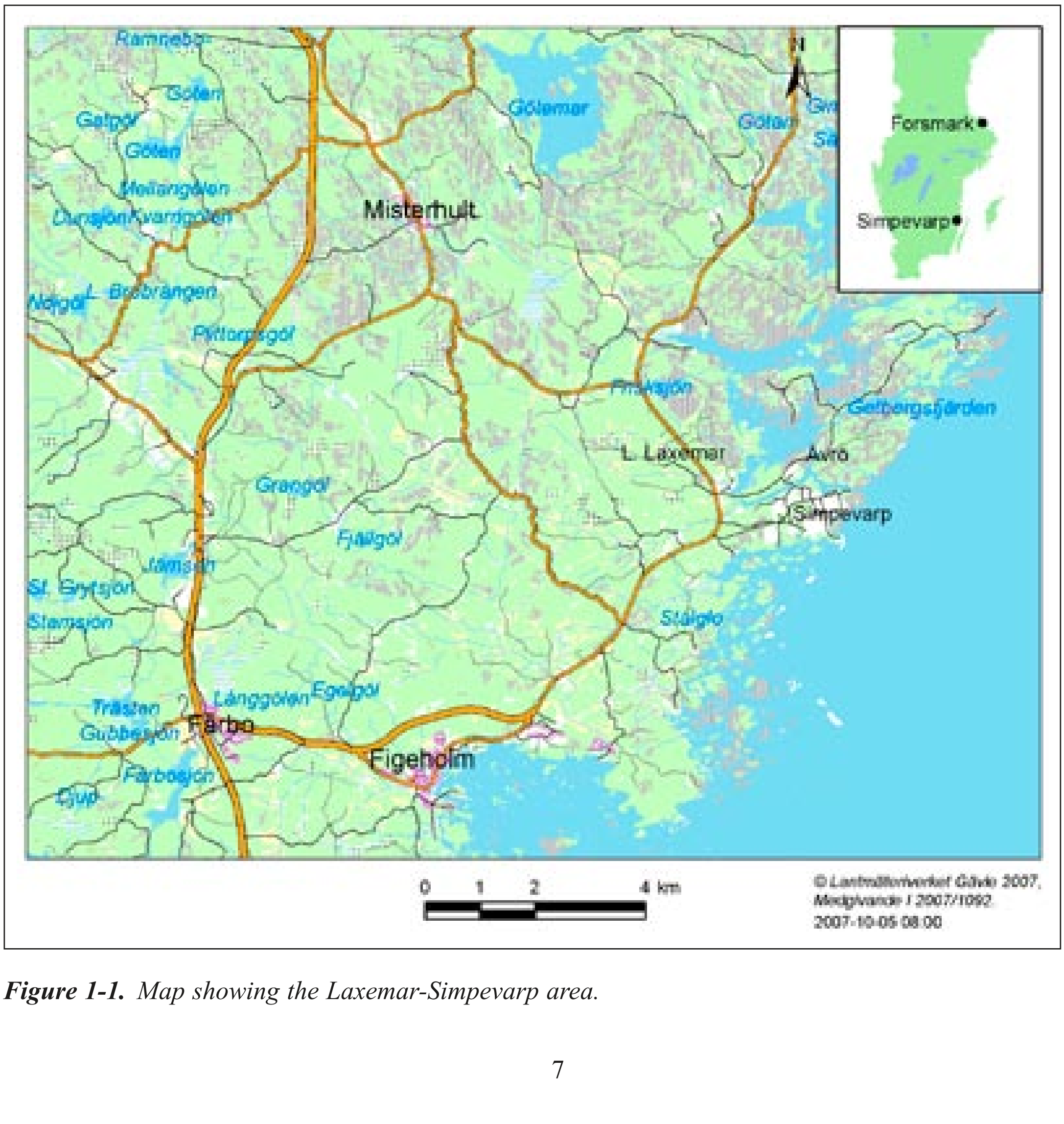

Figure 1-1. Map showing the Laxemar-Simpevarp area.

This report presents a geometric model that illustrates the total regolith depth, subdivided into six layers (Z1–Z6). The layers in the model are purely geometrical and constructed by the use of stratigraphical data from the site. However properties of the six layers must be assigned by the user. For example, the upper layer Z1 can be given different properties in different areas by using the QD or the soil type maps.

The depth model presented here was preceded by an earlier model /Nyman 2005/. The new model uses a much larger number of regolith depth data and a QD map covering the whole modelled area. In the present model interpolations were done with the Kriging method instead of the Natural Neighbour method, which was used in /Nyman 2005/.

Available data from boreholes, stratigraphical observations and geophysical measurements together with the map of QD and the Digital Elevation Model (DEM) were used as input to the RDM. Domains were defined by using the surface distribution of QD (see Section 3.1). The average regolith depths in the domain were calculated with the use of available data. These average depths were used for interpolation in areas with a low density of regolith depth data. The resulting interpolated surfaces are presented in a GIS-environment and delivered on a CD separate from this report. The CD can be found at the SKB archive in Stockholm under media ID C163.

1.1 The model area

The model area represents the Laxemar-Simpevarp regional model area with some extensions (Figure 1-2). These extensions were made to follow the present and future catchment area boundaries.

The area is characterised by a relatively flat bedrock surface intersected by a number of narrow topographical lineaments, i.e. valleys. The highest areas are dominated by till and exposed bedrock, whereas the valleys, often used as arable land, are covered by relatively thick layers of regolith /Rudmark et al. 2005/.

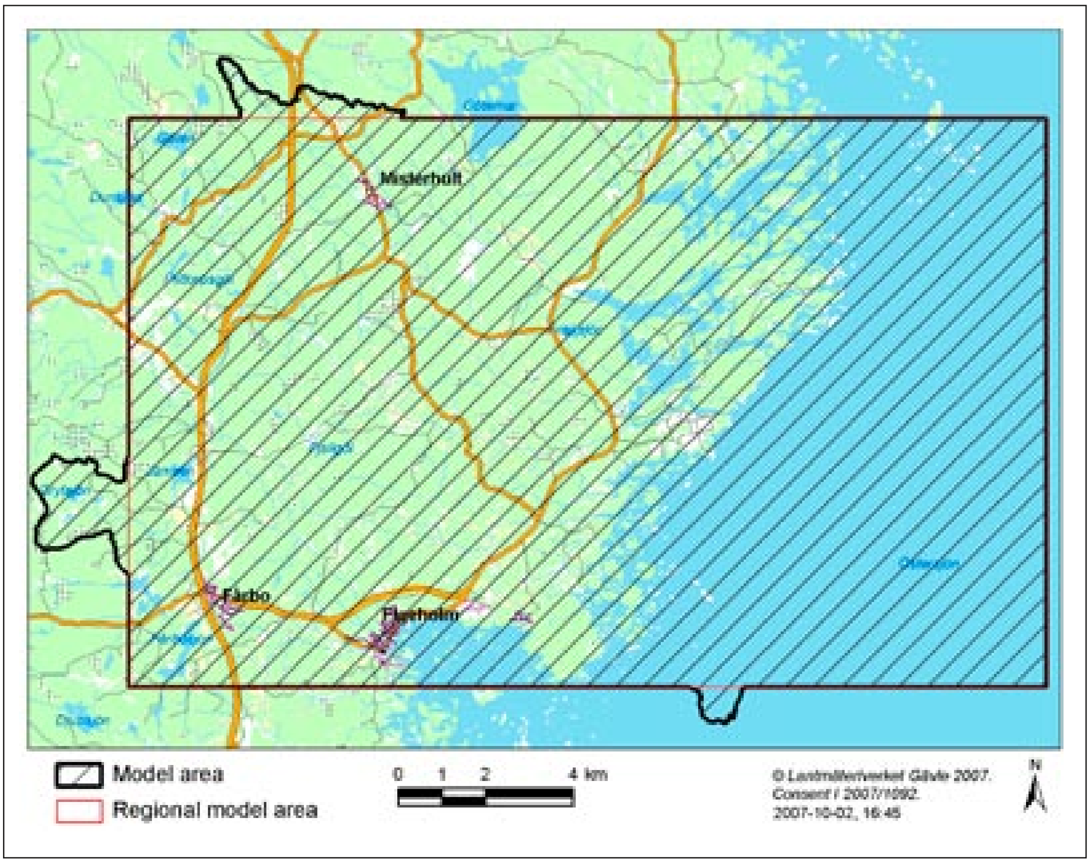

Figure 1-2. *The RDM area equal to the Laxemar-Simpevarp regional model area with some extensions.*

2 Input data

2.1 Available data

Stratigraphical and regolith depth data available at data freeze 2.2 in Laxemar, 31st December 2006 is shown in Table 2-1 and Figure 2-1. After a data evaluation (see Sections 3.2 and 3.3) certain data of the data shown in Table 2-1 was excluded for the modelling of regolith depths.

Table 2-1. Stratigraphical and regolith depth data available for regolith depth model. The geographical distribution of the data is shown in Figure 2-1. Certain data was excluded after a data evaluation (see Sections 3.2 and 3.3).

Data	Description	No of observations	Reference
DEM	The DEM used in the model is based on the DEM produced from laser scanning measurements, the existing DEM from the Swedish national land survey (LMV), the SKB DEM, nautical chart and depth soundings.The DEM has a resolution of 20 metre and describes the whole modelled area.		/Strömgren and Brydsten in prep./
QD map	The map of QD was produced by using several methods.		See Table 2-2
Corings and excavations			
Geotechnical drilling soil observations	Stratigraphy and regolith depth from drilling and weight sounding.	189 observations	/Johansson and Adestam 2004ab/, /Sohlenius et al. 2006/, /Morosini et al. 2007/
Percussion drilling,	Regolith depth from percussion drilling in bedrock.	93 observations	*
Core drilling	Regolith depth from core drilling in bedrock.	37	*
Quarten. deposit mapping, stratig. obs	Mostly shallow observation points with detailed stratigraphy is used.	303 observations	/Rudmark 2004/, /Rudmark et al. 2005/, /Bergman et al. 2005/
In-organic sediment mapping and peat land mapping	Stratigraphic information from lakes and mires. The corings are performed using hand driven corer, hence data contains information of the soft sediments and peat.	28 observations	/Nilsson 2004/
Ocean sediment core sampling	Grab samples and sediment cores of the upper sediment in the marine area, used for validation of the seismic and sediment echo sounding data.	37 observations	/Elhammer and Sandkvist 2005/
SGU's well archive	Data from private wells, which contains regolith depth to bedrock surface. The quality of the coordinates in the well archive is very varied.	57 wells	/SGU 2007/
Geophysical data			
Refraction seismic data	Each observed point along the profiles has coordinates, and an estimated regolith depth.	51 profiles including 2,860 points.	/Lindqvist 2004abc, 2005, 2006/
Resistivity measurements	The regolith thickness was interpreted from the inverted resistivity data. Each observed point along the profiles has coordinates and an estimated regolith depth.	10,971 points	/Thunehed and Triumf 2005, 2006/
Seismic and sediment echo sounding data	Data contains estimated depth to bedrock and stratigraphy for each site.	138,571 points	/Elhammer and Sandkvist 2005/

* These observations are compiled from numerous reports, which not are shown here.

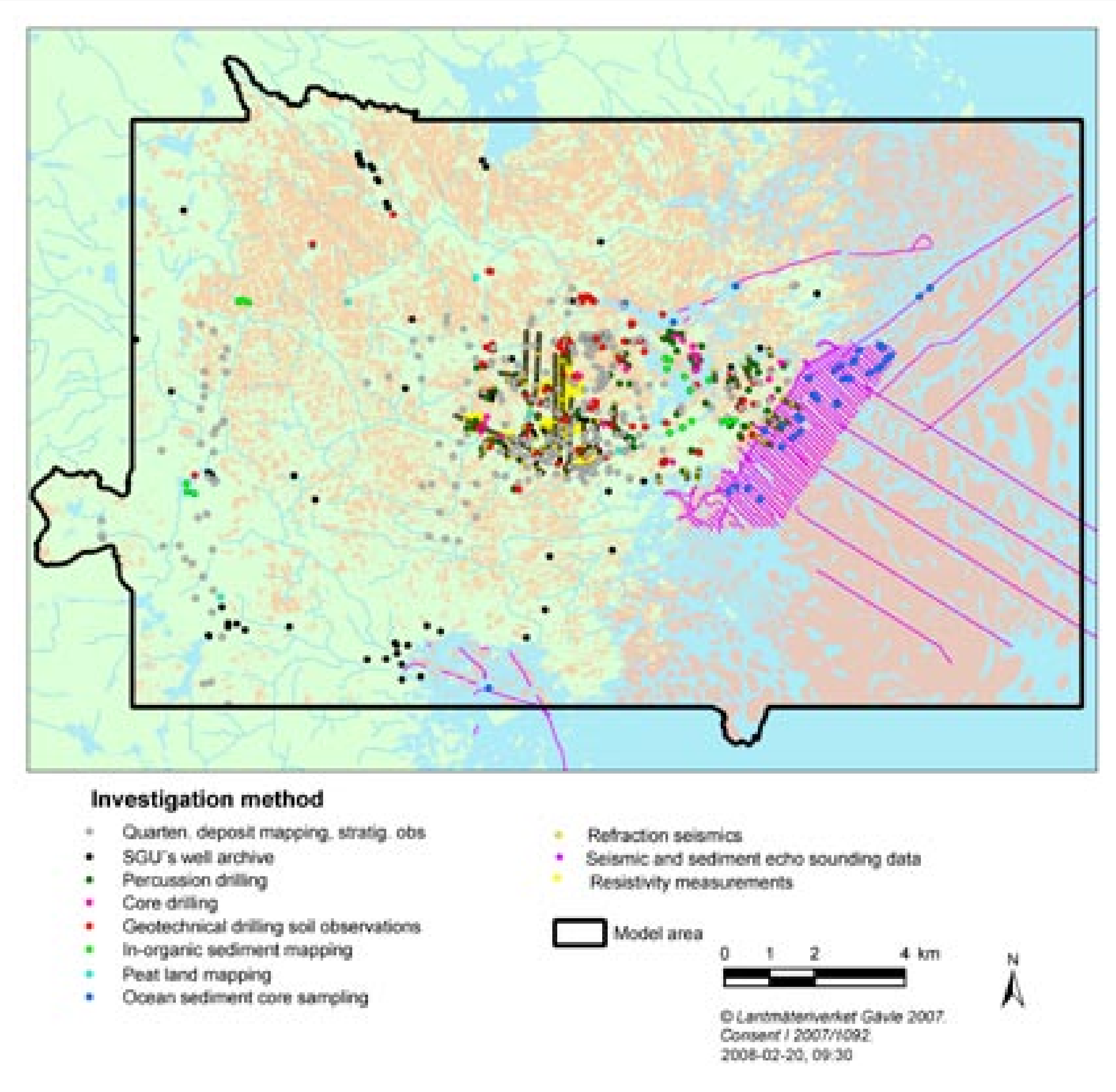

Figure 2-1. *Distribution of data used for interpreting the depth and stratigraphy of regolith in the Laxemar-Simpevarp area. Table 2-1 explains the different types of data shown in the figure. The black line represents the extension of the RDM area.*

Areas shown as outcrops on the QD map are almost lacking a regolith coverage. The distribution of these areas was therefore used as input to the RDM. The QD map was produced by the use of several methods (Figure 2-2 and Table 2-2). In Areas 9 and 10 (Figure 2-2) the map was produced from observations in the field. Area 10 was mapped for presentation at the scale 1:10,000. That means that the part of the map shows all identified bedrock exposures and QD that has a surface extension, which exceed 100 m^2. Area 9 was mapped for presentation at the scale 1:50,000. The smallest mapped area is in general about 40×40 m. Remaining parts of the terrestrial part of the model area were also mapped for presentation at the scale 1:50,000 (Areas 8 and 11). This part of the map is, however, to a large part based on interpretations of aerial photos, which only were checked along the road net. A more generalised method of classification was therefore used in these areas. It was not possible to access Area 8. The distribution of QD in that area is therefore entirely based on interpretations of aerial photos.

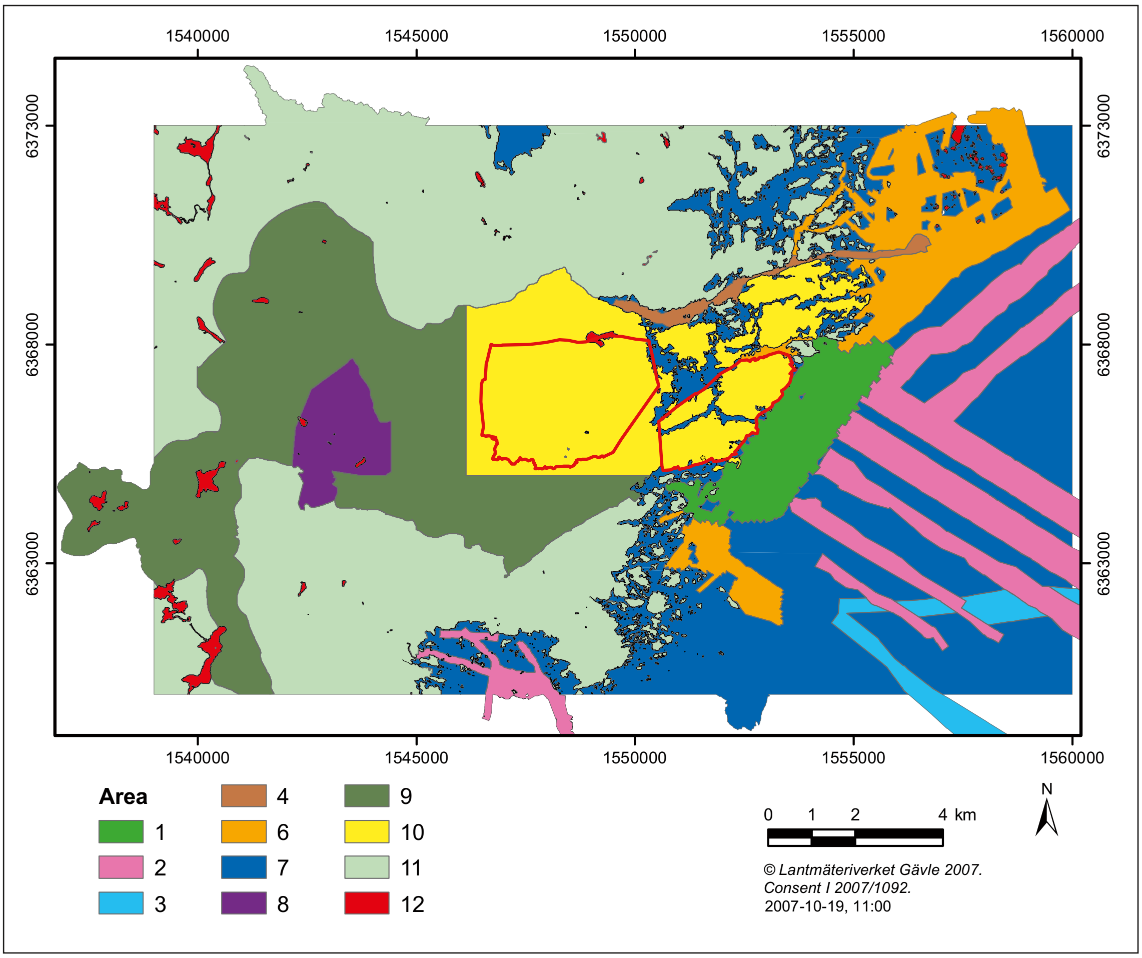

Figure 2-2. *The QD map was produced by the use of several methods. The methods used for the different areas are explained in the text and in (Table 2-2). The boundaries of the Laxemar and Simpevarp subareas are marked with a red line on the map.*

Table 2-2. Short description and references to the methods used to produce the QD map. The geographical distribution of the different areas is shown in Figure 2-2. T = terrestrial areas, M = marine areas, L = lakes.

Area	Type of data	Reference
1 (M)	Detailed marine information (SGU, line spacing 100 m)	/Elhammer and Sandkvist 2005/ modified by /Kjellin 2007/
2 (M)	Local marine information (SGU, line spacing 1 km)	/Elhammer and Sandkvist 2005/ modified by /Kjellin 2007/
3 (M)	Mapped within SGUs regular survey program	/Kjellin 2007/
4 (M)	Local marine information (SGU and MMT)	/Elhammer and Sandkvist 2005, Ingvarson et al. 2004/ modified by /Kjellin 2007/
6 (M)	Mapped by MMT	/Ingvarson et al. 2004/ modified by /Kjellin 2007/
7 (M/L)	Interpreted from bathymetry and surrounding geology (SGU)	/Kjellin 2007/
8 (T)	Interpretations only from aerial photos	/Rudmark et al. 2005/
9 (T)	Information for presentation in 1:50,000	/Rudmark et al. 2005/
10 (T)	Detailed information for presentation in 1:10,000	/Rudmark et al. 2005/
11 (T)	Interpretations from aerial photos and field checks	/Rudmark et al. 2005/
12 (L)	Interpreted from surrounding geology and bathymetry	Sohlenius (no report)

The distribution of QD on the floors of lakes and ponds (Area 12) was interpreted by the results from sediment samples and after comparison with the terrestrial map of QD. Some of the lakes have bathymetric information, which also was used. The marine areas were mapped by the use of several techniques. The map over Areas 1, 2, 3 and 4 was produced by methods, which obtained not only the surface distribution of QD but also the total depth and stratigraphical distribution of these deposits. Area 6 was mapped by techniques, which only obtained data showing the geographical distribution of QD. Area 7 was not included in the marine geological mapping program. The distribution of QD in that area was interpreted from bathymetric information and from the known distribution of QD in the mapped marine and terrestrial areas. The geographical distribution of QD in Area 7 shown should therefore not be regarded as an ordinary map of QD, but more as a general view of the likely composition of the regolith coverage.

The Digital Elevation Model (DEM) used for this regolith depth model has a resolution of 20×20 m /Strömgren and Brydsten in prep/ and displays the elevation of the ground surface (Figure 2-3). The original DEM has a resolution of 10×10 m /Strömgren and Brydsten (in prep)/. However it was not possible to use the 10×10 m DEM in the marine area for security reasons. The 20×20 m DEM was therefore used for the whole modelled area.

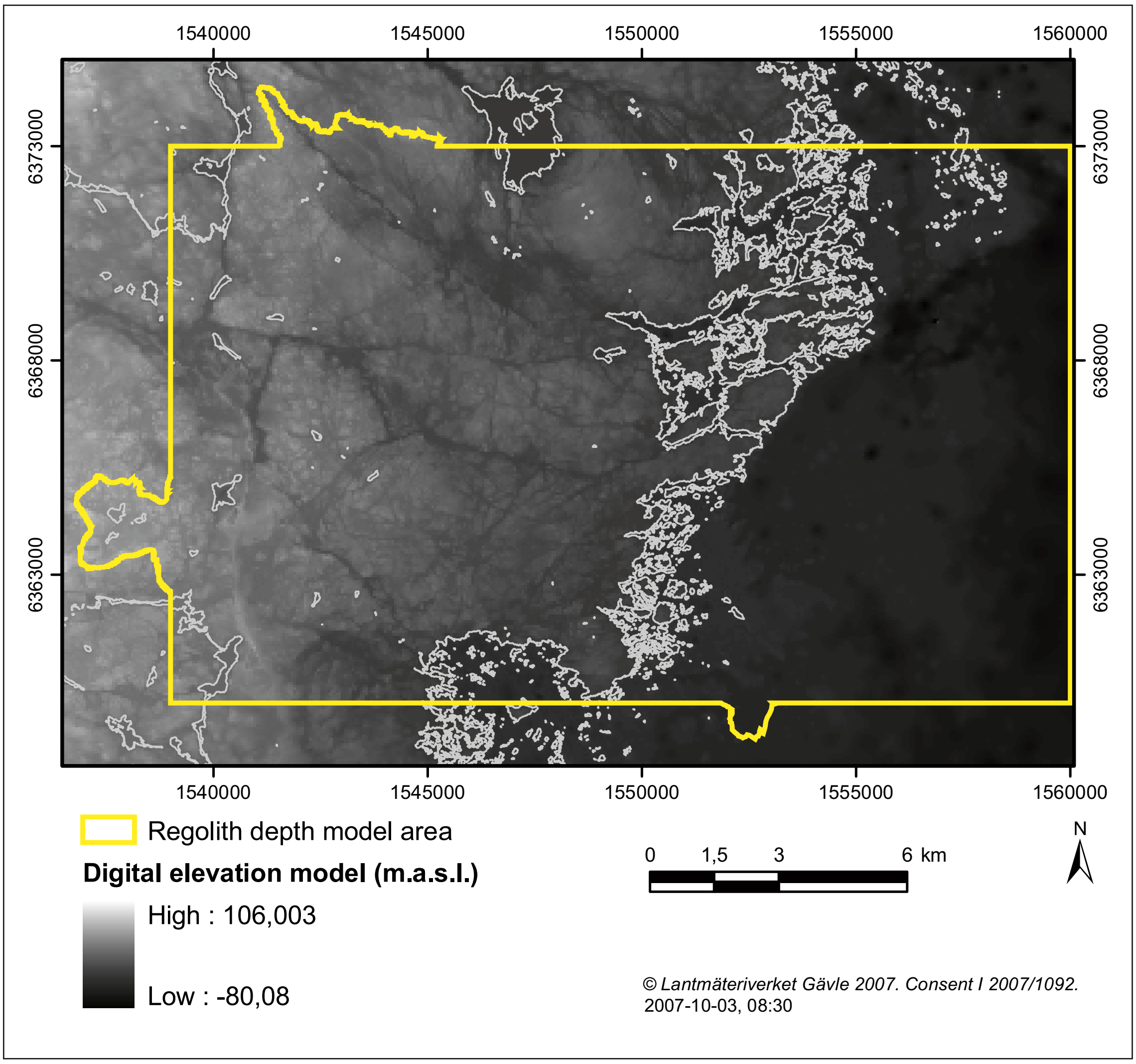

Figure 2-3. The 20×20 m Digital elevation model (DEM) /Strömgren and Brydsten in prep/. The yellow line represents the model area.

Figure 2-1 shows the distribution of regolith depth data used in the model. The outer parts of the area have a low data density. Some observation points do not reach the bedrock surface and do consequently not describe the actual bedrock elevation. They do, however, describe the minimum QD depth at each location.

Data showing total regolith depths were obtained from drillings and geophysical measurements (Table 2-1). The drillings gives information concerning both the stratigraphy and total depth of regolith.

Refraction seismic measurements were mainly carried out in terrestrial areas with a low frequency of exposed bedrock /Lindqvist 2004abc, 2005, 2006/. The results give information about the total depth of regolith.

In selected areas in the Laxemar subarea the electrical resistivity was measured along profiles on the ground /Thunehed and Triumf 2005, 2006/. The resistivity data have earlier been interpreted, together with the results from the refraction seismic surveys e.g. /Lindqvist 2004abc/, to calculate the total depth of the QD /Thunehed 2006/.

The results from the reflection seismic in the marine areas /Elhammer and Sandkvist 2005/ were used to calculate the stratigraphy and thickness of till, glacial clay, postglacial sand and clay gyttja (data from almost 140,000 points). These results were also used to estimate the total thickness of QD.

A helicopter-borne geophysical survey was carried out during 2002 /Triumf et al. 2003/, which covers large parts of the Laxemar-Simpevarp regional model area. These data was earlier used to calculate the total depth of regolith in the area /Thunehed 2006/. It was, however, decided to omit these data from the present RDM (see Section 3.2.3).

2.2 Description of the Quaternary geology in the model area

2.2.1 General description

All known regolith in the Laxemar-Simpevarp regional model area was formed during the Quaternary period and is sometimes therefore referred to as Quaternary deposits (QD). Most QD were formed during the latest glaciation or after the following deglaciation. In the Laxemar-Simpevarp area the latest deglaciation occurred c. 12,000 years BC /Lundqvist and Wohlfarth 2001/. Due to the pressure of the inland ice large parts of Sweden, including the whole Laxemar-Simpevarp regional model area, were covered by water after deglaciation /Agrell 1976/. The highest altitude covered by water in an area is referred to as the highest coastline.

For a thorough description of the genesis and distribution of QD in Sweden the readers are referred to /Lindström et al. 2000/ and /Fredén 2002/. The QD in Sweden are subdivided in two main groups according to genesis and depositional environment: glacial and postglacial deposits.

Glacial deposits were deposited either directly from the inland ice or by the water, derived from the melting of the ice.

The glacial till was deposited directly by the glacier ice. Till is the most common type of QD in Sweden and often contains all grain sizes from clay particles to large boulders. The ground surface in till areas is often characterised by the occurrence of large boulders. The till matrix is dominated by sand and gravel in most of Sweden (e.g. in the Laxemar-Simpevarp area).

The melt water from the ice deposited glaciofluvial deposits. These deposits comprise coarse material, often forming eskers. Compared to the glacial till the glaciofluvial deposits are commonly well sorted with respect to grain size. The glaciofluvial deposits commonly rest directly upon the bedrock surface.

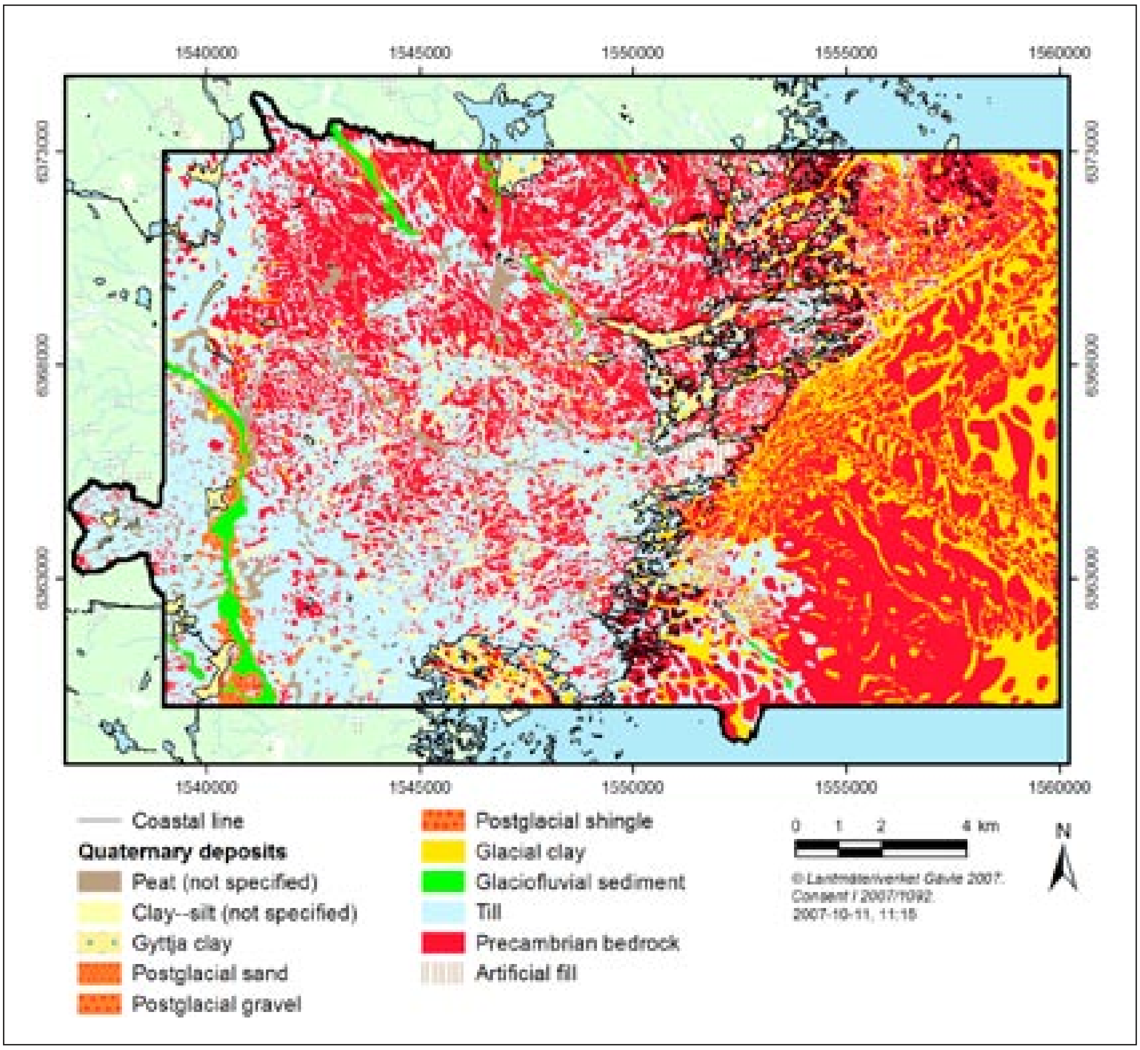

Figure 2-4. *The distribution of Quaternary deposits in the Laxemar-Simpevarp area. The map was produced within several activities, which are summarised in Figure 2-2 and Table 2-2.*

The melt water from the ice also deposited fine-grained material such as silt and clay. These deposits are referred to as glacial clay or silt and are commonly found below the highest coastline where they form flat fields.

Postglacial deposits were formed after the inland ice had melted and retreated from an area. Postglacial sediments and peat form the youngest group of regolith. In general, they overlie till and, locally, glacial clay. Clay, organic sediment, peat, sand and gravel dominate the postglacial deposits.

The postglacial clay can often be found in the deeper parts of valleys below the highest coastline. These clay deposits may contain organic material and is then referred to as gyttja, clay gyttja or gyttja clay.

Postglacial sand and gravel was deposited by currents and waves, which have altered and reworked glaciofluvial deposits and till as the water depth in the sea successively decreased.

Peat consists of remnants of dead vegetation, which are preserved in areas (often mires) where the prevailing wet conditions preclude the breakdown of the organic material.

The typical stratigraphical distribution of QD in areas below the highest coastline is shown in Figure 2-5. The results from SKB's site investigation show that regolith in the Laxemar-Simpevarp area is distributed in a similar way /Rudmark et al. 2005, Sohlenius et al. 2006/.

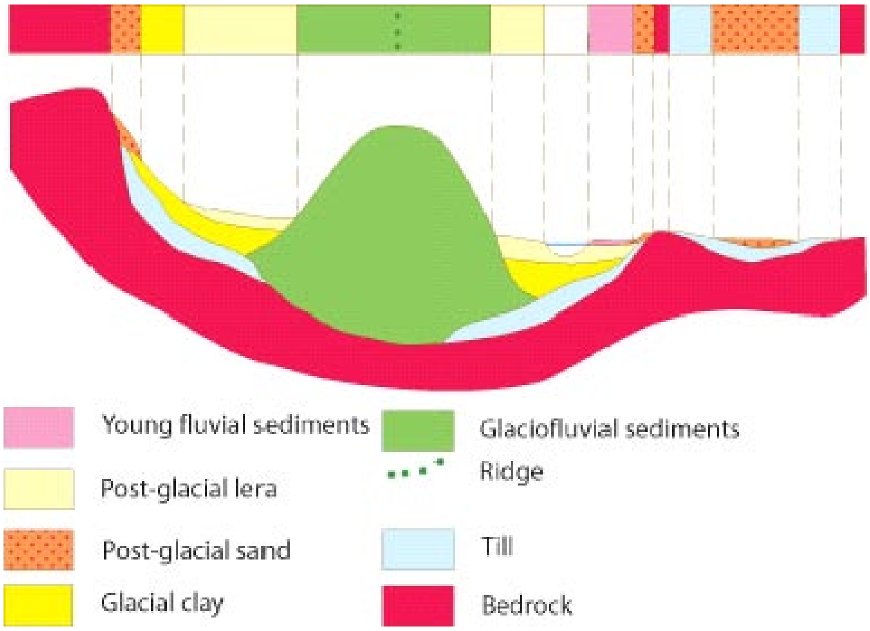

Figure 2-5. *Typical stratigraphical distribution of QD below the highest coastline. Results from the Laxemar-Simpevarp area show that the QD in that area are distributed in a similar way.*

2.2.2 The Laxemar-Simpevarp area

The geographical and stratigraphical distribution of the QD in the Laxemar-Simpevarp area is shown in Figure 2-4 and Table 3-1 respectively. In both the marine and terrestrial parts of the Laxemar-Simpevarp regional model area the distribution of QD is strongly related to the local bedrock morphology. The highest areas have been eroded by the actions of water and/or glacial ice. In both the marine and terrestrial areas exposed bedrock and till dominate these areas. Since the Laxemar-Simpevarp area is situated below the highest coastline, fine-grained water laid deposits have accumulated in the long and narrow valleys, which are characteristic for the investigated area. Artificial fill is regolith emanating from bedrock and QD that has been deposited at a certain location during construction works. The largest areas with artificial fill are situated around the Oskarshamn nuclear power plant on the Simpevarp peninsula. The distribution and properties of regolith in the Laxemar-Simpevarp area is thoroughly described in /Sohlenius and Hedenström 2008/.

Three type areas were defined based on the topography and distribution of QD in the Laxemar-Simpevarp area:

The topographically high areas

These areas are dominated by exposed bedrock and till. In the central and northern parts of the terrestrial areas the proportion of exposed bedrock is high. The high areas on most of the seafloor outside the archipelago are totally dominated by exposed bedrock. In the terrestrial areas some of the areas shown as bedrock on the QD map may partly be covered by thin layers of QD and have richer vegetation than exposed outcrops. Observation at the sea floor shows that a thin boulder layer may cover some areas shown as bedrock outcrops on the QD map.

Till is the most commonly occurring QD in the model area and rests directly upon the bedrock surface. Most till areas are characterised by a high frequency of bedrock outcrops. In certain areas the till has a more coherent distribution than in the area in general. These areas are characterised by hummocks, which probably not are due to the morphology of the underlying bedrock. The till in these areas is thicker than the till in general. One area with a coherent till layer is situated in the south-western part of the model area and another in the central part of the Laxemar subarea.

There are numerous small wetlands in depressions in the till and bedrock dominated areas. Most of these wetlands are covered by peat. The wetlands in the high topographical areas have generally thinner QD coverage compared to the larger present and former wetlands situated in the larger valleys. It is, however, possible that small pockets with thicker QD occur also in these small wetlands.

The valleys

Peat and fine-grained water laid deposits are the dominating surface deposits in the valleys. The total thickness of QD is often several metres in the valleys. Results from drillings show a maximum regolith depth of more than 30 metre and results from geophysical measurements indicates regolith depths of nearly 50 metres. The oldest QD in the valleys is till that is overlain by glacial clay and postglacial sand/gravel, which in some areas is overlain by clay gyttja, and peat.

The floor of the lakes and the seafloor of the valleys, close to the coast, are dominated by clay gyttja, which is currently deposited. In the marine areas outside the archipelago the valleys are dominated by glacial clay covered by a thin layer of postglacial sand.

In the terrestrial area peat, gyttja, clay and postglacial sand/gravel dominate the floor in many of the valleys. The peat is continuously accumulating in the wetlands, whereas the other deposits were formed when the valleys were covered by water. Ditches have lowered the groundwater table in many of the former wetlands and the peat is consequently oxidising. The present layer of peat will therefore become thinner in the future.

The glaciofluvial deposits

There are three small and one large (the Tuna esker) glaciofluvial deposits in the regional model area. These deposits are assumed to rest directly upon the bedrock surface. There are unfortunately only a few data available from the model area supporting that assumption. The glaciofluvial deposit in the western part of the model area, the Tuna esker, has among the largest thickness of regolith in the model area, over 20 metres /SGU 2007/. The other eskers are not well pronounced in a morphological sense and are much thinner with regard to regolith thickness.

3 Methods

3.1 Conceptual model

The Regolith depth model (RDM) presents the total regolith depth and bedrock topography. The conceptual model for the construction of the different layers is based on knowledge from the site /Sohlenius and Hedenström 2008/. The stratigraphical distribution of QD in the Laxemar-Simpevarp area is shown in Table 3-1.

The regolith depth model is subdivided into six layers (Z1–Z6), which are explained in Tables 3-1 and 3-2. The principle for the stratigraphical distribution of the six Z-layers is illustrated in Figure 3-1. Observe that the layer thicknesses are shown in a principle way, and that more combinations of layer exists in the actual model. All the Z-layers can have thickness zero.

The model presents the geometry of the lower level for each layer, as elevation above sea level (RHB 70). The model has a spatial resolution of 20×20 m. The lower level for Z6 is partly interpolated from available data of regolith depth and bedrock outcrops and partly from the average regolith depth in the different domains (see below). Thus, the lower level of Z6 represents the bedrock surface regardless if it is covered by QD or not.

Table 3-1. The stratigraphical distribution of Quaternary deposits in the Laxemar-Simpevarp area and the Z-layers corresponding to the different stratigraphical units.

Quaternary deposit	Relative age	Layer
Bog peat	Youngest	Z2
Fen peat	↑	Z2
Gyttja clay/clay gyttja		Z3
Postglacial sand/gravel	↑	Z4
Glacial clay		Z5
Till	↑	Z6
Bedrock	Oldest	

Table 3-2. Explanation of the six layers used in the RDM.

Type of regolith	Z-Layer	Description/Occurrence
Layer affected by surface processes	Z1	This layer represents the uppermost regolith and is present within the entire area, except in areas covered by peat. On bedrock outcrops, Z1 is 0.1 m and in other areas 0.6 m. If the regolith depth is less than 0.6 m, Z1 will be the only layer. In the terrestrial areas, this layer is supposed to be affected by soil forming processes.
Peat	Z2	This layer is present where peat is shown on the QD map. The peat areas were sub-divided into deep and shallow peat lands (see Table 3-3).
Clay gyttja	Z3	The layer represents clay gyttja, gyttja or recent fluvial sediments.
Postglacial sand/gravel, glaciofluvial sediment and/or artificial fill	Z4	This layer represents postglacial coarse-grained sediments (mostly sand and gravel), artificial fill and glaciofluvial material. The glaciofluvial sediment and artificial fill rest directly upon the bedrock. The postglacial sand and gravel are always underlain by glacial clay (Z5) and till (Z6).
Glacial clay	Z5	The layer represents glacial clay. Z5 is often overlain by postglacial sand/gravel (Z4).
Till (glacial)	Z6	This layer is present in the major part of the model area. The thickness of the layer is based on interpolation and has no maximum or minimum values. Thickness of Z6 is 0 m at bedrock outcrops, if the total regolith depth is < 0.6 m or if the layers above are located directly on the bedrock surface. The lower limitation of Z6 represents the bedrock surface, i.e. the lower level of Z6 represents a Digital Elevation Model of the bedrock surface.

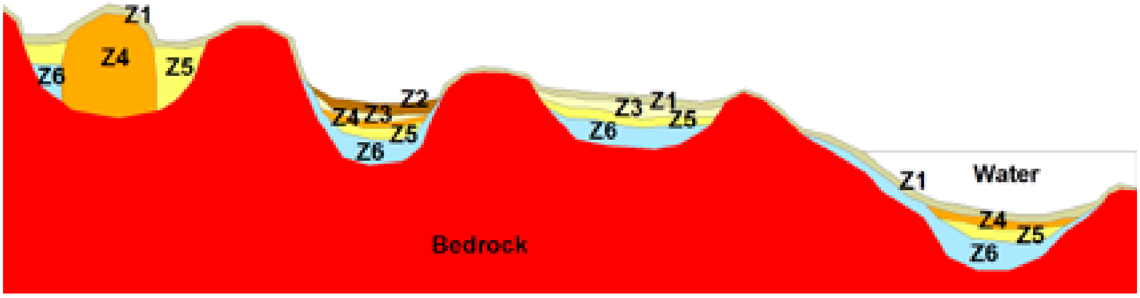

Figure 3-1. *The stratigraphical distribution of the six layers used in the RDM. The layers are explained in Tables 3-1 and 3-2.*

Since there are large parts of the model area with few or no regolith depth data, the area is subdivided into nine domains (Table 3-3 and Figure 3-2). This subdivision into domains is based on the regolith depth data obtained from the area. The surface distribution of QD (Figure 2-4) was used to define the surface extension of these domains. For each domain, the average total regolith depth and the average depth for each Z-layer was calculated by the use of data from the site. Grid points were assigned these average values, which were then used for the interpolation. Next chapter describes the calculation of the average values applied to the model.

3.2 Evaluation of data

3.2.1 Data files

The information from all observation points and profiles was stored in a Microsoft Access database (i.e. mdb-format). The database contains information such as observation ID, surface elevation, x- and y-coordinates, observation depth and stratigraphy of each observation. The database was imported to and interpreted in the GeoModel tool.

Table 3-3. The different domains used for the QD depth model. The type areas are described in the chapter describing the distribution of Quaternary deposits in the area. The different Z-layers used for the stratigraphy are explained in Table 3-2 and Figure 3-1.

Type area	Domain	Deposit on the QD map	Stratigraphy from the ground surface and downwards
I	**1**	Bedrock outcrops with no or almost no regolith coverage.	Z1/bedrock
I	**2**	Till, shingle and boulders.	Z1/Z6/bedrock
II	**3**	Clay gyttja, gyttja and recent fluvial sediments.	Z1/Z3/Z4/Z5/Z6/bedrock
I	**4**	Peat, shallow (peat areas that not border areas with clay or postglacial sand/gravel and are covered by forest or clear cuts).	Z2/Z6/bedrock
II	**5**	Peat, deep.	Z2/Z3/Z4/Z5/Z6/bedrock
II	**6**	Glacial clay and postglacial sand/gravel.	Z1/Z4/Z5/Z6/bedrock
III	**7**	Glaciofluvial deposits, shallow.	Z1/Z4/bedrock
III	**8**	Glaciofluvial deposits, deep.	Z1/Z4/bedrock
	9	Artificial fill.	Z1/Z4/bedrock

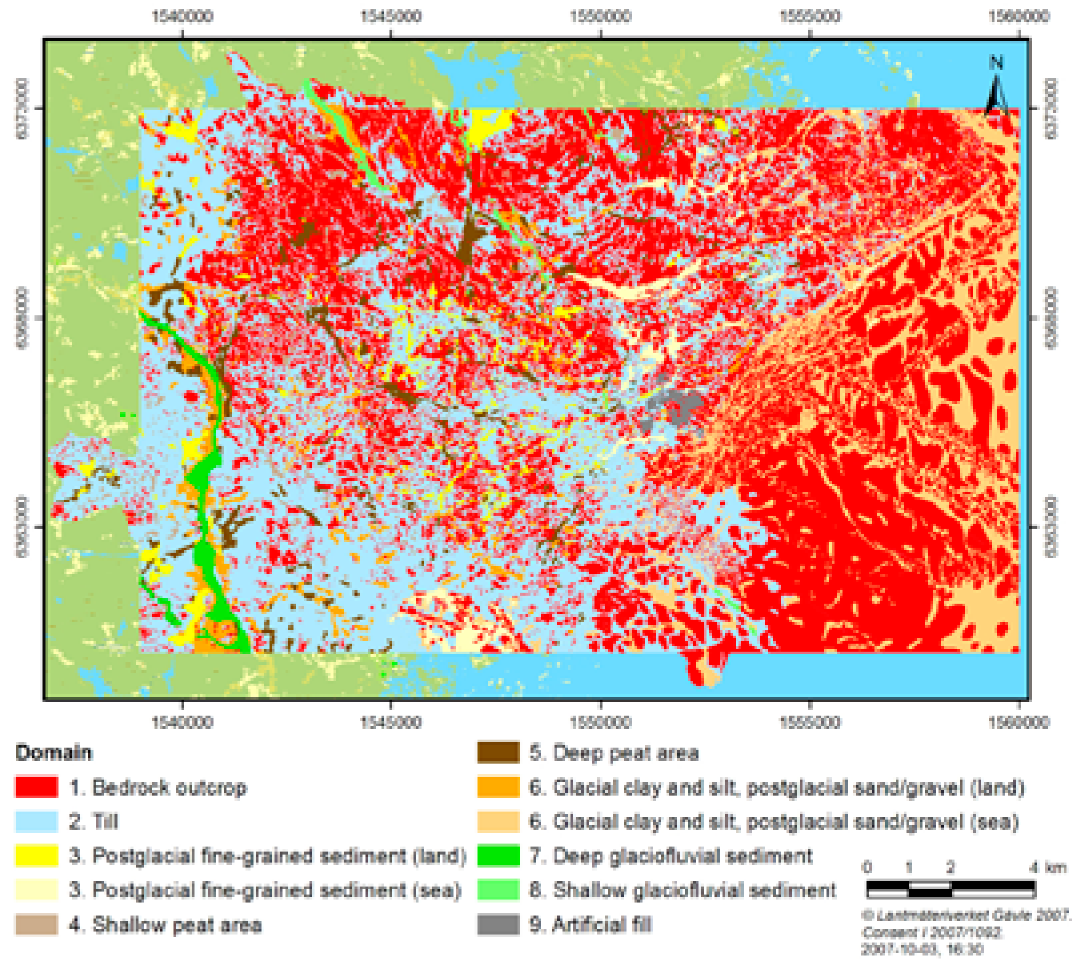

Figure 3-2. The model area classified in the nine domains used in the model. The domains are explained in Table 3-3.

3.2.2 Elevation of boreholes and other data

Some data points lack surface elevation. They were therefore given surface elevations from the DEM. This was done for some of the boreholes and other stratigraphical observations as well as for the resistivity measurements and wells from SGU's well archive.

3.2.3 Usage of different data sets

The input data to the regolith model have different accuracy and sometimes data at the same point but from different investigations are conflicting. For that reason, some data sets had to be screened in different ways.

Inversion of helicopter-borne electromagnetic measurements

A helicopter-borne geophysical survey was carried out during 2002 /Triumf et al. 2003/, which covers large parts of the Laxemar-Simpevarp regional model area. The measurements were carried out along lines with a separation of c. 50 metres. Electromagnetic (EM) data from that survey provides information about the electrical properties of the regolith and the bedrock. The EM data was used to calculate the total depth of the regolith in the investigated area /Thunehed 2006/. The regolith depth was calculated at points, which have a separation of four metres along the measured lines. Each depth point represents a "footprint" with a diameter of 100 metres. As mentioned above, the landscape in the Laxemar-Simpevarp area is characterised by long and narrow valleys with a relatively thick layer of QD. These valleys are surrounded by areas dominated by outcrops and till having a relatively thin regolith layers. A "footprint" with a diameter of 100 metres should therefore represent a large span of different regolith depths. Furthermore, an evaluation of the regolith depths calculated from the helicopter-borne survey compared with results obtained from drillings and other stratigraphical studies showed that the geophysical data underestimated the regolith depths in the valleys. The regolith depth data from the helicopter-borne survey were therefore not used for the present RDM.

Seismic and sediment echo sounding data from the marine area

These data are available from areas 2 and 9 in Figure 2-2.

- In areas 2 and 9 every second point was used since the point density along the profiles is too high compared to the distance between the profiles.
- Only observation points with complete Z3, Z4 or Z5 layers were used for interpolation, i.e. the level of the upper part of the underlying layer must be determined.

Resistivity measurements

The electrical resistivity was measured along profiles on the ground and the results were used to calculate the total depth of the regolith. The data can not be used to accurately resolve regolith cover thinner than around one to two metres. The datasets contain a few points with diverse depths, these points were not used for interpolation. In total 10,971 observation points was used for the RDM.

Bedrock outcrops

A total of 7,084 outcrops within in the model area are shown on the QD map. All grid points from the DEM situated inside outcrop areas were chosen and used in the interpolation. A few small outcrops were not falling inside any grid point and were consequently not used in the interpolations.

Data from SGUs well archive

An extract from SGUs well archive was made in February 2007 /SGU 2007/. The quality of the coordinates in the well archive is varied and the uncertainty for the X- and Y-coordinates can be up to 250 m. Therefore only wells with a regolith depth > 0 m and uncertainty < 70 m for X- and Y-coordinates were used. The distribution of bedrock shown on the QD map has higher quality than the geographical accuracy of the coordinates in the well archive. Wells with regolith depth zero were therefore excluded.

Depth data not reaching the bedrock surface

Some observations did not reach the bedrock surface, but can still give valuable regolith depth information. Initially, an interpolation was made without these points. Thereafter, a control was made to find out if the interpolated bedrock surface was above or beneath the lower end of the observations that did not reach the bedrock. Only data that indicate a thicker regolith than the interpolated result was used for the final interpolation.

Average regolith depths in the domains

Since large parts of the area lacks depth data, the interpolation was supported by average values. The average values of the Z-layers were calculated from input data. In the terrestrial areas, including the lakes, the average values for the different deposits were calculated using data from drillings and excavations. In the marine area seismic and sediment echo sounding data were used to compute the average values. Only observations with complete thickness of the specific deposit were used for calculating the average values. Regolith depths less than 0.5 metre from the marine area were not used for calculation of average values. That is since smaller depths are considered to be below the detection limit for the methods used. In the terrestrial areas, regolith depths below 0.5 metre were included in the calculations.

The average depths of the Z-layers from the marine area were calculated by the use of all depth data collected by /Elhammer and Sandkvist 2005/. Certain of the data from area 2 were collected outside the regional model area and consequently also outside the RDM area.

The average depths of the Z-layers from the marine and terrestrial areas are shown in Tables 3-4 and 3-5, respectively. The stratigraphical units (Z-layers) are generally thicker in the marine areas compared to the terrestrial (compare Table 3-4 and Table 3-5). The domains on the sea floor have therefore thicker average values than corresponding domains on land. Figure 3-2 shows the geographical distribution of the domains in the model area.

The average depths in the domains (Table 3-6) were calculated by adding together the average Z-layer values according to the general stratigraphy of the domains (see Table 3-3). There are no available data showing the thickness of the artificial fill (Domain 9). The depth value (5 metres) used in the RDM is an estimation.

Note that that Z1 is included in the uppermost regolith layer. That is explained by the following example: Till is the uppermost deposit in areas shown as till on the QD map. The average regolith depth in till areas is 2.1 metre and consists of two Z-layer in the RDM (Z1 and Z6). The average total depth of regolith can be calculated as follows: Z1 (0.6 m) + Z6 (1.5 m) = 2.1 metre.

Table 3-4. The average depths of Quaternary deposits in the marine areas mapped by SGU. Only sites with a thickness larger than 0.5 metre were used.

Quaternary deposit	In the QD depth model	Number	Average depth (m)	Max (m)	Standard dev.
Till in the valleys*	Z6	4,575	3.6*	23.8	2.6
Glacial clay	Z5	14,886	2.6	25.7	2.3
Postglacial sand	Z4	2,405	0.8	2.9	0.3
Clay gyttja	Z3	2,359	1.7	4.7	0.8

* The average depth of till in the clay covered valleys.

Table 3-5. The average depth of Quaternary deposits in the terrestrial areas.

Quaternary deposit	In the QD depth model	Number	Average depth (m)	Max (m)	Standard dev.
Till obtained from refraction seismic*	Z6	343	2.3	10.2	2.4
Till in the valleys**	Z6	65	2.0	6.6	1.3
Till in areas shown as till on the QD map	Z6	35	2.1	7.0	1.7
The Tuna esker	Z4	8	13.8	20.0	4.1
Other glaciofluvial deposits	Z4	18	4.1	9.0	2.3
Glacial clay	Z5	54	1.3	8.4	1.3
Postglacial sand	Z4	96	0.7	4.9	0.8
Clay gyttja	Z3	110	1.6	10.1	2.0
Peat	Z2	83	0.85	3.8	0.7

* Areas shown as till on the QD map, corresponding to topographical high areas. Data from the southern parts of the Laxemar subarea were excluded, due to a large till thickness.

** Areas where other deposits, e.g. clay gyttja, covers the till.

Table 3-6. The average regolith depths in the nine domains. The average depths in the domains were calculated by the use of the values from the different stratigraphical units shown in Tables 3-4 and 3-5. The stratigraphical distribution of QD in the different domains is also shown in Table 3-3.

Domain/Quaternary deposit	Z-layers	Calculations of total average depths (m)	Average total regolith depths (m)
1. Bedrock outcrop	Z1	0.1	0.1
2. Till	Z6*	2.1*	2.1
3. Postglacial fine-grained sediment (land)	Z6+Z5+Z4+Z3*	2.1+1.3+0.7+1.6*	5.7
3. Postglacial fine-grained sediment (sea)	Z6+Z5+Z4+Z3*	3.6+2.6+0.8+1.7*	8.7
4. Shallow peat area	Z6+Z2	2.1+0.9	3.0
5. Deep peat area	Z6+Z5+Z4+Z3+Z2	2.1+1.3+0.7+1.6+0.9	6.6
6. Glacial clay and silt, postglacial sand/gravel (land)	Z6+Z5+Z4*	2.1+1.3+0.7*	4.1
6. Glacial clay and silt, postglacial sand/gravel (sea)	Z6+Z5+Z4*	3.6+2.6+0.8*	7.1
7. Deep glaciofluvial sediment	Z4*	13.8*	13.8
8. Shallow glaciofluvial sediment	Z4*	4.1*	4.1
9. Artificial fill	Z4*	5.0*	5.0

*Including Z1.

3.3 Construction of databases used for interpolation of raster surfaces

Data used for interpolation of raster surfaces in the RDM are of different origin (Table 2-1) and quality. In order to generate a good interpolation result, data of lower quality were removed from data of higher quality in overlapping areas. The methodology for construction of databases used for interpolation of raster surfaces described below is based on judgement of test interpolations and knowledge of how the interpolation procedure works.

The proportions of different data in the database used for interpolation of the bedrock surface (Z6) are described in Table 3-7. The geographical distribution of the data is shown in Figure 3-3. Table 3-8 shows the density of data in different parts of the model area.

Because of high point density in the dataset from the sediment and echo sounding measurements performed by SGU /Elhammer and Sandkvist 2005/ only every second measurement point was included in the Z6 database.

The 20 m DEM /Strömgren and Brydsten in prep/ was converted to points. All these points within areas for bedrock outcrops (Domain 1 in Table 3-6) were included in the Z6 database. These points were given regolith depth zero (i.e. 0.1 m) in the model. All points within the Domains 2-6 (Table 3-6) were given average values for the QD depth according to which domain they were located in. These average QD depth values were recalculated to elevation levels by subtraction from the corresponding elevation levels from the DEM.

All average QD depth points and bedrock outcrops within a buffering distance of 50 m from all other data were excluded from the Z6 database. All data not reaching bedrock (No in Table 3-7) within a buffering distance of 30 m from measurement points from the sediment and echo sounding measurements were excluded from the Z6 database. All data not reaching bedrock within a buffering distance of 30 m from data reaching bedrock (Yes in Table 3-7) were excluded from the Z6 database.

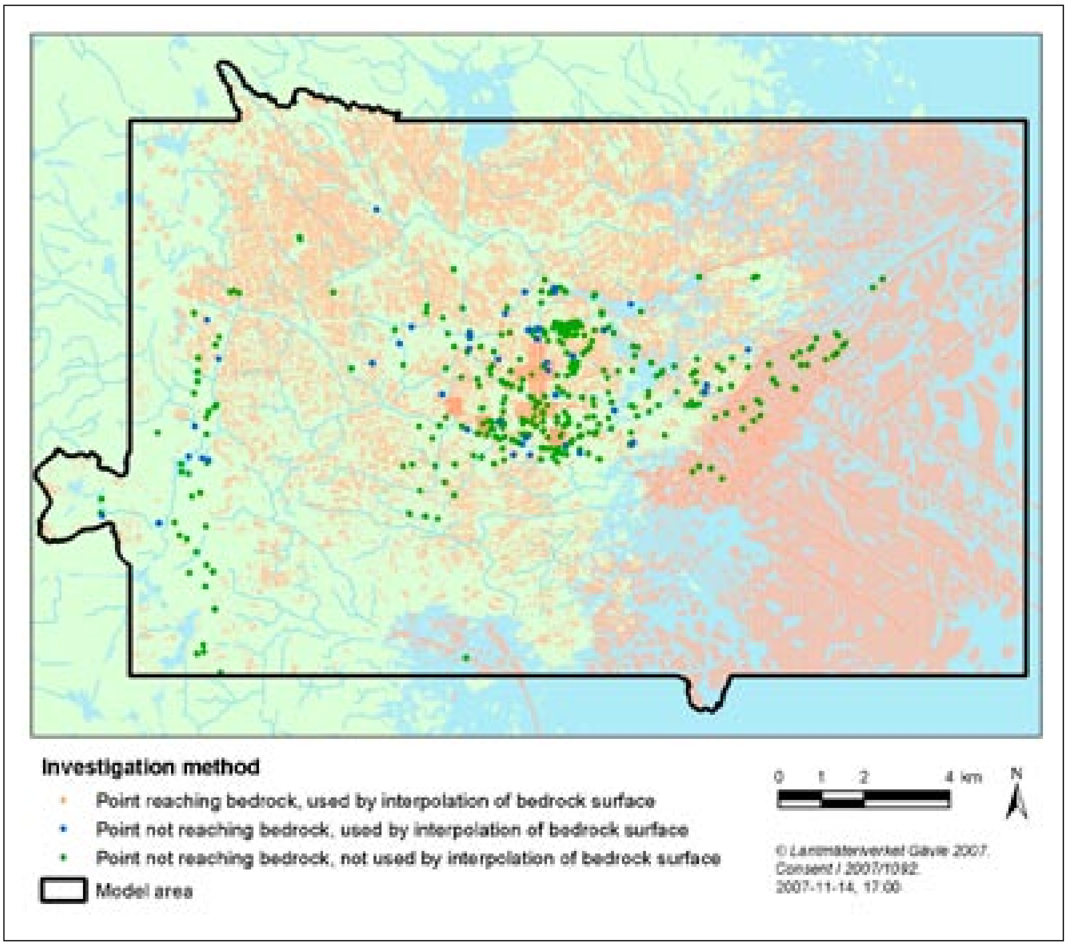

Figure 3-3. Data used for interpolation of the bedrock surface. The point colour indicates if the observation has reached bedrock or not.

Table 3-7. Data used for interpolation of the bedrock surface, which correspond to the lower level of Z6. Data excluded for interpolation of regolith depths are also shown in the table.

Data type	Bedrock reached	No of points used for interpolation of Z6	No of points excluded by buffering	No of points excluded by test interpolation
Seismic and sediment echo sounding data	Yes	138,571		
Refraction seismic data	Yes	2,860		
Percussion drilling, percussion drilling soil observation	Yes	93		
Geotechnical drilling soil observations	Yes	112		
Well from SGU´s well archive	Yes	57		
Core drilling	Yes	37		
Quarten. deposit mapping, stratig. obs	No	30	41	231
Geotechnical drilling soil observations	No	25	37	15
In-organic sediment mapping	No			21
Peat land mapping	No			7
Ocean sediment core sampling	No		31	6
Neotectonic stratigraphic observation	No			1
Resistivity measurements		10,971		
Bedrock outcrops		270,125	20,988	
Average regolith depth values		378,652	26,036	
Total no of points used for interpolation of Z6		801,533		

Table 3-8. Point density (number of points per square kilometre) for data used for interpolation of the Z6 layer. The calculated average regolith depths are not included in the table. The different areas referred to in the table are shown in Figure 2-2.

Sub-domain	Area (km²)	No. Points	Density (points × km⁻²)
Land (Areas 8, 9, 10 and 11)	169.5	13,953	82
Detailed Marine Geology Survey (Area 1)	8.2	101,005	12,364
Regional Marine Geology Survey (Areas 2 and 4)	26.8	30,929	1,154
Other sea areas (Areas 3, 6 and 12)	74.5	1,840	25

Databases used for interpolation of raster surfaces for the lower boundaries of glacial clay (Z5), clay gyttja (Z4), sand/gravel (Z3), peat (Z2) were constructed. The proportions of different data in these databases are described in Table 3-9.

All data, except data not reaching bedrock (No in Table 3-7), were merged to a database. An interpolation was made of a raster surface with a resolution of 20 m using this database. All points not reaching bedrock with elevation levels above the interpolated raster surface (referred to as "No of points excluded by test interpolation" in Table 3-7) were excluded from the final Z6 database.

Measurement points from the seismic and sediment echo sounding data corresponding to the Z3–Z5 layers were included in the databases. Average QD depths from Domains 3-9 (Table 3-6) were included in the Z2–Z5 databases in areas between the measurement points. These average QD depths were calculated to elevation levels used in the databases by subtraction from the corresponding DEM values.

All average QD depth points for the Z2–Z5 databases, within a buffering distance of 20 m from the observation points were excluded from the databases. The boundary of Domains 3–9 were divided in points, every 30 m. These points, named as extension points in Table 3-8 were given values from the 20 m DEM and included in the Z2–Z5 databases.

3.3.1 Kriging interpolation

Raster surfaces for the lower levels of Z2–Z6 were calculated in ArcGis 9.2 Geostatistical Analyst extension. The resolution was set to 20 m. Kriging was chosen as the interpolation method /Davis 1986, Isaaks and Srivastava 1989/. Kriging is often associated with the acronym B.L.U.E ("best linear unbiased estimator"). Ordinary Kriging is linear because its estimates are weighted linear combinations of all available data; it is "unbiased" since it tries to have mean residual equal to 0; it is "best" because it aims at minimizing the variations of the errors. The choice of semivariogram model and the parameters scale, length and nugget was done with the Geostatistical Analyst extension.

Table 3-9. Databases used for interpolation of glacial clay (Z5), clay gyttja (Z4), sand/gravel (Z3), and peat (Z2) raster layers.

	Layer			
Datasource (no of points)	Z2	Z3	Z4	Z5
Average regolith depth values	30,976	42,138	152,869	141,889
Seismic and sediment echo sounding data		5,359	19,632	66,763
Observation points	63	88	111	96
Extension points	16,467	17,260	61,783	60,991
Total no of points	47,506	64,845	234,395	269,739

Before the interpolation started, the models were validated both with cross-validation (one data point is removed and the rest of the data is used to predict the removed data point) and ordinary validation (part of the data is removed and the rest of the data is used to predict the removed data). Both the cross-validation and ordinary validation goals produce a standardized mean prediction error near 0, small root-mean-square prediction errors, average standard error near root-mean-square prediction errors, and standardized root-mean-square prediction errors near 1. Cross validations using different combinations of Kriging parameters were performed and the model with the most reasonable statistics was chosen. Finally, validations were performed using the most appropriate Kriging parameters in order to verify that the models fit unmeasured locations. Unfortunately, the standardized mean prediction errors and the standardized root-mean-square prediction errors were not calculated for all models. The Kriging parameters and the models used for interpolations are presented in Appendix 1.

3.4 Adjustment and combining of interpolated and calculated surfaces

Below follows a description of adjustments made when importing all the raster layers into Arc GIS 9.1, Spatial Analyst extension. In addition to the adjustment described below all layers were cut inside the model area. The six Z-layers are explained in Table 3-2.

The interpolated bedrock surface is equal to the lower level of Z6 and was adjusted not to exceed the DEM topography. Z6 correspond to till but it should be observed that Z6 is present in the whole modelled area also where the thickness of that layer is zero. All Z-layers were adjusted not to exceed the DEM and not to be below the bedrock surface (lower level of Z6). Z-layers overlain by another Z-layer were adjusted not to exceed the level of the overlying layer. In areas with bedrock outcrops the lower level Z6 is adjusted to ensure a regolith thickness of 0.1 metre (i.e. the thickness of Z1). That was included in the interpolation by discrete points but was adjusted to be exactly 0.1 m in areas where the results showed smaller or larger depths.

The different types of regolith shown on the QD map have a thickness of at least 0.5 metre. However, in some areas with regolith the interpolated elevation of the bedrock surface lied close to that of the DEM (less than 0.1 m below the DEM). In these areas the bedrock surface was lowered 0.6 m below the DEM.

Z2 corresponds to peat, which only exists in the terrestrial area. After interpolation, the lower level of Z2 (equal to the lower level of a peat layer) was adjusted to only appear where the map of QD shows peat.

Z1 is covering the whole model area, except peat areas where Z1 has no thickness. On bedrock outcrops Z1 was set to 0.1 m and in other areas to 0.6 m. Z1 is in other words not created from observations but from estimated values.

Z3 corresponds to clay gyttja. After interpolation, the lower level of Z3 was adjusted to only appear where the map of QD shows clay gyttja or peat within Domain 5 (deep peat areas).

Z4 corresponds to postglacial sand/gravel, glaciofluvial sediment or artificial fill. After interpolation, the lower level of Z4 was adjusted to only appear where the map of QD shows postglacial sand/gravel, glaciofluvial sediment, artificial fill or peat within Domain 5 (deep peat areas).

The lower level of Z4 was adjusted to the same level as the bedrock surface (lower level of Z6) where glaciofluvial sediment and artificial fill appear at the map of QD.

Z5 corresponds to glacial clay. After interpolation, the lower level of Z5 was adjusted to only appear where the map of QD shows postglacial sand/gravel, glacial clay or peat within Domain 5 (deep peat areas).

3.5 Import of the layers into the GeoModel tool

The GeoModel program was used for the final stage of regolith depth modelling. That program is a graphical tool for geological modelling and editing in a GIS-environment (ArcGIS 9.2) /DHI Water & Environment 2008/. The concept of the GeoModel is to provide a simple GIS-based model in which the user can view existing observation data, interpolate geological formations based on observation points, evaluate and adjust the interpolated layers and present the results as layers in profiles.

A database was compiled with generalised stratigraphical data from all corings and excavations. That database was used in the GeoModel for viewing the information stored for each observation point. Additionally, the GeoModel was used for extracting 11 stratigraphical profiles from the area. The stratigraphical data was included in these profiles.

The GeoModel provides a close link to the hydrological modelling tool MIKE SHE, which is being used for the hydrological and near-surface hydrogeological modelling at the Laxemar-Simpevarp site. Input files for the hydrological model can be prepared in the GeoModel and results from the MIKE SHE model can be imported and presented in the GeoModel-environment. The model can also be transferred to ASCII-files or ESRI grids.

4 Results

4.1 Total regolith depth

Figure 4-1 shows the modelled distribution of total depths in the Laxemar-Simpevarp regional model area. Figure 4-2 shows the distribution of regolith depths in the central part of the model area. The result clearly reflects the overall character of the area with thin layers of regolith in high topographical areas and thicker layers in valleys. The relatively thick regolith layer in areas covered by glaciofluvial material and artificial fill differs, however, from that pattern. Especially the large glaciofluvial esker, the Tuna esker, is clearly recognisable in the western part of the modelled area (Figure 4-1). There are a relatively small number of data on the total depth of regolith in the large valleys. In the regolith depth model, most of the depths in these valleys are calculated from the average thickness of the deposits present in these areas. Results from drillings indicate, however, that the regolith depth in the large valleys is generally larger than the average values used in the model. It is therefore possible that the total depth of regolith in the large valleys is generally larger than shown in the model. The average and median regolith depth of the interpolated and adjusted model is shown in Table 4-1. The maximum total regolith depth in the model is about 48 m, in the bay Getbergsfjärden.

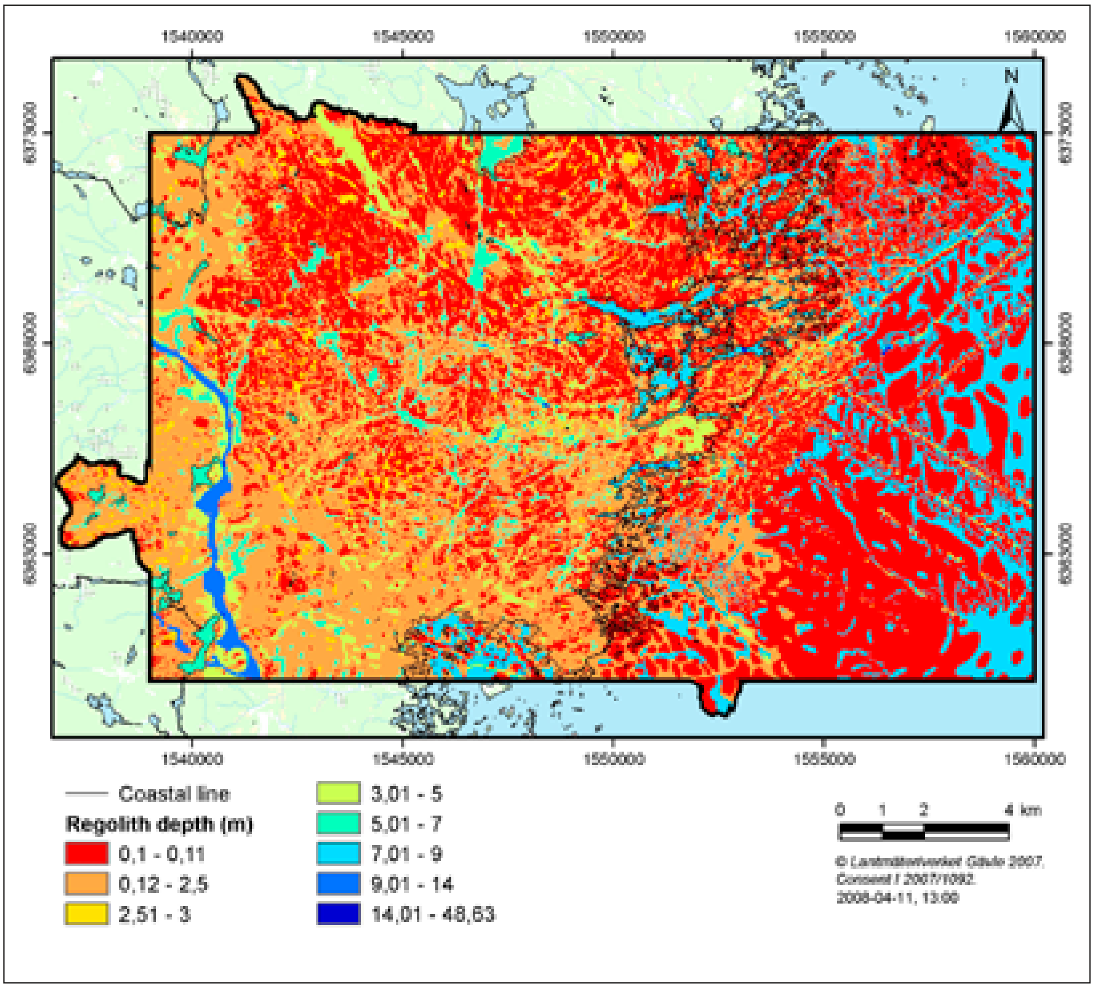

Figure 4-1. The modelled total regolith depths in the Laxemar-Simpevarp area.

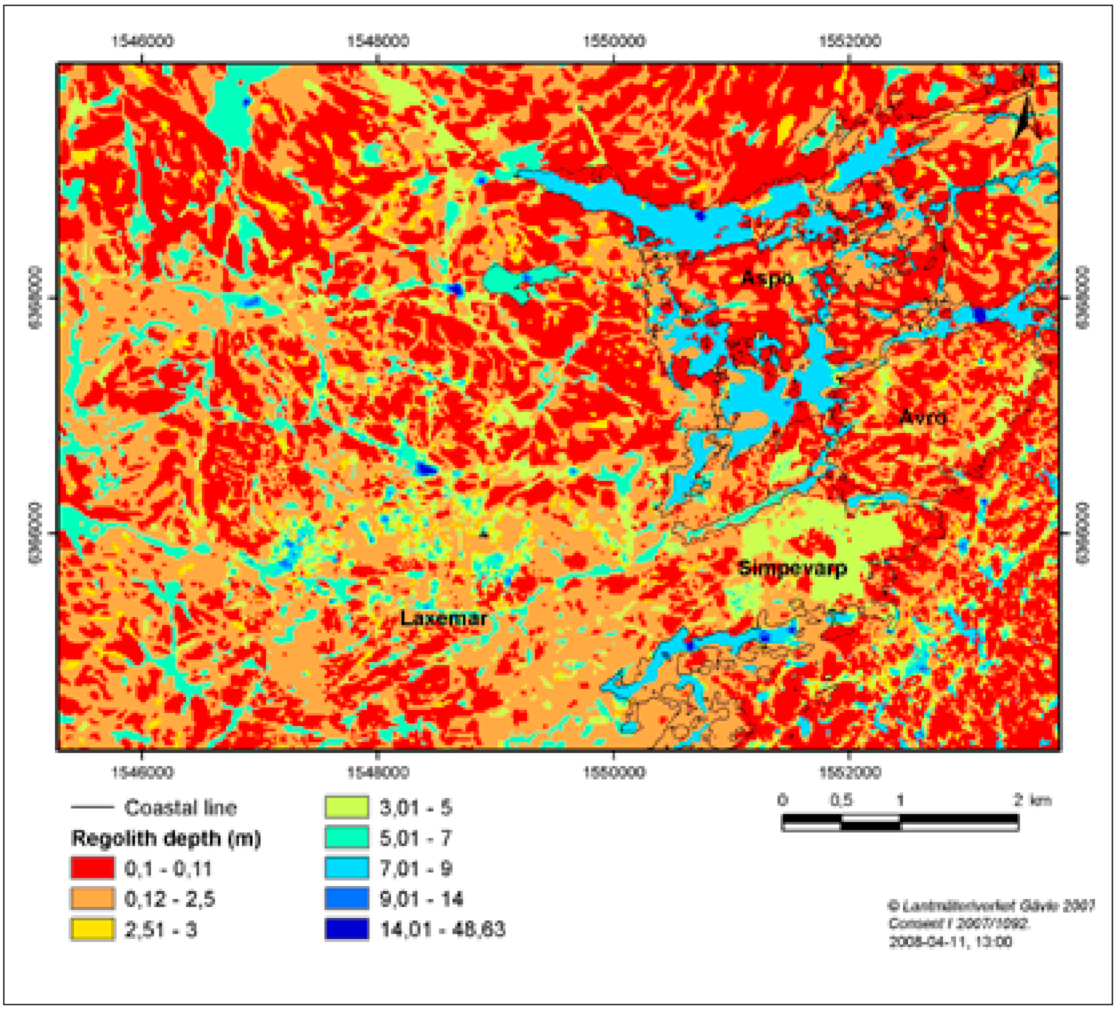

Figure 4-2. *The modelled total regolith depths in the central part of the Laxemar-Simpevarp area.*

Table 4-1. Average and median regolith depth.

Type of data	Average QD depth (m)	Standard deviation of average QD depth (m)	Median QD depth (m)
Whole model (including bedrock outcrops)	2.2	2.6	2.1
Whole model except bedrock outcrops	3.7	2.5	2.1

Table 4-1 shows the average value and median QD depth, based on input data from the different data sources. Generally, input data shows higher average and median regolith depths than those derived from the interpolated results that are affected by areas of bedrock outcrop (i.e. a QD depth of 0.1 m). The reason for this is that the observations were done at sites with large regolith depth. On the other hand, the average QD depth from the model excluding bedrock outcrops agree approximately with the average values from the input data.

4.2 Vertical profiles

Altogether 11 vertical profiles from the model area are presented in this chapter and in Appendix 2. To generate such profiles the GeoModel tool is needed. The profiles show the interpolated thickness of the different Z-layer. The Z-layers correspond to stratigraphical units, which are explained in Tables 3-1 and 3-2. The profiles also show all observation points that fall within a 20 m band width of the line. This means that observation points situated up to 10 m from the line will be included. In some illustrated profiles, the elevations of observation points and depths of geological units may therefore differ from the modelled layers displayed in the profiles. The profiles shown here are drawn along manually defined lines (Figure 4-3). Figures 4-4 and 4-5 show profiles, which illustrates the typical stratigraphical distribution of QD in the area. In Appendix 2, additional profiles are presented. The geological layers are listed in the legend but are also represented within each interpreted profile.

The total regolith depth model is mainly produced by the use of the average thickness of the different deposits. That is also reflected in the often smooth thickness of the Z-layers shown in the profiles. The large glaciofluvial deposit in the western part of the model area, the Tuna esker, is an example of a deposit, which was modelled by the use of a small data set. The thickness of the esker shown in the profile (Figure A1-2) is therefore the calculated average thickness of the Tuna esker. As a consequence of that the topography of the modelled bedrock surface follows that of the overlying ground surface. The true bedrock surface has probably a different appearance.

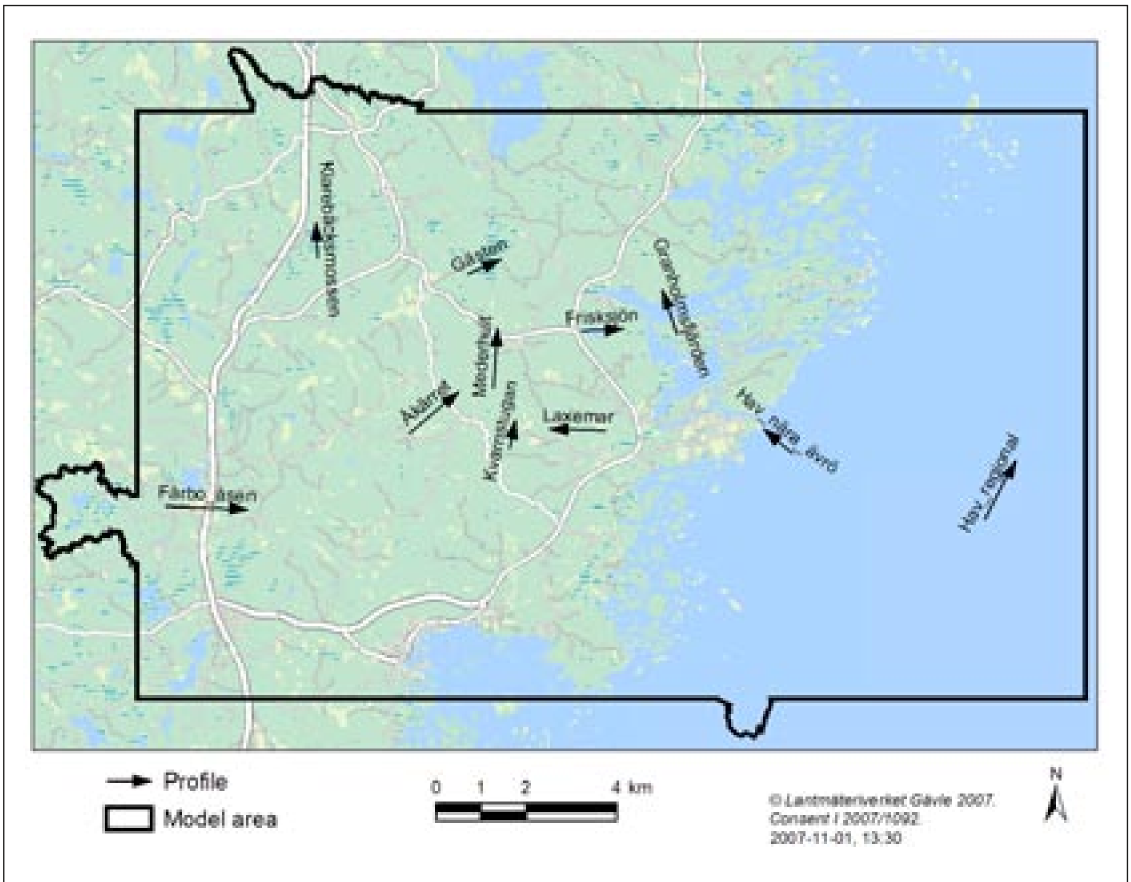

Figure 4-3. *The location of the stratigraphical profiles. The names of the profiles refer to the profile names shown in the section below and in Appendix 2.*

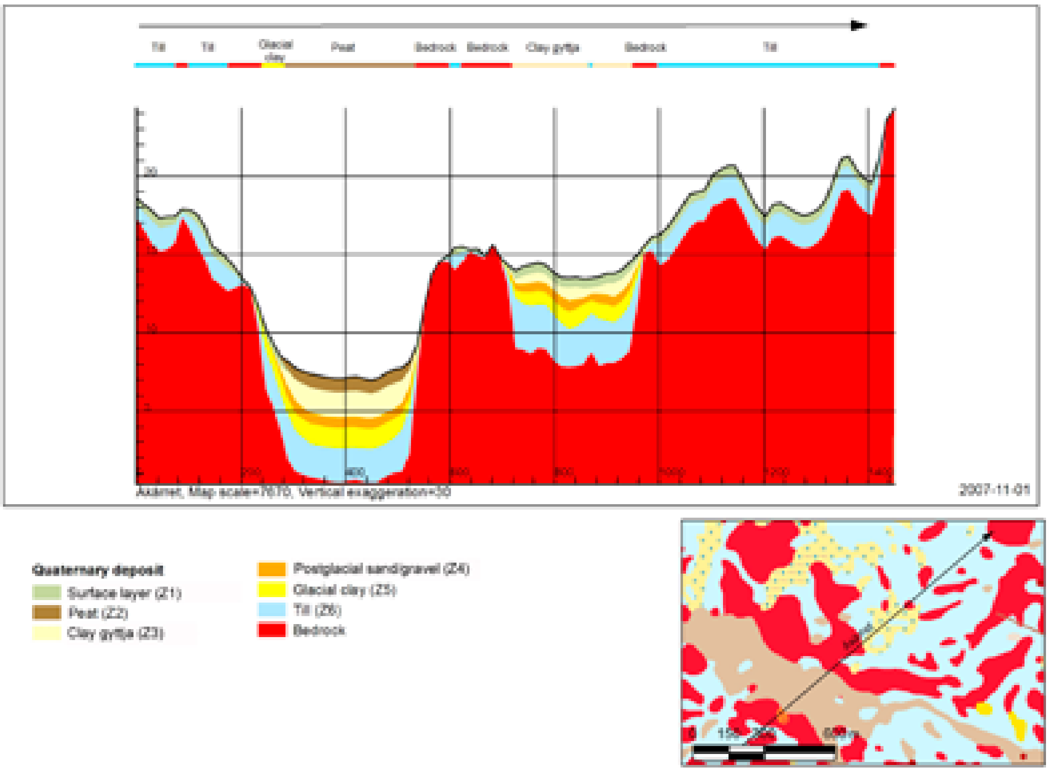

Figure 4-4. *Vertical profile showing stratigraphy and total regolith depth along profile "Åkärret". The profile clearly shows the valleys with thick layers of clay and the higher areas dominated by till and bedrock outcrops. This distribution of regolith is typical for most of the Laxemar-Simpevarp regional model area. For location of the profile, see Figure 4-3.*

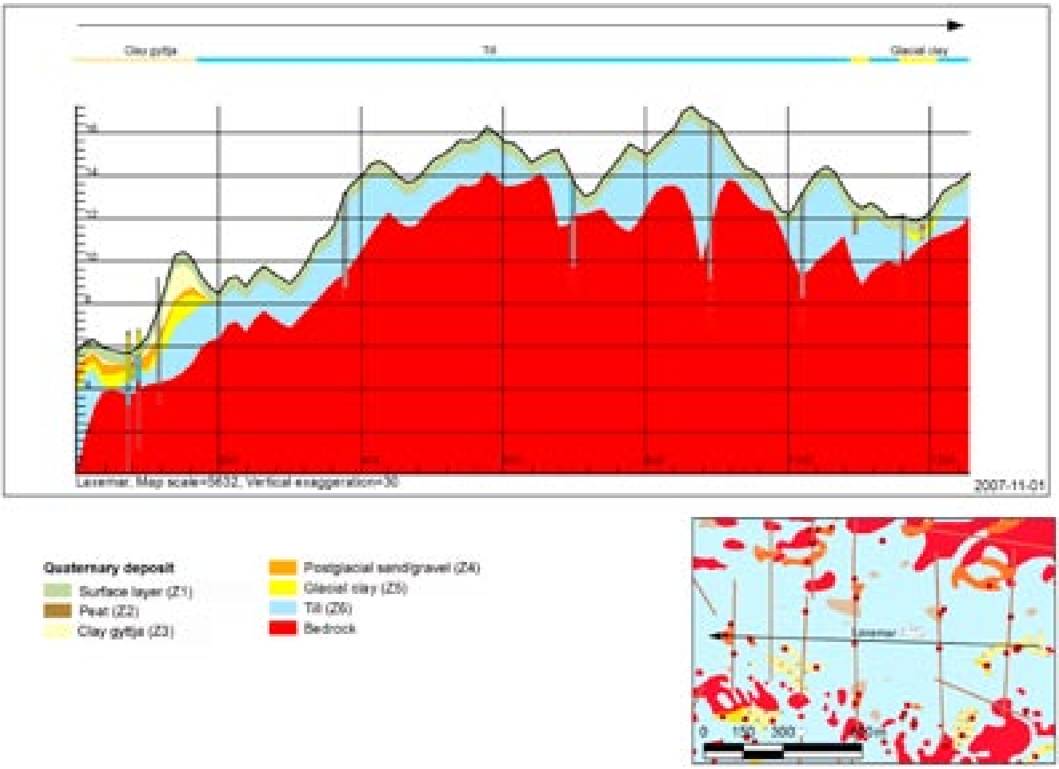

Figure 4-5. *Vertical profile showing stratigraphy and total regolith depth along profile "Laxemar". This profile is from an area where the till coverage is relatively thick and the frequency of bedrock outcrops is low. The profile indicates that the morphology of the till surface differs from that of the underlying bedrock. In most part of the model area the till coverage is thinner than shown in this profile. For location of the profile, see Figure 4-3.*

4.3 Resulting files

The dataset is to be found in the SKB's GIS database /SDEADM.POS_SM_GEO_5541 – SDEADM.POS_SM_GEO_5552/ under the reference Media ID C163.

4.4 Quality check of the regolith depth model (RDM)

The quality check in this chapter concerns the total regolith thickness, i.e. the thickness between the regolith surface and the bedrock surface.

The regolith surface is defined as the digital elevation model (DEM) with a resolution of 20 metres, and consequently all errors in the DEM will be present in the (RDM) as well. The quality check of the DEM is reported in /Strömgren and Brydsten (in prep)/, which also includes a quality check of the RDM. The quality check presented here is therefore restricted to the anomalies that can be seen in different RDM displays while the mathematical and statistical analyses are presented in /Strömgren and Brydsten (in prep)/.

The digital data accessible for the check are:

(i) The elevation of the bedrock surface (Z6) in raster format with 20 metres resolution.

(ii) The DEM with the same extension and resolution as the Z6 raster layer (Figure 2-3).

(iii) The Z-points that were used in the interpolation of the Z6 layer.

The regolith depth model (RDM) was computed as the difference between the DEM and the Z6-layer and the subsequent check was done on this new layer (Figure 4-1).

The value range in the RDM is 0.1–48 metres. Very thick regolith (> 20 metres) is found at the glaciofluvial Tuna esker in the western part of the area and at many small areas distributed over the whole domain. The largest regolith thickness (48 metres) is located in the sea (Figure 4-6). For large areas the regolith is less than 5 metres thick (Figure 4-7), and the average regolith thickness is 2.2 metres (Table 4-1).

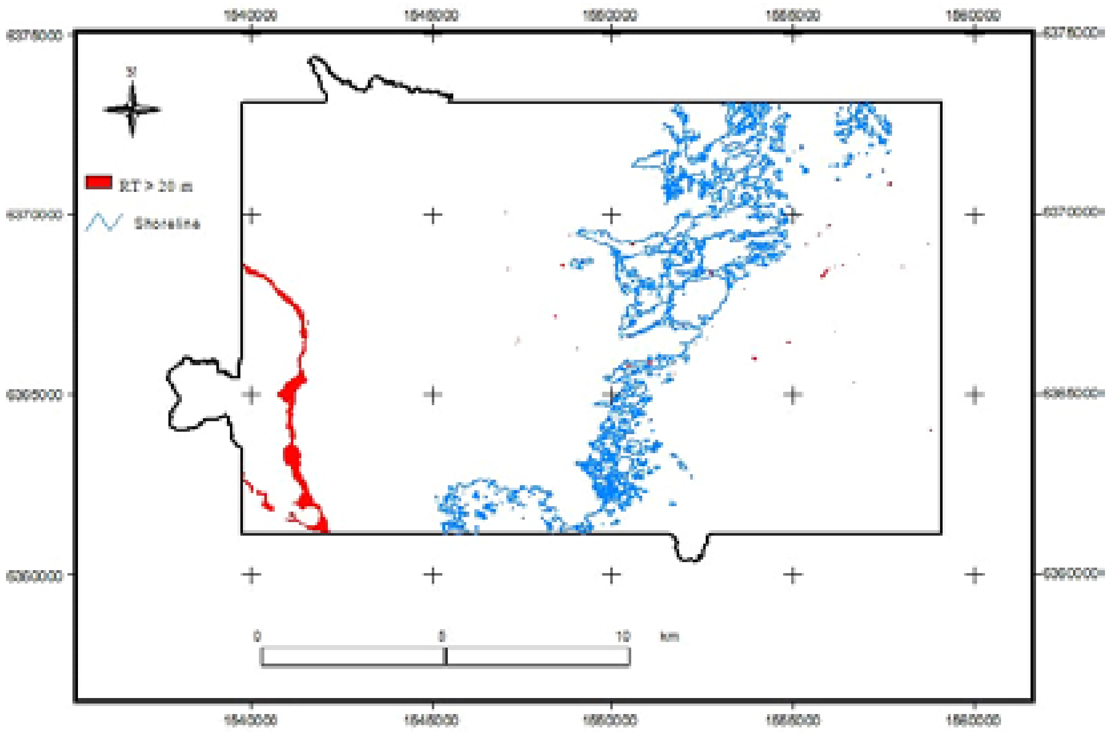

Figure 4-6. Areas with a regolith thickness greater than 20 metres.

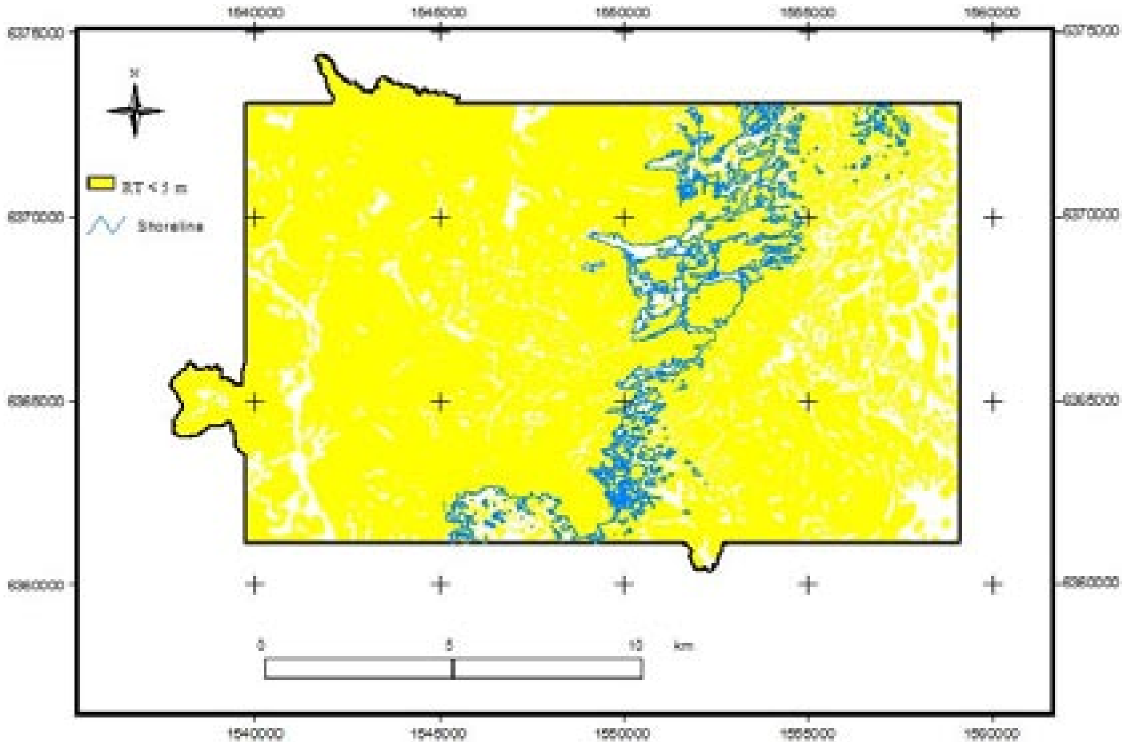

Figure 4-7. *Areas with regolith thickness less than 5 metres are marked with yellow on the map.*

The RDM shows a number of linear structures (lineaments). The most conspicuous lineaments are marked in Figure 4-8. Some of these are probably based on geological grounds while other indicates some errors, either in lack of raw data, distribution of the data points or a result of chosen interpolation parameters.

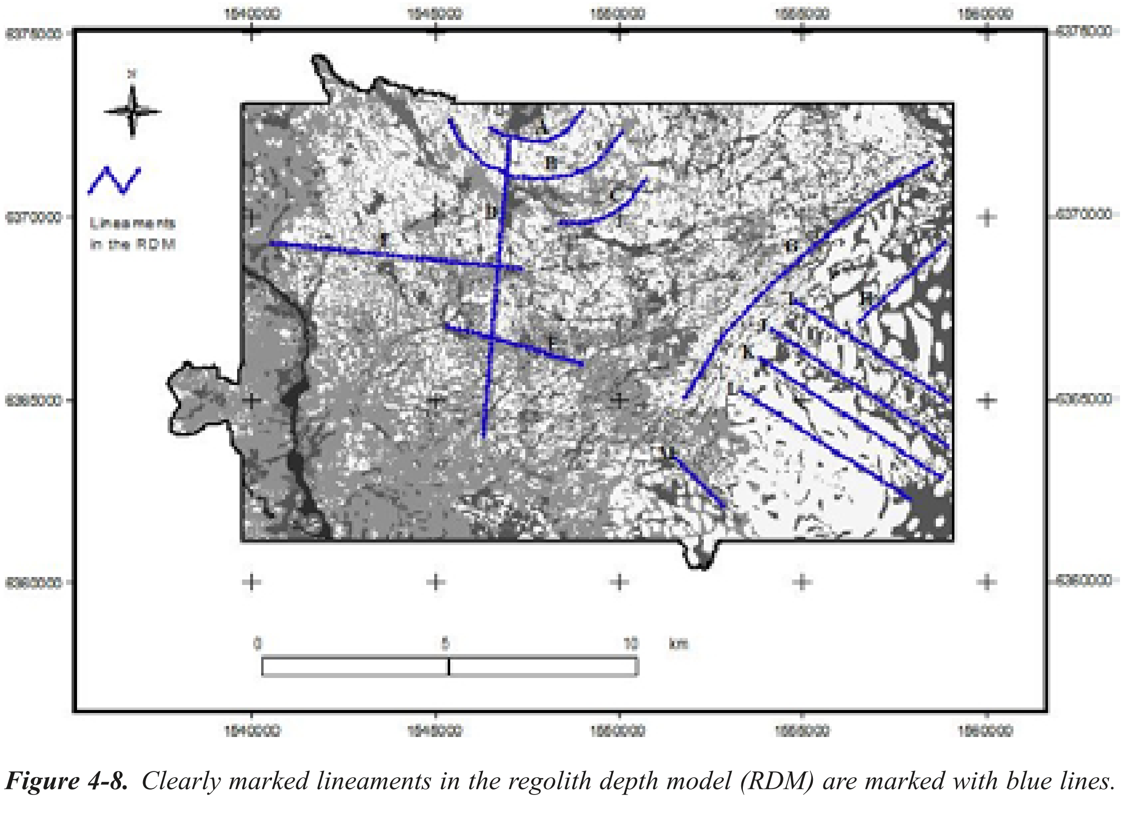

Figure 4-8. *Clearly marked lineaments in the regolith depth model (RDM) are marked with blue lines.*

One real cause to the marked lineaments in the RDM might be existing lineaments in the bedrock, for example a fracture, fissure or fault in the bedrock. The loosened up bedrock could favour erosion with a local depression in the bedrock surface as a result. These depressions can then be filled with unconsolidated sediments resulting in a thicker regolith in these areas as compare to its surroundings.

Figure 4-9 is the same as Figure 4-8 with the addition of lineaments in the bedrock displayed in red (SKB GIS Layer (LX_Defzon_reg). As shown in the figure, many of the RDM lineaments (blue dashed line) coincide with bedrock lineaments (red unbroken line).

A number of lineaments in the RDM can not be explained by features in the bedrock. There are several such lineaments in the south-eastern part of the model area (I-L in Figure 4-9). These lineaments coincide exactly with the survey lines of the marine geological survey /Elhammer and Sandkvist 2005/ thus the lineaments reflect transects of the survey vessel (Figure 4-10). The distance between transects is c. 1 km whereas the distance between raw data points along transects is c. 3 metre. This result in a very clustered data set in these subareas which in turn mean that the interpolation from point data to a continuous raster layer is difficult without getting errors between the transects.

As described in Section 3.1 and 3.3 a number of virtual average regolith depths have been added in areas between the transects where there are no measured data. These virtual points have been assign values that correspond to the average value of regolith thickness in the different domains. The lineaments in the south-eastern part of the model area are consequently an effect of too high or too low average regolith depths.

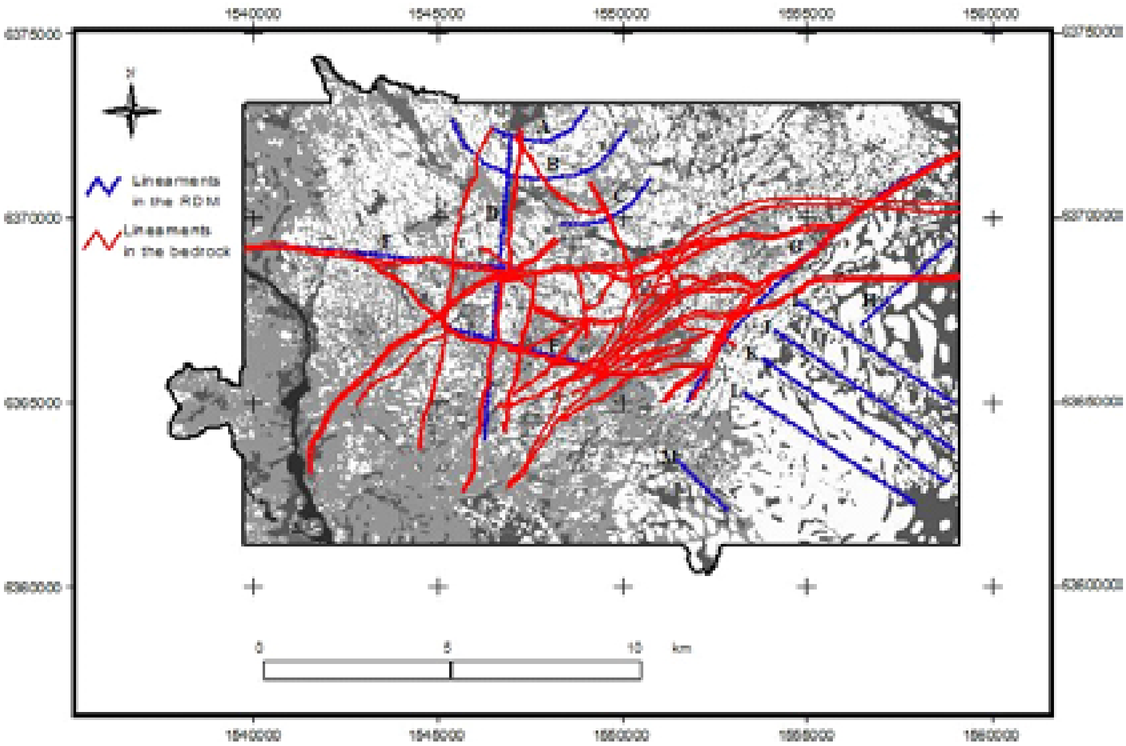

Figure 4-9. *Clearly marked lineament in the RDM (blue) and lineament in the bedrock (red).*

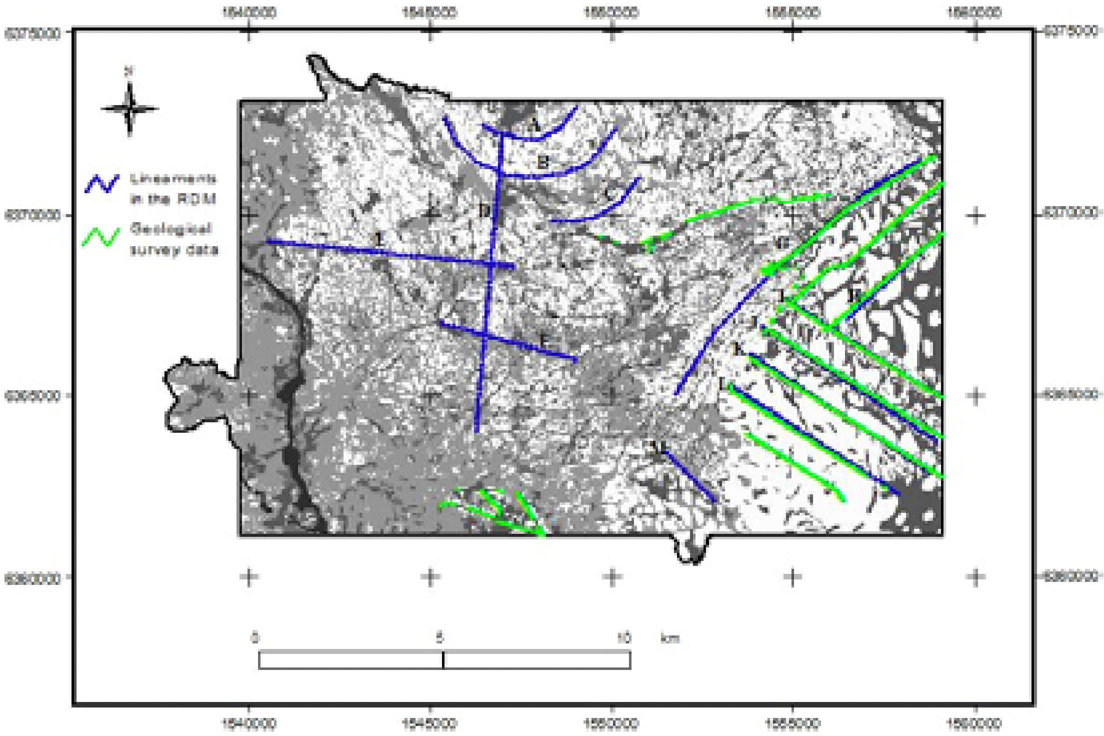

Figure 4-10. *Clearly marked lineament in the RDM (blue lines) and positions for raw data from the regional marine geological survey (green dots).*

In a hillshade view from 315 degrees the appearance of objects elongated in approximately north-east directions will be exaggerated, i.e. the azimuths in Figures 4-11 and 4-12 are chosen so that phenomenon associated with some of the marine geological survey transects will be accentuated. The geological mapping in the marine areas was performed with two different research vessels carrying slightly different equipment, resulting in data sets with different quality and spatial resolutions. In the eastern part of the sea (the regional area) the distance between transects are approximately 1 km while in the western more shallow part of the sea the distance between transects are approximately 100 metres. The border between these two areas is shown in Figure 4-12 with a yellow line.

In Figure 4-11 it is clearly shown that the resolution of the raw data from the marine geological surveys has a high significance for the final shaping of the RDM. The pattern in the RDM shows great similarity between the land areas and the detailed marine geological survey area while the pattern within the regional survey area is completely different.

The characteristics of the deep sea areas of the RDM is both that transects appears as elongated narrow ridges and the areas between transects are gently undulated surfaces. Since transects appears as trenches, it is likely that the Z-values of the virtual points has been assigned a higher value than optimal.

Another factor that strongly affects the quality of the RDM is the quality of the QD map (Figure 2-4). The delineation of the domains is entirely based on that map (Figure 3-2). The average regolith depths vary strongly between the domains. In large parts of Area 7 in the marine area the QD map is more or less a work of guessing (Figure 2-2). It is therefore not surprising that the quality of the RDM turns out to be low in these areas. Section 2.1 describes the methods used for producing the QD map and Section 5.1 discusses the uncertainties of that map.

Figure 4-12 shows the same area and the same light characteristics as for Figure 4-11 but for the DEM. The same pattern stands out as for the RDM which indicates that the unrealistic pattern that appears in the eastern part of the RDM is partly due to errors in the DEM. During the com-

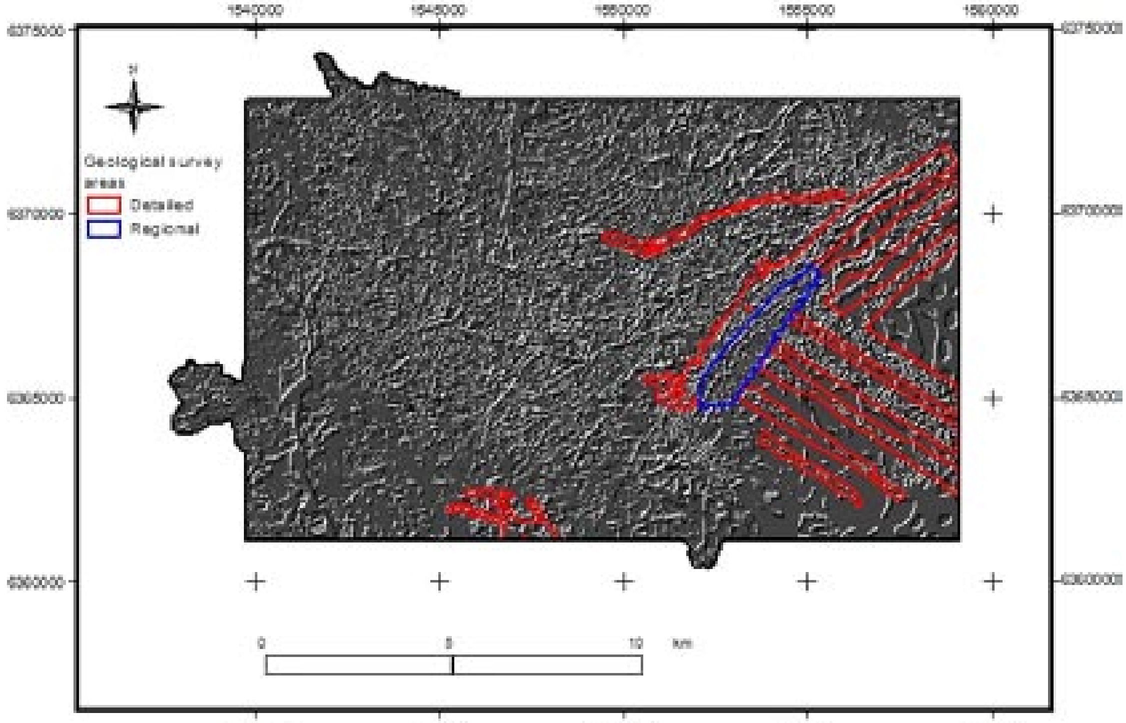

Figure 4-11. *A hillshade view of the RDM with a sun azimuth from 315 degrees and with a sun altitude of 45 degrees.*

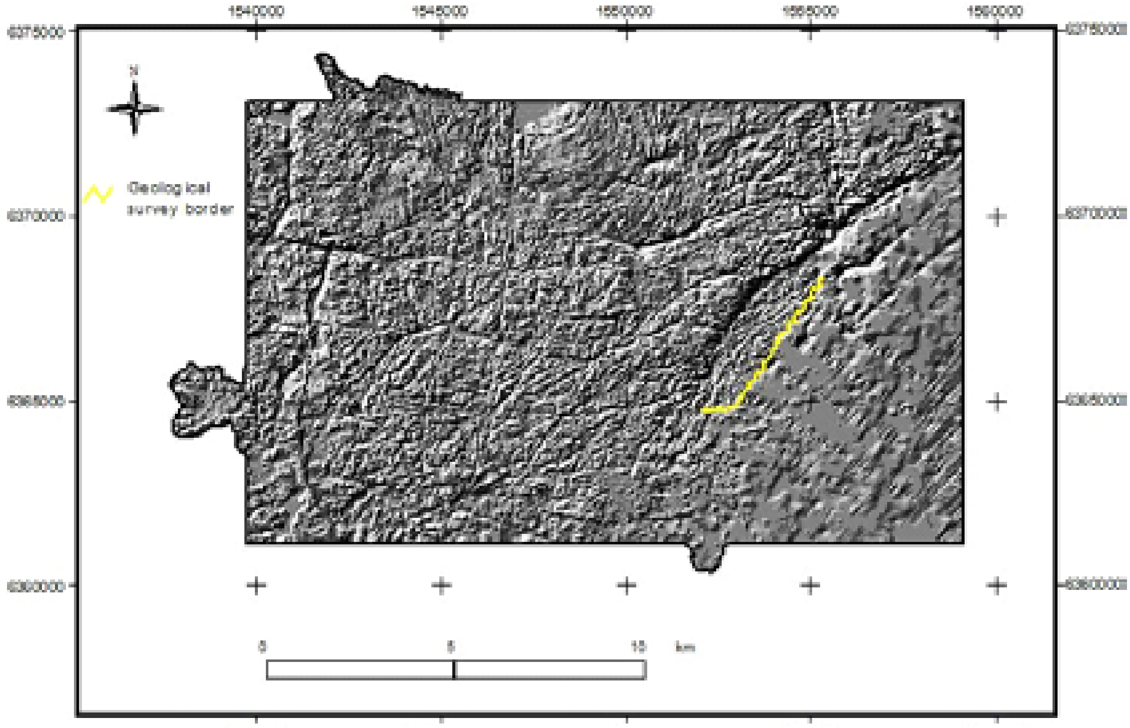

Figure 4-12. *A hillshade view of the DEM with a sun azimuth from 315 degrees and with a sun altitude of 45 degrees.*

pilation of the DEM no virtual points where added to the point data set, so the point density in the raw data to the DEM is always higher in the shallow parts of the sea since the equidistance of the depth curves in the digital sea chart is shorter on shallow water depths. This could be an explanation to the different patterns seen in the RDM between the deep sea and the shallow sea close to the Boskär archipelago in the NE part of the model area.

The concentric lineaments marked with A–C in Figure 4-10 can also be seen in the hillshades of both the RDM and the DEM, so these structures is not an artefact in the regolith depth model. These structures coincide with the extension of the so called Götemar granite, a large circular granite deposit, so the structure is due to features in the rock.

A third method to visually check the quality of the RDM is to compute the slope of the RDM. The slope gradient varies among 0–45 degrees with an average value of 2.1 degrees.

In the RDM slope model, the pattern along the marine transects is completely different from the pattern in the areas between the transects. Flat areas (blue areas in Figure 4-13) coincide with areas with a high share of virtual points, which is logic.

To sum up the quality check of the RDM, most of the structures seen in the model can be explained by observed features in the regolith or bedrock. Bad quality in the RDM can be expected in marine areas with a low density of regolith depth data and low number of points used for interpolation of the DEM. The quality of the QD map is lowest in Area 7 (Figure 2-2) and the quality of the RDM is consequently lowest in that area.

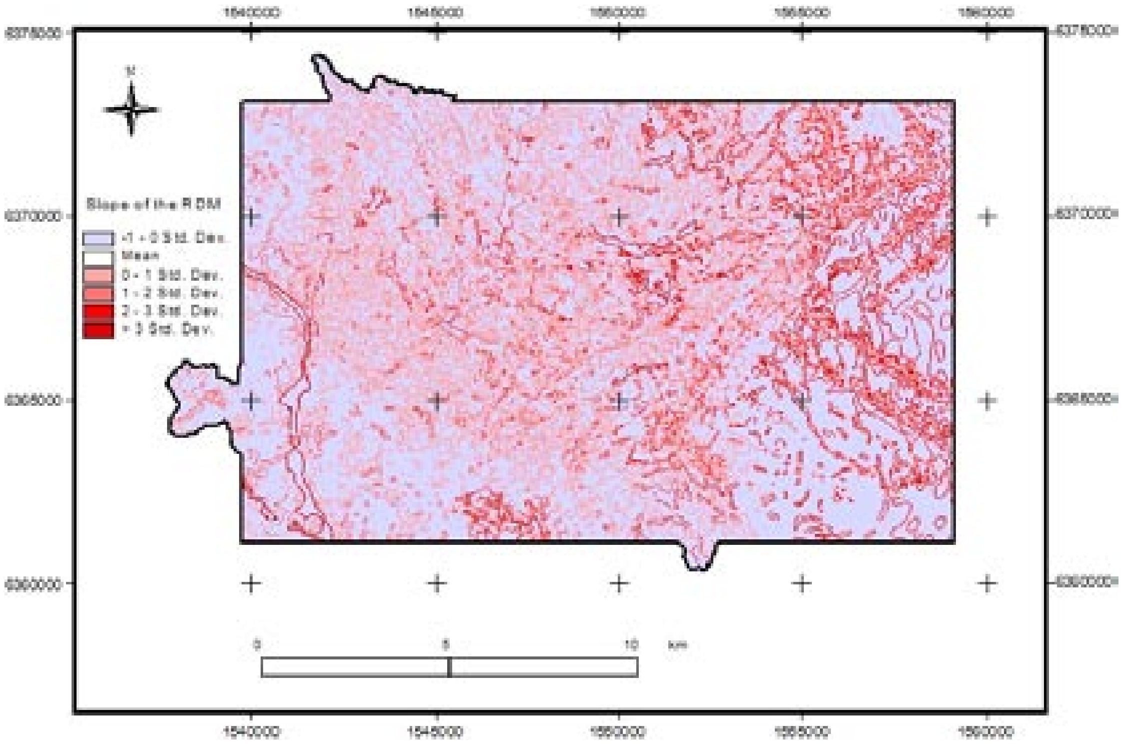

Figure 4-13. *A slope gradient map calculated from the RDM shown in standard deviation classes. Blue areas have a slope less than the average slope (2.1 degrees).*

5 Uncertainties

The uncertainties of the data used for the RDM are discussed in this section. The uncertainties of the regolith depth and stratigraphy model and the data used for that model are also discussed in /Sohlenius and Hedenström 2008/.

5.1 The map of Quaternary deposits

In large parts of the model area the RDM is almost completely produced from the geographical distribution of QD (Figure 2-4) combined with the average thickness of the Z-layers shown in the conceptual stratigraphical model (Figure 3-1). The quality of the QD map has consequently a large impact on the quality of the RDM. Since different methods were used during the mapping of QD in the Laxemar-Simpevarp regional model area (Figure 2-2 and Table 2-2) the quality of the map (Figure 2-4) varies within the investigated area. In Areas 8 and 11, the distribution of QD was to a large extent interpreted from aerial photos. A field check in these areas was performed and showed that forest areas covered by peat are underestimated in these two areas. The forest covered peat areas are often difficult to recognise in the aerial photos, especially at sites where the groundwater level was lowered by ditches. Most large areas with clay are used as arable land and were correctly interpreted in the aerial photos. The field check also showed that most areas with bedrock exposures were correctly interpreted in the aerial photos. Some small exposures have, however, not been recorded. There are no high-resolution aerial photos from the north-western part of the regional model area. The map of QD shows a lower frequency of exposed bedrock in that area compared to neighbouring areas. The field check showed that the frequency and areas with exposed bedrock is strongly underestimated in that particular area. In areas 9 and 10 the QD map was produced after extensive field checks. In these areas the quality of the map is high, even though minor errors are likely to exist. An additional field check showed for example that some areas with clay gyttja close to the sea were incorrectly mapped as peat. It is also possible that the area mapped as till is overestimated in the terrestrial area. That is since it is difficult to conclude if an area with a high frequency of stones and boulders represent a thin till coverage resting directly upon the bedrock or a thick layer of till.

In the marine areas, geophysical methods were used for interpreting the distribution of QD. In Areas 1, 4, and 6 (Figure 2-2) the distribution of QD was interpreted by the use of sonar recordings, which generally have a high quality. The sonar recordings, however, have a lower quality in parts of Area 6 and misinterpretations might therefore occur in that area /Kjellin 2007/. In Areas 2 and 3 sonar recordings with a lower quality were used for interpreting the distribution of QD. It can sometimes be difficult to recognise till from bedrock outcrops in these recordings. The areas with till might therefore be underrepresented in these two areas.

Area 7 was not included in the marine geological mapping program. The distribution of QD in that area was interpreted from bathymetric information and from the known distribution of QD in the mapped marine and terrestrial areas. There is almost no bathymetry information outside the archipelago and in Area 7 the distribution of QD in that area is more or less a product of guessing. The geographical distribution of QD in Area 7 shown should therefore not be regarded as an ordinary map of QD, but more as a general view of the likely composition of the regolith coverage. The interpreted distribution of QD in Area 12 (lakes) is based on a small number of field observations and the reliability of the QD map in that area is consequently low.

5.2 Total depth and stratigraphy of regolith

The quality of the RDM varies with the density of observations reaching the bedrock surface (Figure 3-3). Furthermore, the quality of the RDM is dependent on the reliability of the methods used to determine the elevation of the bedrock surface.

The surface of the bedrock was determined by a number of methods. The bedrock outcrops shown on the QD map were observed in the field, in aerial photos or by geophysical methods. Most of these observations have a high confidence and are generally the most reliable data concerning the bedrock surface (Table 5-1). In the marine areas, the distribution of bedrock outcrops shown on the QD map have varying reliability depending on method used (see section above).

The most reliable data concerning the depth and stratigraphy of regolith were obtained from drillings and excavations. It might, however, be difficult to recognise the difference between till and bedrock with a high frequency of fissures. The frequency of fissures is especially high in the valleys where data concerning regolith depths probably has a higher uncertainty than in other areas.

Stratigraphical observations were made within several campaigns. Most of these observations have a high reliability. However some of the data from drillings, especially till classifications from the valleys seem to be less reliable. The regolit depths are large in the valleys and the samples might have been disturbed during the sampling procedure. Some samples classifieds as till might therefore be sand and gravel or from the uppermost bedrock.

The different geophysical methods used to determine the regolith depth have various sources of errors. These errors were discussed with the geophysical experts at SGU. In the marine area (Areas 1 and 2 in Figure 2-2) the depth and stratigraphy of the regolith were interpreted by results from seismic and echo sounding. These data were used to interpret the thickness of the different stratigraphical units something that not is possible with the other geophysical data. The thickness of the clay deposits can be determined with a relatively high precision using the echo sounding data. However, it may be difficult to interpret the clay thickness in narrow and deep valleys. Furthermore, the clay gyttja often contains gas, which obstructs penetration with the methods used. It was therefore not possible to determine the stratigraphy and total depth of QD in many areas with clay gyttja. The till thickness interpreted from seismic data has a higher uncertainty than the interpreted clay thickness. One reason for that is that it may be difficult to discriminate thin layers of till from bedrock. It may also be difficult to discriminate till from bedrock with a high frequency of fissures.

In the terrestrial area, refraction seismic and resistivity measurements were used to determine the regolith depths. The depths obtained from the seismic data have a medium high reliability and the error is in most case ± 1 metre. The regolith depths were also interpreted from the inverted resistivity measurements. The electrode separation of 5 m does not provide data to accurately resolve regolith cover thinner than around one to two metres. The regolith depths obtained from the resistivity measurements have therefore a lower reliability than corresponding data obtained from refraction seismic.

Table 5-1. The reliability of the data used to determine the elevation of the bedrock surface. The distribution of the Areas referred to in the table is shown in Figure 2-2.

Type of observation	Area	Reliability	Comment
Bedrock outcrops	Areas 1, 4, 6 and 8–11	High	The reliability is lower in the north-western part of the model area.
	Areas 2 and 3	High-Medium	The bedrock in some areas might be covered by till.
	Area 7	Very low	
	Area 12	Medium	
Excavation	Terrestrial	High	
Drilling		High-Medium	It is sometimes difficult to recognise till from bedrock with a high frequency of fractures.
Seismic and sediment echo sounding	Marine	High-Medium	It is sometimes difficult to interpret the thickness of the till.
Refraction seismic	Terrestrial/ marine	Medium	These observations give a more accurate determination of the bedrock surface than resistivity measurements.
Resistivity measurements	Terrestrial	Medium	See refraction seismic.

5.3 Summary

The following main uncertainties were recognised for the RDM:

1 In large parts of the regional model area there is a lack of data showing the total depth of regolith. The regolith depth and stratigraphy model has consequently a low reliability in these areas.

2 The regolith depth has only been determined at a few sites in the large valleys where the thickest layers of regolith occur. It is therefore possible that the regolith depths were underestimated in some of these valleys.

3 The QD map has a low reliability in parts of the model area. The distribution of regolith depths is partly modelled by the use of that map and the depth model has consequently a low reliability in areas where the QD map has a low quality.

6 References

Agrell H, 1976. The highest coastline in south-eastern Sweden. Boreas 5, 143–154.

Bergman T, Malmberg Persson K, Persson M, Albrecht J, 2005. Oskarshamn site investigation – Characterisation of bedrock and Quaternary deposits from excavations in the southern part of Laxemar subarea. SKB P-05-47, Svensk Kärnbränslehantering AB.

Davis J C, 1986. Statistics and data analysis in geology. John Wiley & sons New York, p. 383–404.

DHI Water & Environment, 2005. MIKE GeoModel – User Guide. DHI Water&Environment, Hörsholm, Denmark.

Elhammer A, Sandkvist Å, 2005. Detailed marine geological survey of the sea bottom outside Simpevarp. Oskarshamn site investigation. SKB P-05-35, Svensk Kärnbränslehantering AB.

Fredén C (red.), 2002. Berg och jord. Sveriges nationalatlas. Third edition. 208 pp.

Ingvarson N H, Palmeby A S L F, Svensson L O, Nilsson K O, Ekfeldt T C I, 2004. Oskarshamn site investigation – Marine survey in shallow coastal waters, Bathymetric and geophysical investigation 2004. SKB P-04-254, Svensk Kärnbränslehantering AB.

Isaaks E H, Srivastava R M, 1989. An introduction to applied geostatistics, Oxford University Press, NY, Oxford. ISBN 0-19-505013-4.

Johansson T, Adestam L, 2004a. Oskarshamn site investigation – Drilling and sampling in soil- Installation of ground water monitoring wells. SKB P-04-121, Svensk Kärnbränslehantering AB.

Johansson T, Adestam L, 2004b. Oskarshamn site investigation – Drilling and sampling in soil – Installation of groundwater monitoring wells in the Laxemar area. SKB P-04-317, Svensk Kärnbränslehantering AB.

Kjellin B, 2007. Revidering och komplettering av tidigare maringeologiska undersökningar i Simpevarp- och Forsmark-områdena. Utförd inom programmet för Fysisk planering. SGU report (in Swedish).

Lindqvist G, 2004a. Oskarshamn site investigation: Refraction seismic measurements in Laxemar. SKB P-04-134, Svensk Kärnbränslehantering AB.

Lindqvist G, 2004b. Oskarshamn site investigation: Refraction seismic measurements in the water outside Simpevarp and Ävrö and on land on Ävrö. SKB P-04-201, Svensk Kärnbränslehantering AB.

Lindqvist G, 2004c. Oskarshamn site investigation: Refraction seismic measurements in Laxemar autumn 2004. SKB P-04-298, Svensk Kärnbränslehantering AB.

Lindqvist G, 2005. Oskarshamn site investigation: Refraction seismic measurements in Laxemar spring 2005. Oskarshamn site investigation. SKB P-05-155, Svensk Kärnbränslehantering AB.

Lindqvist G, 2006. Oskarshamn site investigation: Refraction seismic measurements in Laxemar spring 2006. Oskarshamn site investigation. SKB P-06-49, Svensk Kärnbränslehantering AB.

Lindström M, Lundqvist J, Lundqvist Th, 2000. Sveriges geologi från urtid till nutid. Studentlitteratur, Lund, 531 pp.

Lundqvist J, Wohlfarth B, 2001. Timing and east-west correlation of south Swedish ice marginal lines during the Late Weichselian. Quaternary Science Reviews 20, 1127–1148.

Morosini M, Jenkins C, Simson S, Albrecht J, 2007. Oskarshamn site investigation – Hydrogeological characterization of deep valley soil aquifers and soil-rock transition at Laxemar, 2006. P-07-91, Svensk Kärnbränslehantering AB.

Nilsson G, 2004. Oskarshamn site investigation – Investigation of sediments, peat lands and wetlands Stratigraphical and analytical data. SKB P-04-273. Svensk kärnbränslehantering AB.

Nyman H, 2005. Oskarshamn site investigation: Depth and stratigraphy of Quaternary deposits. Preliminary site description Laxemar subarea – version 1.2. R-05-54, Svensk Kärnbränslehantering AB.

Rudmark L, 2004. Oskarshamn site investigation – Investigation of Quaternary deposits at Simpevarp peninsula and the islands of Ävrö and Hålö. SKB P-04-22, Svensk Kärnbränslehantering AB.

Rudmark L, Malmberg-Persson K, Mikko H, 2005. Oskarshamn site investigation – Investigation of Quaternary deposits 2003–2004. SKB P-05-49, Svensk Kärnbränslehantering AB.

SGU, 2007. Brunnsarkivet. www.sgu.se. (Accessed 2007-02-27)

Sohlenius G, Bergman T, Snäll S, Lundin L, Lode E, Stendahl J, Riise A, Nilsson J, Johansson T, Göransson M, 2006. Oskarshamn site investigation – Soils, Quaternary deposits and bedrock in topographic lineaments situated in the Laxemar subarea. SKB P-06-121, Svensk Kärnbränslehantering AB.

Sohlenius G, Hedenström A, 2008. Description of regolith at Laxemar. SKB R-08-05. Svensk Kärnbränslehantering AB.

Strömgren M, Brydsten L, (in prep). Digital elevation models for site investigation programme in Oskarshamn. SKB R-report, Svensk Kärnbränslehantering AB.

Thunehed H, 2006. Oskarshamn site investigation: Vertical electric sounding and inversion of helicopter-borne EM measurements. SKB P-06-284, Svensk Kärnbränslehantering AB.

Thunehed H, Triumf C-A, 2005. Oskarshamn site investigation – Detailed ground geophysical survey at Laxemar. Magnetic total field and resistivity. SKB P-05-188, Svensk Kärnbränslehantering AB.

Thunehed H, Triumf C-A, 2006. Oskarshamn site investigation: Detailed ground geophysics at Laxemar, autumn/winter 2005/2006. Magnetic total field and resistivity. SKB P-06-137, Svensk Kärnbränslehantering AB.

Triumf C-A, Thunehed H, Kero L, Persson L, 2003. Interpretation of airborne geophysical survey data. Helicopter borne survey data of gamma ray spectrometry, magnetics and EM from 2002 and fixed wing airborne survey data of the VLF-field from 1986. Oskarshamn site investigation. SKB P-03-100, Svensk Kärnbränslehantering AB.

Appendix 1

Cross validation of models

Layer	Lag size	Number of Lags	Regression function	Mean	RMS[1)]	Average SE[1)]	Mean stand	RMS stand[1)]	Samples
Z6	14	12	0.998 · x + 0.002	–0.0002667	1.121	1.474	–0.0003039	0.7752	801,533
Z5	60	12	0.992 · x + 0.030	–0.005608	1.693	1.762	0.006843	0.9297	269,679
Z4	80	12	0.998 · x + 0.047	–0.007233	1.245	1.224	0.004068	0.9987	234,378
Z3	133	12	0.996 · x + 0.174	–0.007352	1.237	0.8803	0.0101	1.374	64,845
Z2	37	12	0.997 · x + 0.121	–0.01908	0.8646	0.752	–0.002102	1.129	47,506

[1)] RMS = root-mean-square prediction error, Average SE = average standard error, Mean stand = standardized mean prediction error, RMS stand = standardized root-mean-square prediction error.

Validation of models

Layer	Lag size	Number of Lags	Regression function	Mean	RMS[1)]	Average SE[1)]	Mean stand[1)]	RMS stand[1)]	Samples
Z6	14	12	0.997 · x + 0.007	0.005186	1.327	1.665	0.003044	0.7773	400,767
Z5	60	12	0.991 · x + 0.028	–0.02279	1.74	1.857	–	–	134,870
Z4	80	12	0.997 · x + 0.032	–0.01761	1.317	1.321	–	–	117,198
Z3	133	12	0.994 · x + 0.108	–0.03227	1.293	0.9397	–0.01196	1.34	32,423
Z2	37	12	0.995 · x + 0.119	–0.03364	0.9897	0.8448	–0.01484	1.145	23,753

[1)] RMS = root-mean-square prediction error, Average SE = average standard error, Mean stand = standardized mean prediction error, RMS stand = standardized root-mean-square prediction error.

Model parameters

Common to all models are Ordinary Kriging with a spherical model. The model equation should be read as follows:

Partial sill × Theoretical Semiovariogram (Major Range, Minor Range, Anisotropy Direction) + (Nugget value × Nugget)

Layer	Points	Modell	MS[1)]	Me[1)]	N[1)]	A[1)]
Z6	801,553	18.583 × Spherical (165.95,165.95,63.8) + 0 × Nugget	1.2252 (100%)	0 (0%)	5/2	4
Z5	269,679	25.369 × Spherical (711.2,445.71,38.9) + 1.9914 × Nugget	0 (100%)	0 (0%)	5/2	4
Z4	234,378	25.755 × Spherical (948.26,737.51,35.6) + 0.71996 × Nugget	0 (100%)	0 (0%)	5/2	4
Z3	64,845	18.283 × Spherical (1576.5,1453.2,275.5) + 0.43852 × Nugget	0 (100%)	0 (0%)	5/2	4
Z2	47,506	6.5092 × Spherical (438.57,438.57,8.9) + 0.18679 × Nugget	0 (100%)	0 (0%)	5/2	4

[1)] MS = Microstructure, Me = Measurement error, N = Searching Neighborhood and A = Angular Sectors.

Profiles with interpreted geological layers Appendix 1

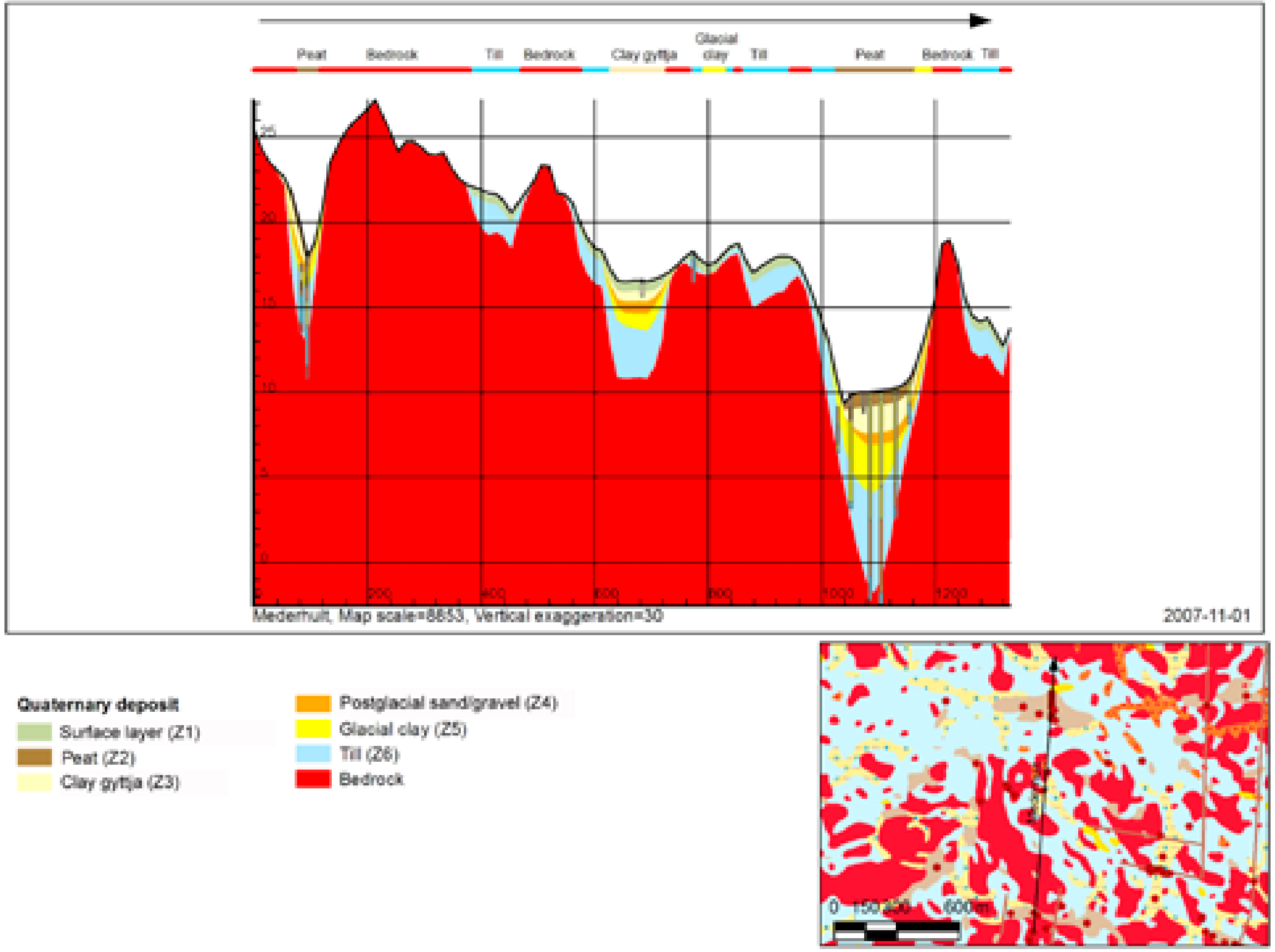

Figure A2-1. *Vertical profile showing stratigraphy and total regolith depth along profile "Mederhult". For location of the profile, see Figure 4-3.*

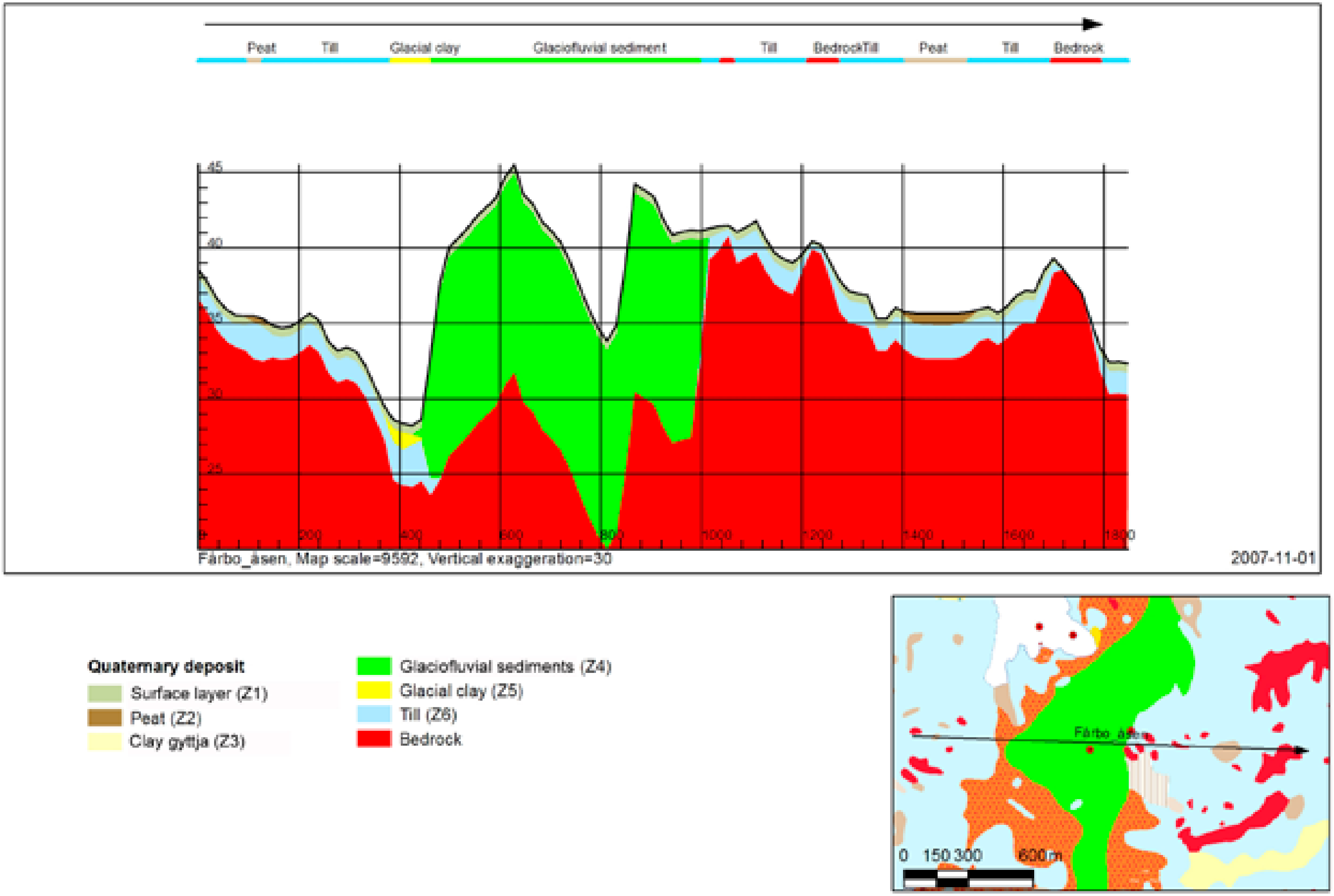

Figure A2-2. *Vertical profile showing stratigraphy and total regolith depth along profile "Fårbo_åsen". For location of the profile, see Figure 4-3.*

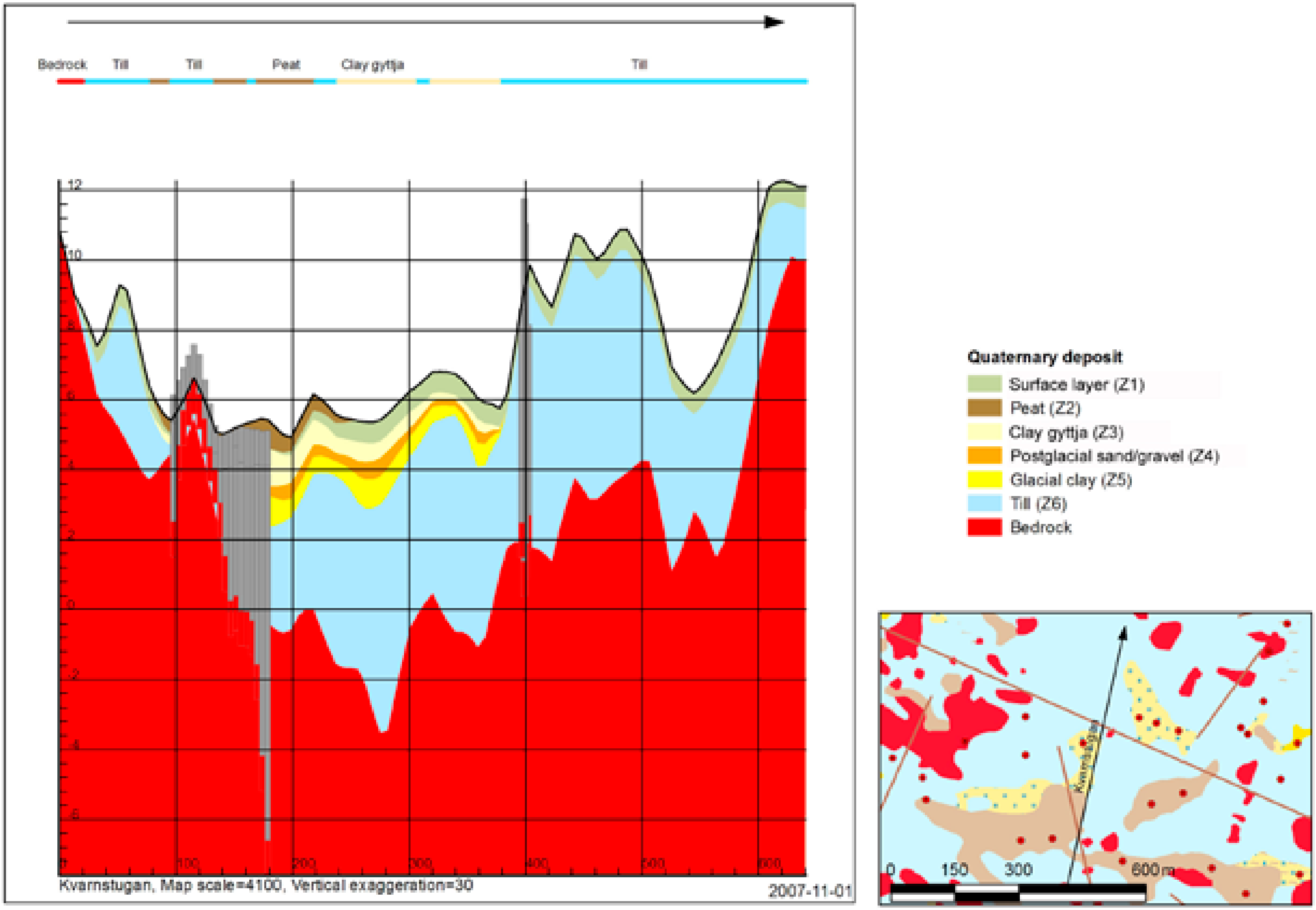

Figure A2-3. *Vertical profile showing stratigraphy and total regolith depth along profile "Kvarnstugan". For location of the profile, see Figure 4-3.*

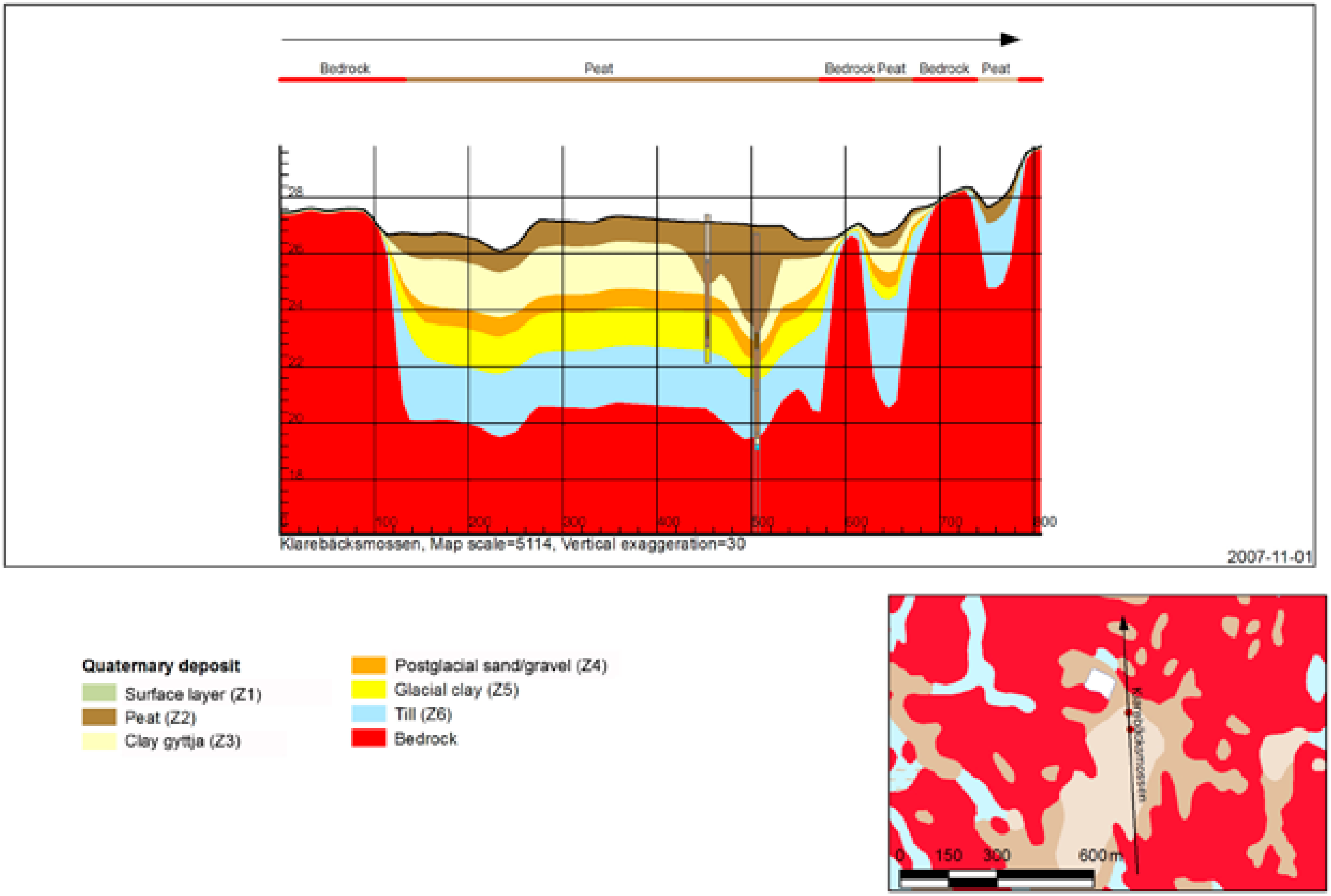

Figure A2-4. *Vertical profile showing stratigraphy and total regolith depth along profile "Klarebäcksmossen". For location of the profile, see Figure 4-3.*

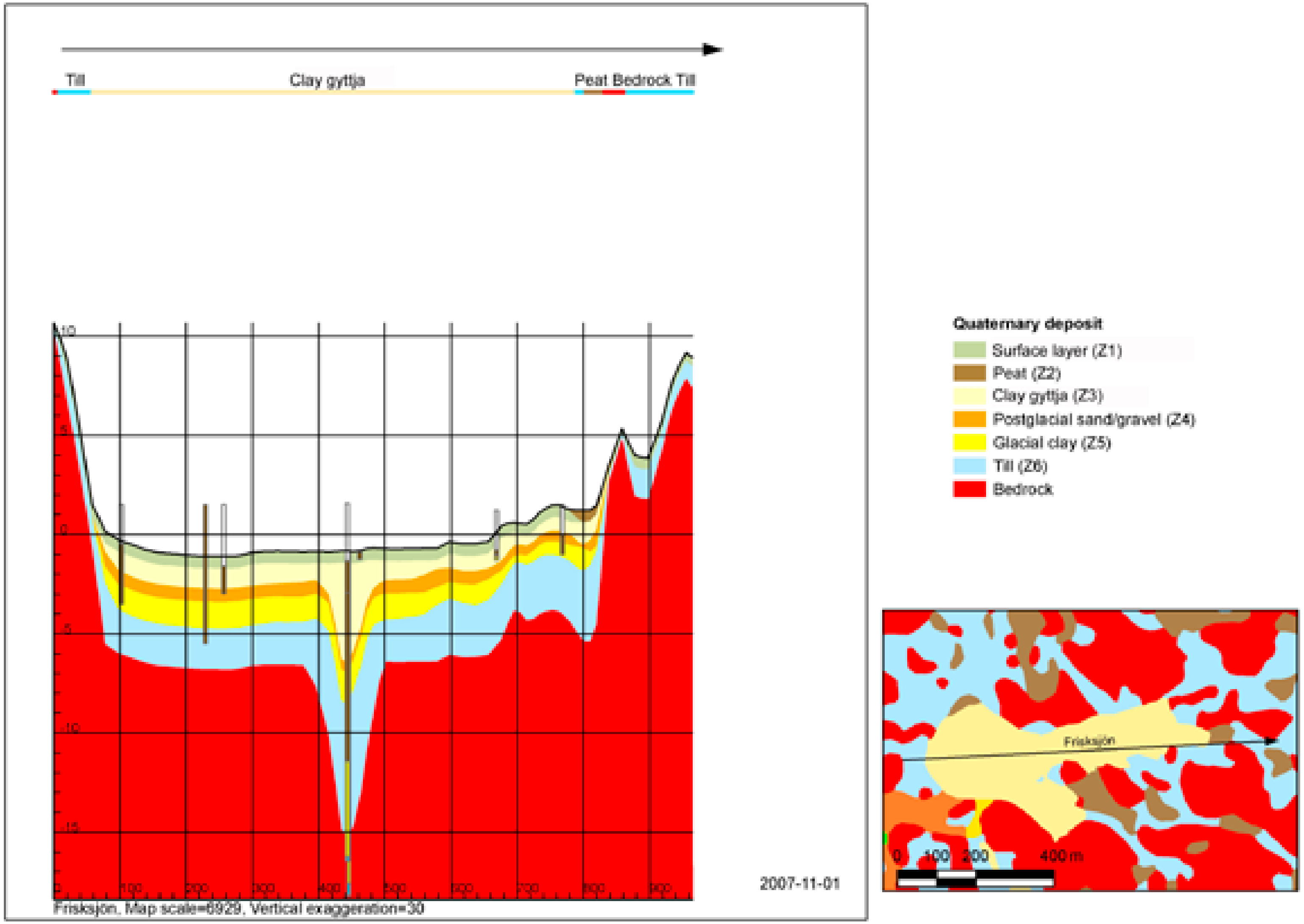

Figure A2-5. *Vertical profile showing stratigraphy and total regolith depth along profile "Frisksjön". For location of the profile, see Figure 4-3.*

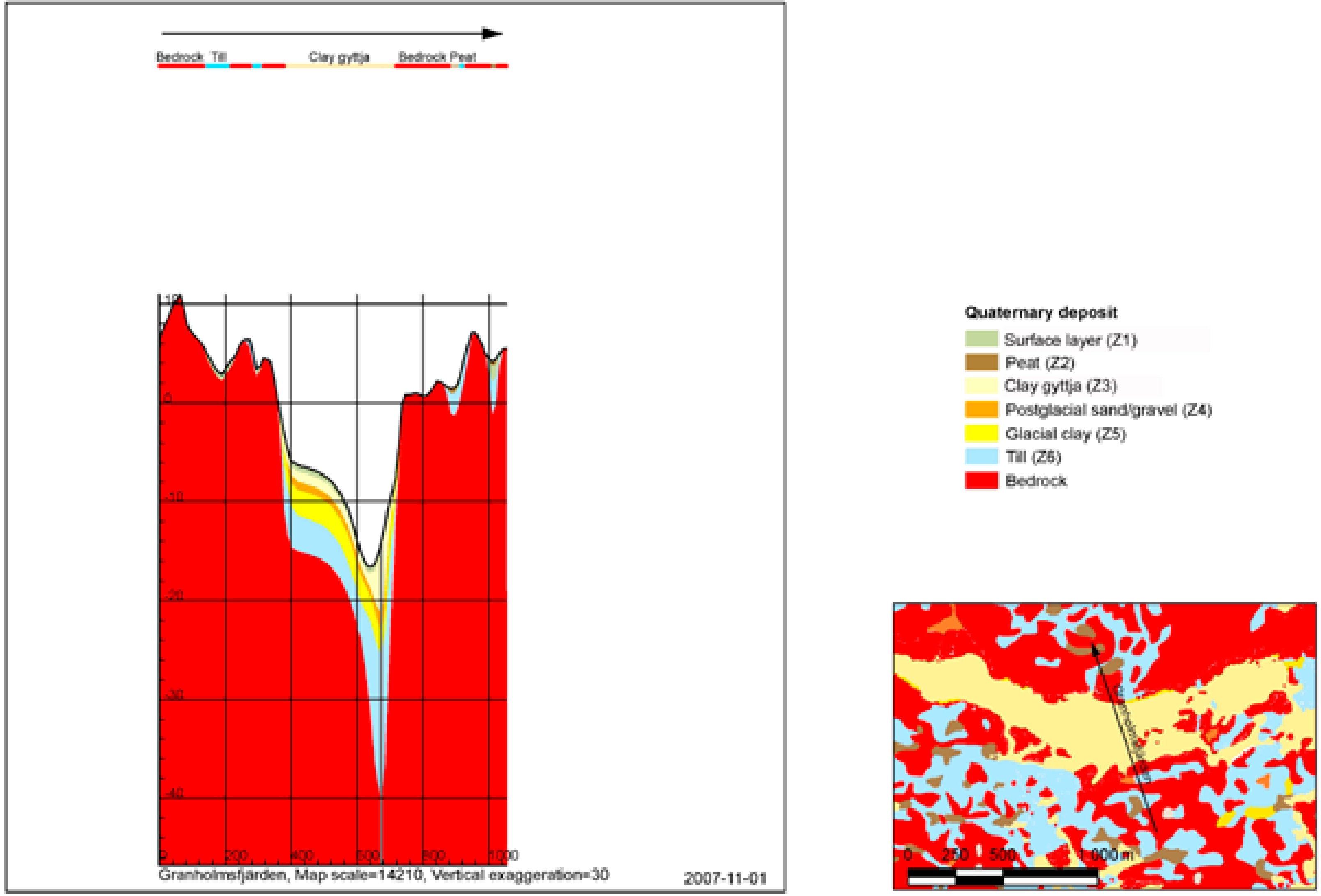

__Figure A2-6.__ Vertical profile showing stratigraphy and total regolith depth along profile "Granholmsfjärden". For location of the profile, see Figure 4-3.

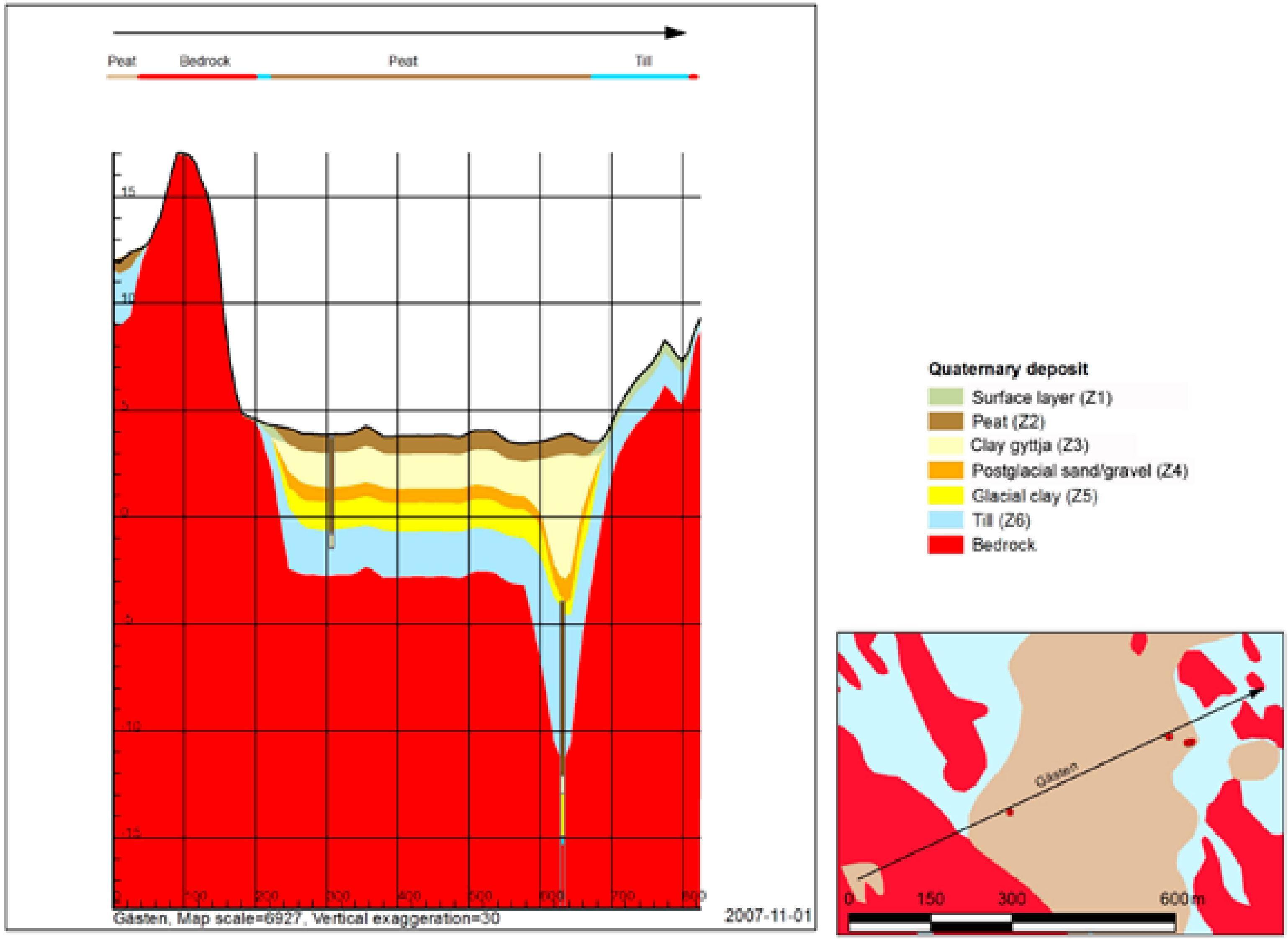

__Figure A2-7.__ Vertical profile showing stratigraphy and total regolith depth along profile "Gästen". For location of the profile, see Figure 4-3.

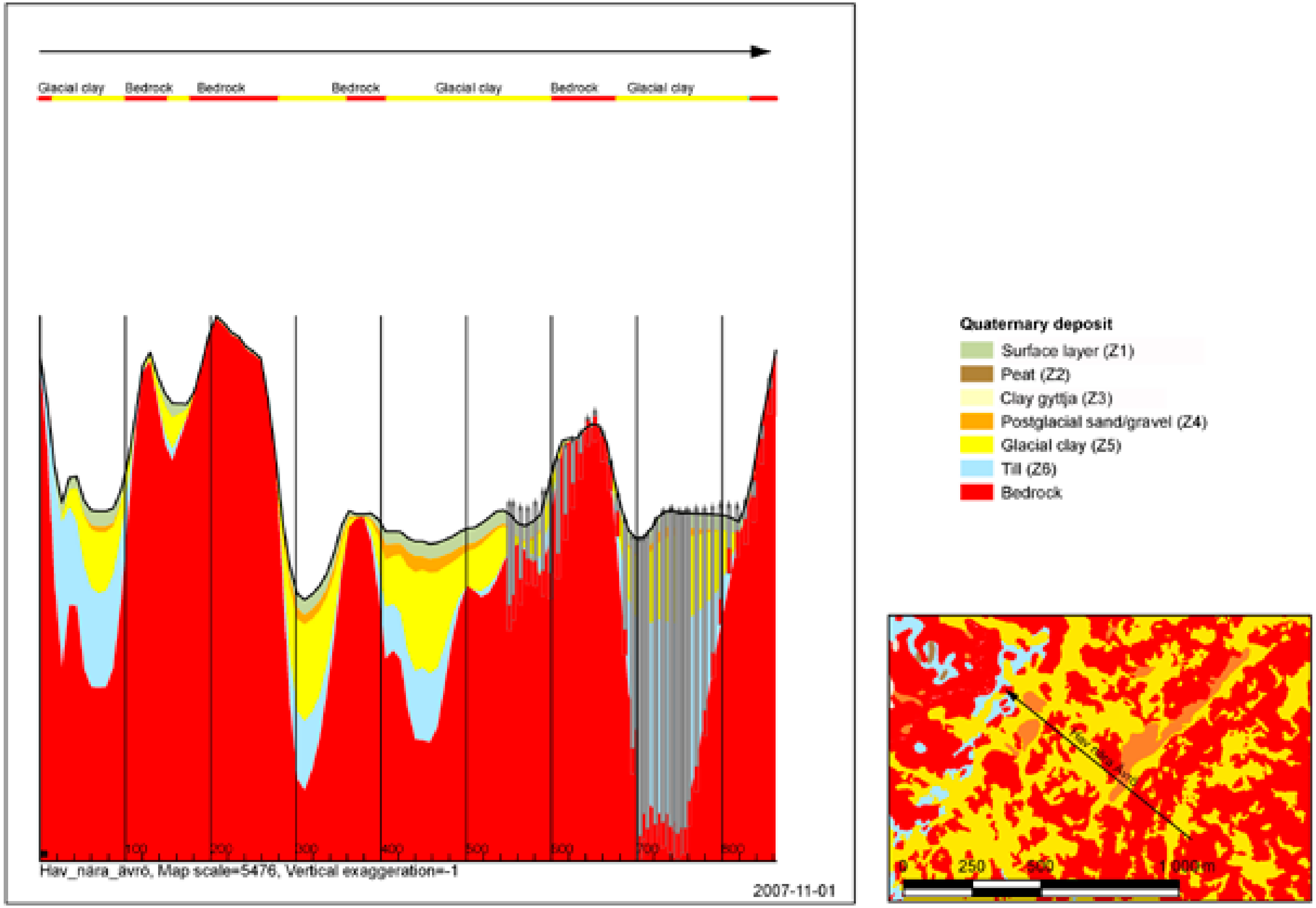

Figure A2-8. *Vertical profile showing stratigraphy and total regolith depth along profile "Hav_nära_ävrö". For location of the profile, see Figure 4-3.*

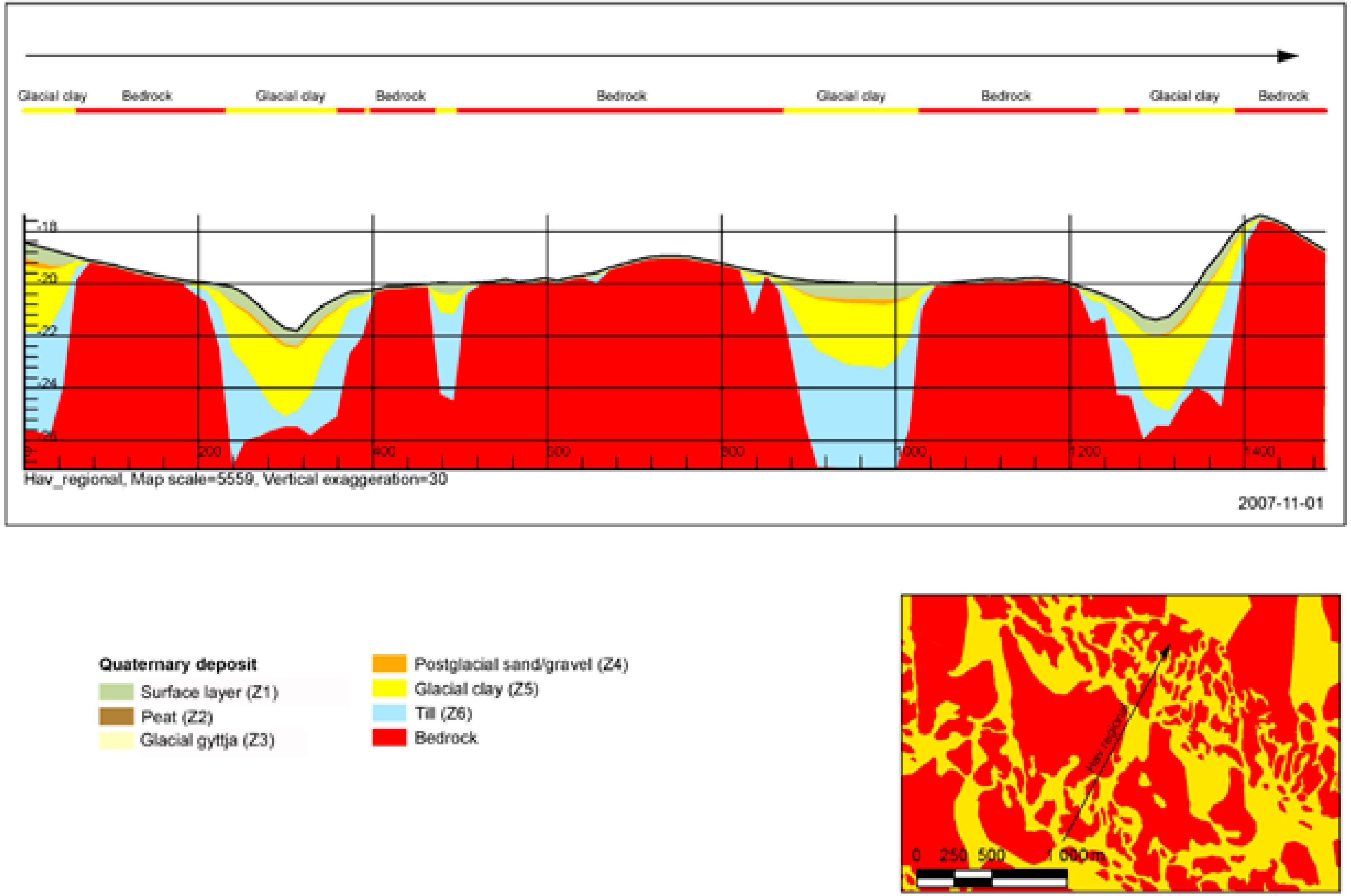

Figure A2-9. *Vertical profile showing stratigraphy and total regolith depth along profile "Hav_regional". For location of the profile, see Figure 4-3.*