R-08-07

Depth and stratigraphy of regolith at Forsmark

Site descriptive modelling SDM-Site Forsmark

Anna Hedenström, Gustav Sohlenius
Geological Survey of Sweden

Mårten Strömgren, Lars Brydsten
Umeå University

Helena Nyman, SWECO Position

January 2008

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

ISSN 1402-3091
SKB Rapport R-08-07

Depth and stratigraphy of regolith at Forsmark

Site descriptive modelling SDM-Site Forsmark

Anna Hedenström, Gustav Sohlenius
Geological Survey of Sweden

Mårten Strömgren, Lars Brydsten
Umeå University

Helena Nyman, SWECO Position

January 2008

Keywords: Quaternary deposits, Regolith, Depth model, GeoModel, Bedrock surface, DEM, Forsmark, Site investigations.

This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the client.

A pdf version of this document can be downloaded from www.skb.se.

Summary

At the Forsmark site, numerical and descriptive modelling is 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. This model presents the total depth and stratigraphy of regolith at the Forsmark. Regolith refers to all the unconsolidated deposits overlying the bedrock. The regolith depth model presented here visualizes the spatial distribution of the regolith as well as the upper surface of the bedrock. The model covers 155 km^2 including both terrestrial and marine areas. The model is pure geometrical and properties are ascribed by the user according to the purpose. According to the conceptual understanding of the distribution of the different Quaternary deposits, seven layers and three lake sediment lenses with different geological and hydrological properties are modelled to represent the stratigraphy at Forsmark. The program used in the modelling of regolith depths is ArcGis and the extension GeoModel.

The input data used for interpolation of the bedrock surface in the model consist of 115 boreholes and 23 stratigraphical observations from excavations and coring points and 5 records of regolith depth from the SGU archive of wells. A large number of observation points interpreted from geophysical investigations were also used as input to the modelling; 6,853 points based on refraction seismic measurements, 421 points from reflection seismic measurements, 439 observation points based on ground penetration radar, 264 points from electrical soundings (CVES), 147,151 points from seismic and sediment echo sounding data in the marine area. A detailed topographical Digital Elevation Model (DEM) and points representing bedrock outcrops in geological maps of Quaternary deposits were also used as input to the model. Altogether 88,322 bedrock outcrops were identified in the geological maps. Some parts of the area have a low data density and the model area was therefore divided into a number of sub-domains. These sub-domains were defined by using the known distribution of Quaternary deposits. In these sub-domains different average regolith depth values have been used for interpolation. Some of the used points are generally not very deep and do not describe the actual bedrock elevation. They do, however, describe the minimum regolith depth at each location and is therefore used where the regolith depth would have been thinner without using the observation points.

The model is based on a seven-layer-principle where each layer can be given certain properties. The uppermost layer, Z1, represents the layer that may have been influenced by the impact from surface processes, e.g. bioturbation, frost action and chemical weathering. Next layer, Z2 represents peat. After that follows Z3 that represents sand/gravel, glaciofluvial sediment or artificial fill, followed by Z4a which corresponds to postglacial clay and clay gyttja/gyttja clay. Z4b consists of glacial clay while Z5 symbolizes till. The bottom layer, Z6, represents the uppermost bedrock, which have a high frequency of fissures and fractures. The lower level of Z5 constitutes the bedrock surface. All layers except Z6 may have thickness zero.

The water laid sediments in eight of the lakes have been modelled according to three classes of deposits; L1 corresponding to different type of gyttja, L2 corresponding to postglacial sand and gravel and L3 that represents glacial and postglacial clay.

The resulting model clearly shows that the regolith depth reflects the large scale morphology of the bedrock surface. The maximum depth of regolith in the model is about 42 m. The average modelled regolith depth is 6.5 m if areas with bedrock outcrops are excluded. The average regolith depth within the model domain, including bedrock outcrops is 5.6 m. There is a general difference between the regolith depth in the terrestrial and marine area: the average depth in the terrestrial area is 4.0 m and 8.3 m in the marine part. Some of the major lineaments in Forsmark are characterised by deeper regolith.

The 2.3 regolith model presented in this report was preceded by a 2.2 regolith depth model. In this report the earlier model is presented in Appendix 2.

Sammanfattning

Numerisk och beskrivande modellering utförs både för det djupa berget och för ytsystemen i Forsmark. Fördelningen av jordarter och berggrund i ytan och på djupet är viktiga parametrar till exempel för hydrogeologisk och geokemisk modellering samt för den övergripande förståelsen av platsen. Föreliggande rapport beskriver det modellerade jorddjupet i ett område som är modifierat från Forsmarks regionala modellområde. Jorddjupsmodellen som presenteras här visualiserar utbredningen av de lösa avlagringarna samt bergets överyta. Modellen inkluderar en 155 km^2 stor yta som inkluderar både land- och havsområden. Modelleringsprinciperna har varit en indelning av jordprofilen i sju lager som representerar olika geologiska enheter som i sin tur kan tillskrivas olika egenskaper. Modellverktyget som använts vid modelleringen av jorddjup är ArcGis med tillägget GeoModel.

Indata till modellen har varit 115 borrhål och 23 provgropar eller observationspunkter samt 5 borrhål från SGUs brunnsarkiv. Som indata har också ett stort antal värden där jorddjupet är tolkat från geofysiska undersökningar använts; 6 853 punkter baserade på refraktionsseismiska mätningar, 421 punkter från reflektionsseismik, 439 observationspunkter från markradarmätningar, 264 punkter från elektriska sonderingar (CVES), 147 151 punkter från maringeologiska undersökningar. Från den geologiska kartan har 88 322 ytor med berggrund identifierats och använts vid interpolationen. Dessutom har observationspunkter använts som är inte når ner till bergytans nivå. Dessa observationer har använts för att beräkna medeldjup för olika jordarter och att säkerställa ett minsta djup till berg i de fall där jorddjupet hade blivit tunnare om observationen inte använts. I områden där djupuppgifter saknas har jordarternas meddeldjup använts inom definierade sub-domäner. En detaljerad topografisk DEM (digital höjdmodell) och en jordartskarta har också använts i modelleringen.

Modellen är enbart geometrisk men användaren kan tillskriva de olika lagren egenskaper utifrån aktuell tillämpning. Modellen är baserad på en sjulagersprincip som utgår ifrån de geologiska enheterna i Forsmarksområdet. Det översta lagret, Z1, representerar det översta skiktet som har påverkats av ytliga processer, t ex rötter och biologisk aktivitet. Nästa lager, Z2, representerar ytor med torv. Därefter följer Z3 som karaktäriseras av sand/grus, isälvsavlagringar eller fyllnadsmaterial, följt av Z4a som består av postglacial lera och lergyttja. Z4b utgörs av glacial lera medan Z5 motsvarar morän. Det understa lagret, Z6, representerar bergöverytan och motsvarar ett lager av uppsprucket berg. Underkant av lager Z5 utgör bergets överyta. Alla lager utom Z6 kan ha mäktigheten noll.

Sjösedimenten för åtta utvalda sjöar har modellerats som separata sedimentlinser. Linserna är uppbyggda av tre förenklade lager; L1 som består av olika typer av gyttja, L2 som motsvarar sand och grus och L3 som består av glacial och postglacial lera.

Modellen visar tydligt att jorddjupet avspeglar den storskaliga berggrundsmorfologin i Forsmarksområdet. Det största jorddjupet i modellen är ca 42 m, och medelvärdet för jorddjupet i området är 6,5 m, beräknat utan hällar. Det finns en generell skillnad mellan medeljorddjupen i områden belägna på land (4,0 m) och de marina områdena (8,3 m).

Denna jorddjupsmodell (version 2.3) har föregåtts av en modellversion 2.2 som återfinns i Appendix 2.

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 Simpevarp in the Oskarshamn municipality, see Figure 1-1.

At the Forsmark site, numerical and descriptive modellings 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 regolith depth model (RDM) will be used e.g. in hydrological and transportation modelling of the area. The geometrical model will visualize the spatial distribution of the Quaternary deposits as well as the upper surface of the bedrock.The interpolation method used is Kriging. By compiling all available information regarding depth of regolith and location of bedrock surface, the model will also identify areas with a low density of data. Furthermore, the model provides a close link between basic geological and geophysical data, conceptual interpretation and model representation.

Figure 1-1. *Map showing the Forsmark area.*

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 both Quaternary deposits of all kinds, such as till, clay and peat, together with artificial filling material or granular weathered bedrock are included in the regolith. All known regolith in the Forsmark regional model area was formed during the Quaternary period, the term Quaternary deposits (QD) is therefore often used for the regolith in the Forsmark area. In the terrestrial part, the upper part 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.

This report presents a geometric model that describes the total regolith depth, subdivided into seven layers (Z1–Z6) and three generalised lake sediment lenses (L1–L3). The layers and lenses in the model are pure geometrical but constructed after the conceptual and stratigraphical understanding of the site, hence properties of the layers and lake sediment lenses should be ascribed by the user. For example, the upper layer Z1 can be given different properties in different areas through connection to the e.g. maps of Quaternary deposits or soil types.

This report describes the 2.3 version of the RDM for the Forsmark site. Additional to the authors, Malin Andreé and Anna Suska (Sweco position) have imported and adjusted the layers and lenses into Arc Gis Model builder. Bengt Zagerholm (DHI), imported the model into Geo Model where the profiles were constructed. A manuscript of this report was reviewed by Rolf Christiansson (SKB), Rune Johansson (SGU), Emma Bosson (SKB), Tobias Lindborg (SKB) and Sten Berglund (SKB). Their input has contributed to many improvements of the manuscript.

Prior to this version, a 1.2 RDM was presented /Vikström 2005/. A 2.2 RDM has also been produced, however this model version was not described in any report before replaced by this 2.3 RDM. The modelling principles for 2.2 RDM is described in Appendix 2 together with a comparison between the 2.2 and 2.3 model versions. This main report will describe the 2.3 RDM.

The primary differences between the model versions are presented in Table 1-1.

Available data from boreholes, observation points, seismic data, seismic and sediment echo sounding data, and geological maps of Quaternary deposits are used as input data to the model. The resulting interpolated surfaces are presented in a GIS-environment.

Table 1-1. Some principle differences between the three RDM produced for the Forsmark site.

Model version	1.2	2.2	2.3
Area included	Terrestrial, Lake Bolundfjärden catchment area (60 km^2)	Terrestrial and marine, modified regional model area (155 km^2)	Terrestrial and marine, modified regional model area (155 km^2)
No of input data	2,045	311,651	155,273
Lake sediment lenses	Yes	Yes	Yes
Layers according to conceptual model	No	Yes	Yes
Interpolation method	Inverse Distance Weighted	Kriging	Kriging
Spatial resolution	10×10 m	20×20 m	20×20 m
Usage of average depth values	Yes, one average depth in all areas lacking primary data	Only outside regional model area	Yes, in all areas lacking primary data

Figure 1-2. *Area for modelling of regolith depth in the Forsmark area.*

The model area is a modified Forsmark regional model area, shown in Figure 1-2. The regional model area is partly reduced or enlarged to follow the catchment area boundaries of today and future. Two exceptions were made, the entire Kallrigafjärden was included and the Gräsö shoreline was used as boundary instead of the water divide on top of the island. The total area modelled is 159 km^2.

In Chapter 5, an evaluation of the bedrock surface and total thickness of regolith in relation to e.g. data distribution is presented. That chapter focus only on the total thickness, not layers and lenses between the bedrock and the ground surface. In this sense, the model is referred to as regolith thickness model, RTM, whereas the RDM represents all the modelled layers and lenses.

2 Input data

2.1 Data used in the model

The input data used in the model is based on the information available at the data freeze 2.2 in Forsmark, 30th September 2006 complemented with depth to bedrock from 16 probings performed in November 2007.

Table 2-1 shows the data used in the FM 2.3 RDM. All available data was not used for interpolation of the bedrock surface since some observations are shallow and do not reach the bedrock surface. These observations were used for the stratigraphical model.

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. The DEM used in the model is based on the existing DEM from the Swedish national land survey (LMV), the SKB DEM with 10×10 m resolution /Brydsten and Strömgren 2004/, nautical chart and depth soundings. The reason for producing the model in 20×20 m resolution is that the marine areas are included, thus the usage of 10×10 m resolution would inhibit the usage of the model from security reasons.

The Forsmark area has a relatively flat topography with a slope towards the east (see Figure 2-1). The most elevated area is the south western part, reaching c. 25 m a.s.l. The deepest parts are located in the northern part of the model area, west of Gräsö, where the water depth is c. 40 m. In the RDM, the elevation of each observation point was derived as the difference in altitude between the bedrock surface and the DEM, thus any errors in the DEM will be incorporated in the RDM as well, see further Chapter 5.

Figure 2-2 shows the distribution of data used for the modelling of the bedrock surface. The outer parts of the marine area have a no data between the investigated profiles. Some observation points do not describe the actual bedrock elevation. They do, however, describe the minimum regolith depth at each location.

The QD geological map used in the 2.3 model version, which may be used to ascribe properties to the surface layer, covers the whole modelled area. The resulting map (Figure 2-3) is a compilation of six different data sources, initially produced with different methods and adjusted for presentation at different scales. The geographical distribution of bedrock outcrops was derived from the QD map. All grid points from the DEM touching bedrock outcrop areas were selected.

The most detailed map covers the terrestrial area at the central part of the regional model area (Area 1 in Figure 2-3). This map was produced within the initial site investigations /Sohlenius et al. 2004/ and includes bedrock exposures and QD with areas larger than 10×10 m. The detailed geological map was initially presented at the scale 1:10,000.

Area 2 is represented by geological maps in Geological Survey of Sweden ser Ae, adapted for presentation at the scale 1:50,000 /Persson 1985, 1986/. The map covers the distal parts of the terrestrial area.

In the shallow coastal bays, Area 3, the survey vessel used for the regular marine geological mapping could not enter. Therefore, the distribution of Quaternary deposits was investigated in a large number of point observations from the sea ice or using a small boat /Ising 2005/. The investigations were performed along lines or profiles, approximately 200 metres apart. This method makes the precision of the map adapted to presentation at the scale 1:50,000 and no area less than 50×50 metres will be displayed.

Table 2-1. Availiable data to the FM 2.3 Regolith Depth Model. Data marked with an asterix * are not used for the interpolation of the total regolith depth, Z5.

Data	Description	No of observations	Reference
DEM	The DEM has a resolution of 20×20 m and describes the land surface, and the sediment surface of lakes and sea.		/Strömgren and Brydsten in prep/
Geological maps			
QD geological map	The map of QD and bedrock outcrops covering the entire model area. The resulting map comprises of a compilation of six data sets based on different mehtods and scale.		/Elhammer and Sandkvist 2005, Sohlenius et al. 2004, Persson 1985, 1986, Ising 2005, Hedenström and Sohlenius in prep/
Corings and excavations			
Cored, percussion and probing boreholes	Boreholes with an estimated bedrock elevation, i.e. cored, percussion and probing boreholes.	115 bore-holes (*117)	/Johansson 2003, Hedenström et al. 2004, Werner and Johansson 2003/
QD mapping and stratigraphic observations	Mostly shallow observation points from hand driven corers and excavations with detailed stratigraphy is used. Stratigraphic investigations in machine cut trenches.	38 observa-tion points (*322)	/Lokrantz and Hedenström 2006, Sundh et al. 2004, Lagerbäck et al. 2004, 2005/
Organic and in-organic sediment mapping, peat land mapping	Stratigraphic information from lakes and mires. The corings are performed using hand driven corer, hence data contains information of fine grained sediments and peat. Used for construction of lenses in lakes and depth for peat layer and clay layers.	*272 obser-vation points (used for gyttja, clay and sand)	/Fredriksson 2004, Hedenström 2003, 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.	1 (*62) observation points	/Elhammer and Sandkvist 2005/
SGU's archive of wells	Total depth to bedrock as recorded at the installation of private groundwater wells. The information is extracted from SGU database.	7 wells	/SGU 2007/
Geophysical data			
Seismic and sediment echo sounding data	Estimated depth to bedrock and stratigraphy in marine area.	147,151 sites	/Elhammer and Sandkvist 2005/
Refraction seismic measurement data	Each observed point along the profiles has a surface elevation and an estimated smoothed bedrock elevation.	228 profiles including 10,247 observation points	/Keisu and Isaksson 2004,Toresson 2005, 2006/
Seismic tomography, reflection seismic measurement	Each observed point along the profiles has a surface elevation and an estimated smoothed bedrock elevation.	Five profiles including 1,341 observation points	/Bergman et al. 2004, Bergman 2004/
Ground penetration radar measurement data	Each observed point along the profiles has coordinates, a surface elevation and an estimated smoothed bedrock elevation.	31profiles including 766 observation points.	/Marek 2004ab/
Continuous Vertical electrical soundings (CVES)	Observation points from continuous vertical electrical soundings (CVES) where estimated depth to bedrock is used.	4 profiles including 309 observation points	/Thunehed and Pitkänen 2003/

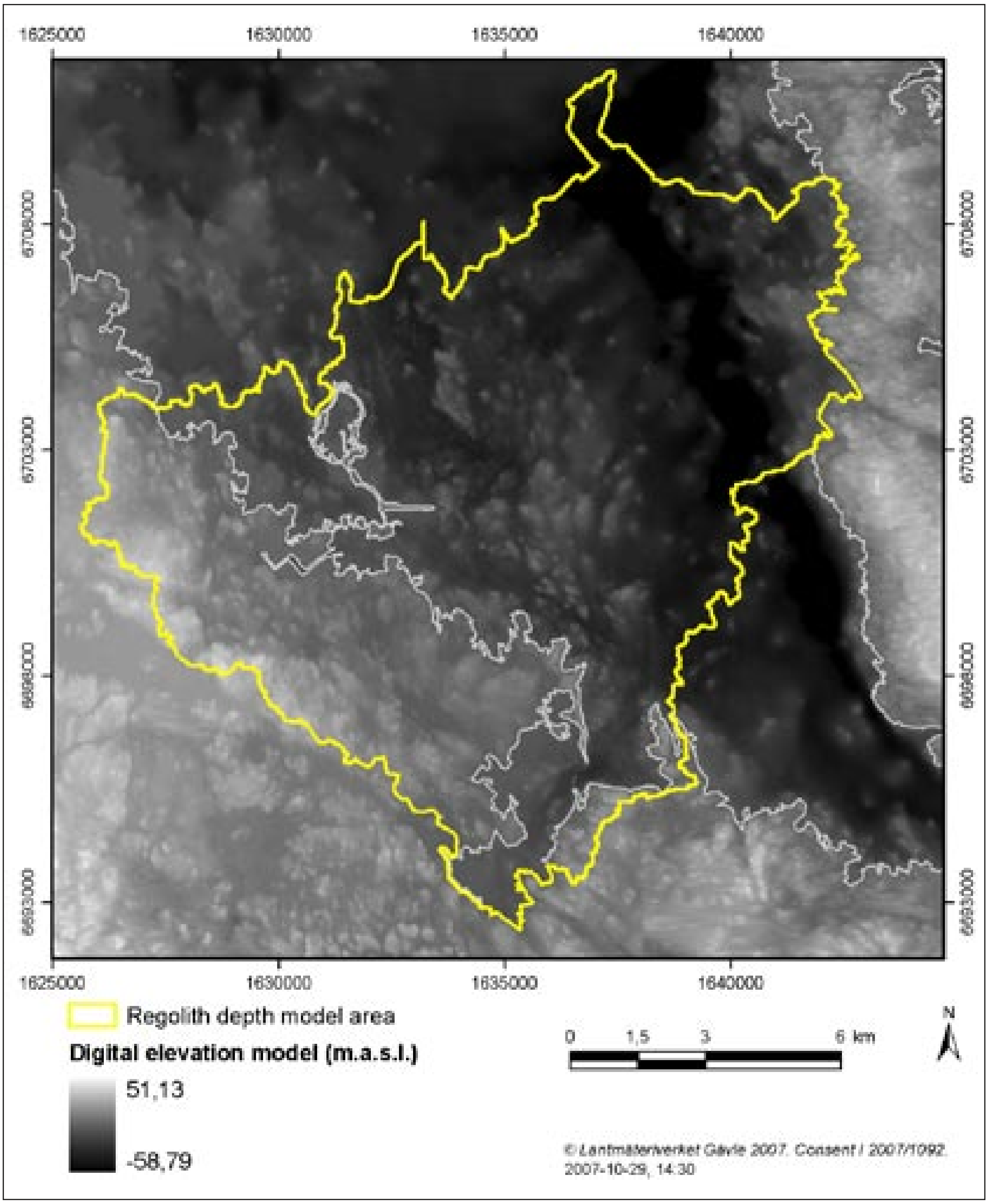


Figure 2-1. *The Digital Elevation Model (DEM) of the ground surface in a 20×20 m resolution /Strömgren and Brydsten in prep/. The yellow line represents the border of the model area.*

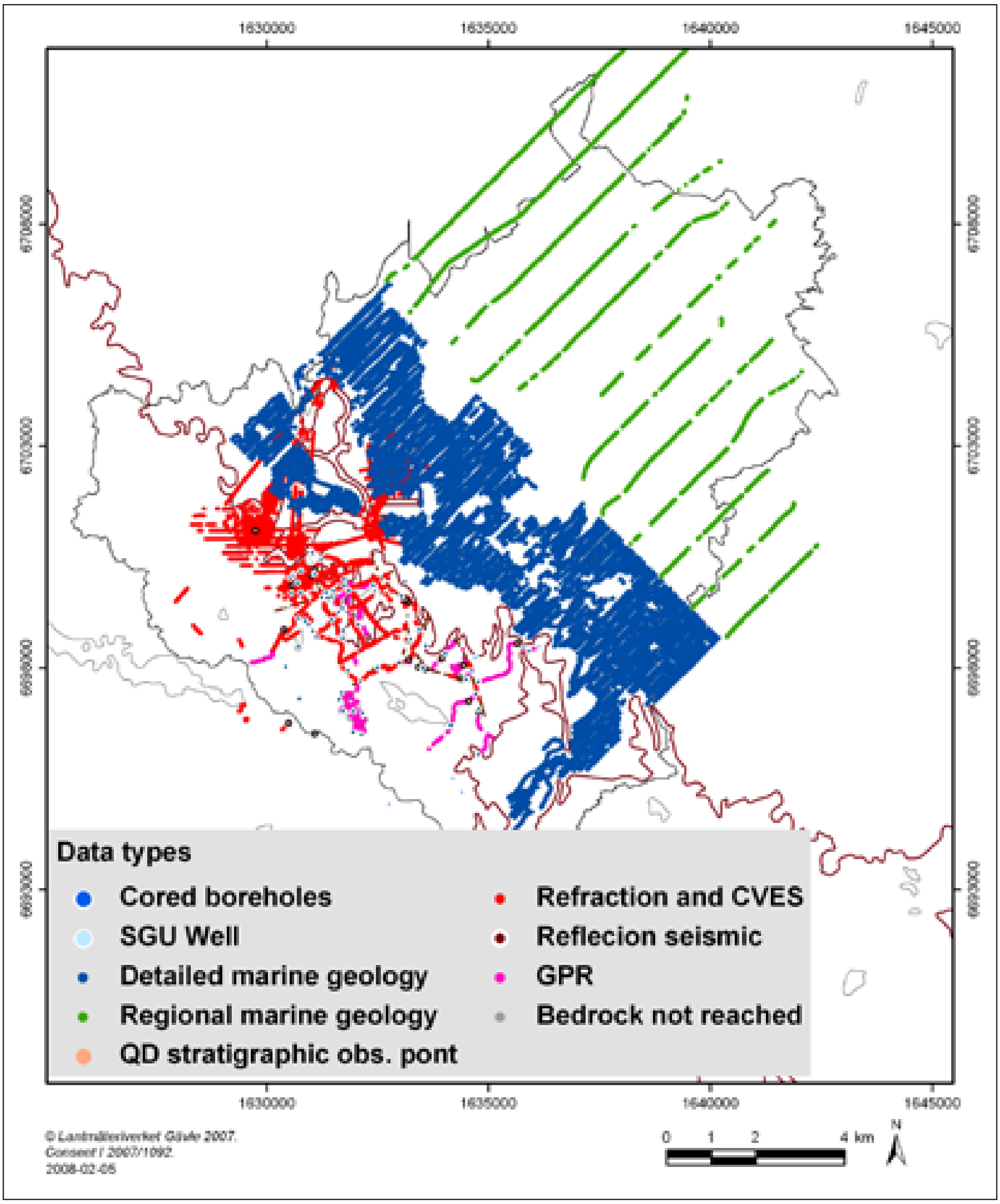


Figure 2-2. *The distribution of observation points and profiles used for modelling of the total regolith depth and the bedrock surface. The black line represents the border of the model area.*

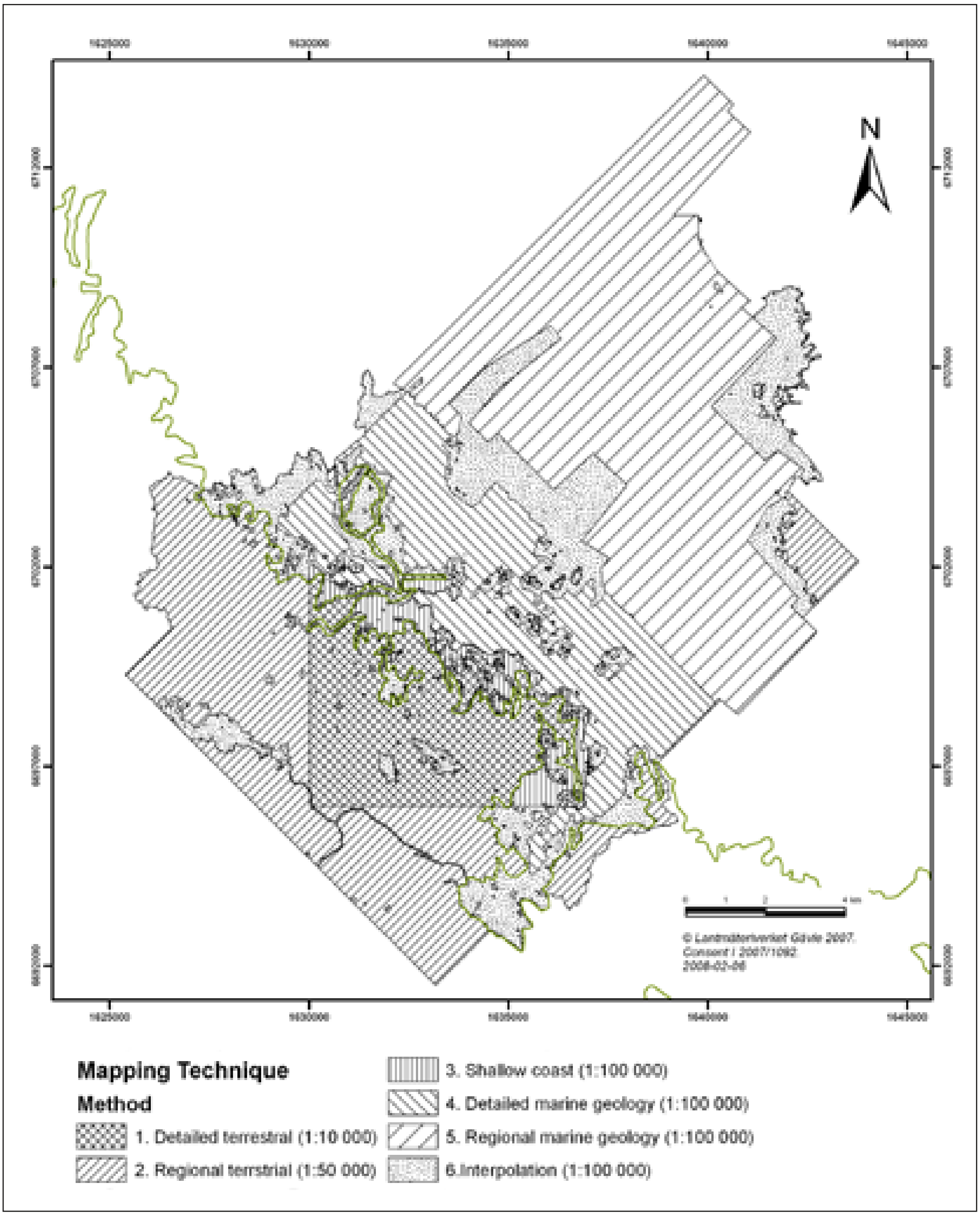


Figure 2-3. *The distribution of the different input data used to construct the resulting QD geological map used in the 2.3 RDM.*

Area 4 contains detailed marine geological information with a distance of 100 m between the investigation lines /Elhammer and Sandkvist 2005/. Area 5 contains regional marine geological information with a distance of 1,000 m between the investigation lines /Elhammer and Sandkvist 2005/. Both marine geological maps were initially presented at the scale 1:100,000.

In order to obtain a complete map, the remaining areas located under shallow water in the marine area and under the lakes and streams in the terrestrial part were interpreted as well. The resulting map (Area 6) is based on interpretations from lake and sediment corings /Hedenström 2003/, bathymetry from the DEM and interpolation from the surrounding Quaternary deposits. It should be noted that this area is the most uncertain in the geological map.

The different observation types used in the regolith depth model have different accuracy. If overlap occurs, data with lower accuracy was excluded. The data sets used were classified and ranked according to accuracy in estimation of regolith depth, Table 2-2.

Below follows a short description of the ranking classes:

1. Direct observations of bedrock outcrops, corings and probings that reach bedrock and have a GPS-measured coordinate.
2. SGU archive of wells, only those with SKB coordinates are used. Marine geological measurements. Data from the detailed measurements (Area 4) are ranked higher than those from the regional (Area 5).
3. Stratigraphical observations from the investigations of Quaternary deposits, many of these do not reach bedrock. Observations from hand driven corers and machine cut excavations.
4. Ground geophysical measurements performed with purpose to investigate regolith thickness.
5. Estimate of bedrock topography using seismic tomography along reflection seismic profiles LFM000002–LFM000006. Data was not initially collected for regolith depth measurements but the data was interpreted for this purpose as well.
6. Ground penetrating radar along profiles with purpose to investigate regolith depth.
7. Stratigraphical information that does not reach bedrock but have regolith depth higher than the average values of its domain.

The hierarchy of the ranking is based on information from the reports describing the data, discussions with some of the geophysics involved in the measurements (Björn Bergman, UU/SGU, pers com 2007, Johan Nissen, Malå Geoscience, pers com 2006) as well as a general assumption that the direct observations from the surface is more reliable than the interpretations from geophysical data.

2.2 Description of the Quaternary geology in the model area

All known regolith in the Forsmark area was formed during the Quaternary period and is therefore referred to as Quaternary deposits (QD) with the exception of artificial filling material. For a detailed description of the properties and distribution of the regolith in Forsmark, see /Hedenström and Sohlenius in prep/ and for the geological development of the site, see /Söderbäck 2008/.

Quaternary deposits cover c. 90% of the ground surface within the model domain. Exposed bedrock or bedrock with only a thin Quaternary cover (< 0.5 m) occupies c. 9% of the land area in the regional model area and only c. 5% of the central part (Figure 2-4, Table 2-1). Areas with low frequency of outcrops are e.g. the eastern part at Storskäret and west of Lake Bolundsfjärden. Areas with high frequency of bedrock outcrops are e.g. the south western and the north eastern part of the regional model, e.g. along the present shoreline and on several of the small islands. Many of the outcrops are Roches mountonnées with a smooth abraded northern side and a rough, steep plucking side towards the south. Numerous observations of striae, crescentic fractures and crescentic gouges indicate that an ice moving from the north (350–360°) has formed a majority of glacial abrasion while an older ice movement, forming a system of striae from north-west is preserved on lee side positions. In areas covered with regolith, the contact zone between bedrock and till is characterised by high hydraulic conductivity /Werner and Johansson 2003/ and open fractures /Leijon 2005/. In this model, a zone representing fractured bedrock is represented by Z6.

Table 2-2. The different data types used for interpolation of regolith depth (Z5) and their internal ranking status. The Buffer distance means how long buffer distance that has been applied to the data of lower rank.

Data type	Rank	Buffer distance	No of points used for interpolation of Z5	No points excluded by buffering
Bedrock outcrops in geological map	1	30	88,322	0
Cored borehole, Percussion borehole, Monitoring well in soil	1	30	99	0
Probings performed in November 2007	1	30	16	0
Well from SGU´s well archive	2	30	5	2
Detailed marine geology	2a	100/30	128,296	10,312
Regional marine geology	2b	100/30	18,855	5,090
Ocean sediment core sampling	3	30	1	0
QD mapping, stratig. obs	3	30	21	17
CVES 7 electrodes	4	30	264	45
Refraction seismics	4	30	6,853	3,394
Reflexion seismic (LFM000002–LFM000006)	5	30	421	920
Ground Penetrating Radar	6	30	439	327
Monitoring well in soil (not reaching bedrock)	7	30	1	0
Neotectonic stratigraphic observation (not reaching bedrock)	7	30	1	0
QD mapping, stratig. observation (not reaching bedrock)	7	30	1	4

Table 2-3. The proportions (% of area) of the different Quaternary deposits and bedrock exposures in the Forsmark area. The terrestrial area includes Area 1 and 2 in Figure 2-3 while the marine area is based on Area 4 and 5. The first column also includes Area 3 (shallow coastal area) and 6 (lakes and remaining areas).

	Forsmark Area 1–6	Forsmark Area 1 and 2	Forsmark Area 2	Forsmark Area 4 and 6
Bedrock exposures	9	13	5	6
Glacial clay	25	4	4	41
Postglacial clay (including gyttja clay and gyttja)	11	4	4	17
Postglacial sand and gravel	4	2	4	6
Till (sandy/clayey)	46/2.5	65 (58/7)	74 (63/11)	30
Glaciofluvial sediment	0.5	1	2	0
Peat	1	8	3	–
Artificial fill	1	3	4	–

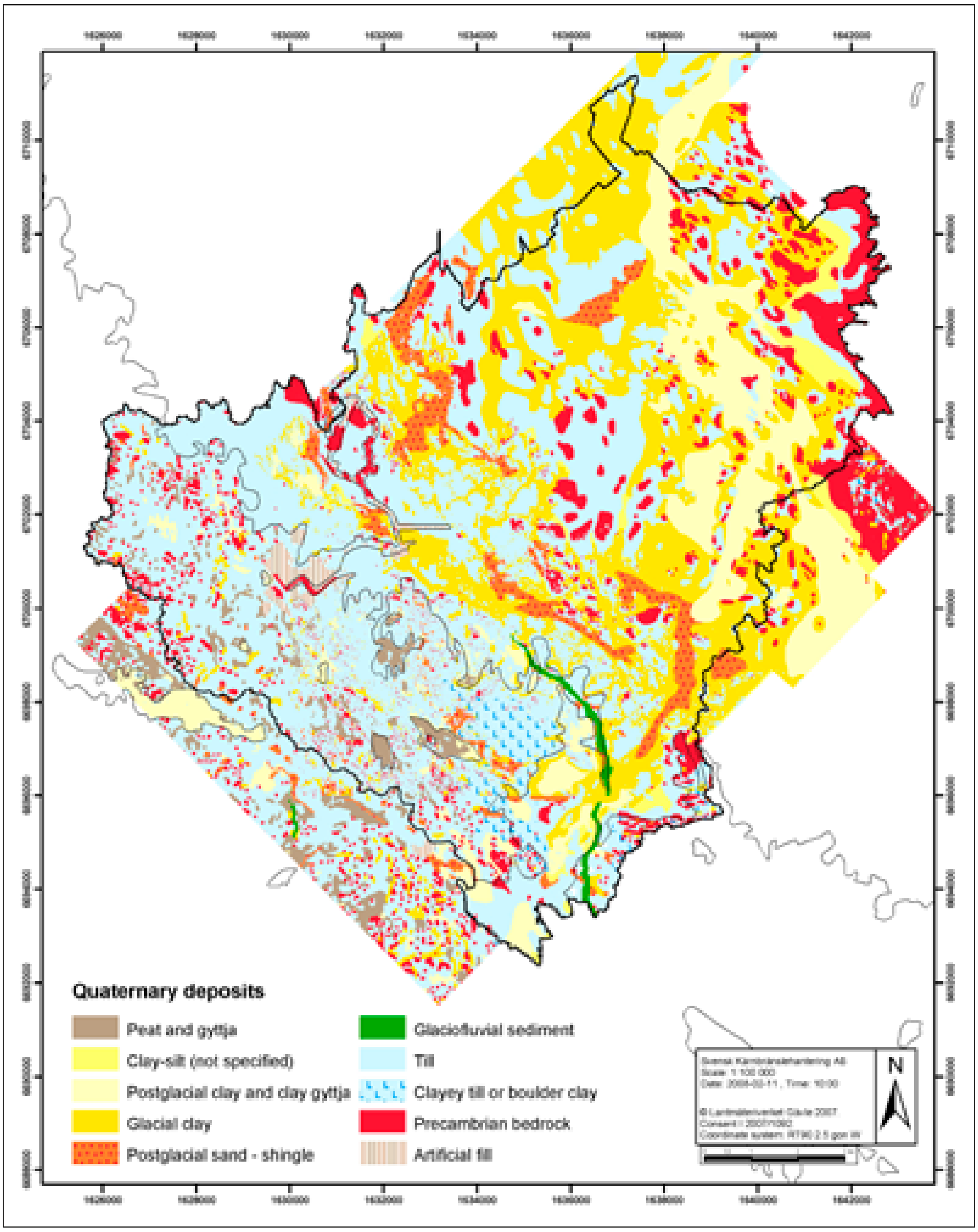


Figure 2-4. *The distribution of the Quaternary deposits in the Forsmark area. The map is a compilation of six different geological maps, originally presented in different scale /Sohlenius et al. 2004, Persson 1985, 1986, Ising 2005, Elhammer and Sandkvist 2005, Hedenström and Sohlenius in prep/. It should be noted that the areas presently covered with water (under lakes, streams and in the sea) are presented without water.*

The Quaternary deposits are divided according to environment in which they were formed into two main categories: *glacial* and *postglacial* deposits.

Glacial deposits are those deposited either directly from the ice sheet or from the water, derived from the melting of this ice. A majority of the Quaternary deposits covering the bedrock were deposited during the later stage of the last glaciation, the Weichselian. Characteristic for the glacial deposits are that they are minerogenic in composition, i.e. they contain no (or very little) organic matter.

Glacial till consist of bedrock fragments and older deposits incorporated and transported by the ice sheet and later deposited. Generally till is characterised by poor sorting, resulting in grain size composition including all grain sizes from clay particles to large boulders. In the geological classification, till is subdivided according to the grain-size composition of the matrix and the boulder frequency of the surface.

In Forsmark, till is the over-all dominating Quaternary deposit. Based on the frequency of boulders in the surface layer, the till in the terrestrial part of Forsmark has been divided into three areas (Figure 2-4). In the 2.3 RDM, till is represented by Z5.

Till area I constitutes the major part of the Forsmark area, especially in the western and southern parts of the model area. In this area, sandy till with medium frequency of superficial boulders dominates. *Till area II* is dominated by clayey till and boulder clay, i.e. a clay content > 5% of the matrix. In the eastern part of the model area, at Storskäret clayey till with low frequency of boulders dominates. The major part of the arable land in Forsmark is located within this area. In this model, this area has been separated into one domain. *Till area III* is located in the eastern part of the investigated area, close to the Börstilåsen esker. The surface layer of this area is characterised by a high frequency of large boulders with a volume often > 1 m^3.

During the deglaciation, a large quantity of melt water was produced. The melt water was concentrated to tunnels under the ice, and fractures on the surface, seeking its way to the ice front.

Glaciofluvial sediments were formed when bedrock material was transported, sorted and rounded with the melt water and deposited in cavities within the ice or at the ice margin. Glaciofluvial deposits are characterised by well sorted sediments, often forming eskers of sand and gravel. The glaciofluvial deposits are often deposited directly on the bedrock or on top of the till. In Forsmark, only 1% of the land area is covered with glaciofluvial sediments, represented by one small esker, the Börstilåsen esker, which passes through the south eastern part of the model area. The Börstilåsen esker is the largest glaciofluvial deposit in the Östhammar region and can be followed from Harg situated c. 30 km south Forsmark. The part of the esker located

Table 2-4. General stratigraphical distribution for the Quaternary deposits in the Forsmark area and their relative age. Note that not all layers are present everywhere.

Lithology	Relative age	Layer/lens in RDM
Bog peat	Youngest	Z2
Fen peat		Z2
Gyttja/Calcareous gyttja	↑	L1
Algal gyttja		L1
Clay gyttja	↑	L1
Postglacial sand and gravel		L2
Postglacial clay	↑	L3/Z4a
Glacial clay		L3/Z4b
Glaciofluvial sediment		Z3
Till	Oldest	Z5
Bedrock		

within the model area contains sand, gravel and stones. In this model, glaciofluvial sediment is represented by a separate sub-domain, represented by Z3. The finest particles, clay and silt, were transported with the meltwater and deposited further from the ice margin in deep and stagnant water. Glacial clay and silt are often characterised by varves, i.e. layers representing summer and winter accumulation. The areas covered with glacial clay are small in the terrestrial area and concentrated to local depressions such as the bottom of lakes and small ponds. In the terrestrial area, especially if not associated to the larger lakes, glacial clay is often only a few dm thick and is probably remnants after erosion on the bottom of the sea. In off shore areas glacial clay is more frequently occurring, c. 40% of the surface, especially in the areas with a water depth of more than 6 metres /Elhammer and Sandkvist 2005/.

Both in the terrestrial area and offshore, a layer of postglacial sand and/or gravel often covers the glacial clay. This is interpreted as the result of erosion and transportation of sand/gravel on the bottom. In this model, glacial clay is represented by Z4b and is included in the L3 lens.

Postglacial deposits were formed after the inland ice had melted and retreated from the area, c. 9,000 years BC /Fredén 2002/. Due to the pressure from the ice sheet, the bedrock was submerged and sea level in the Forsmark area was c.150 m higher than at present. The Forsmark area has been situated below the Baltic until the last few thousand years. Thus, the formation, erosion and relocation of postglacial deposits have mainly been taking place at the sea floor, and in the water column, of the Baltic. In general, postglacial deposits overlie till and glacial clay but they may also rest directly on crystalline bedrock.

In Forsmark, the postglacial deposits are dominated by sand and gravel, clay gyttja-gyttja clay, gyttja and peat. The postglacial gravel and sand often cuts discordantly and superimpose glacial clay and are interpreted to mainly represent deposition after erosion and transport by currents on the sea floor. In this model, postglacial sand and gravel is represented by Z3 and the L2 lens. *Postglacial clay/*clay gyttja was deposited after erosion and re-deposition of some of the previously deposited sediments, such as glacial clay. The postglacial clay is predominantly found in the deeper parts of valleys on the sea floor. The postglacial clay often have higher organic content than the glacial clay and is then often referred to as clay gyttja or gyttja clay. In this model, postglacial clay is represented by Z4a and may be included in the L3 lens. The ongoing isostatic uplift results in the emergence of new land areas, which transfer sedimentary basins to a sheltered position, favouring the accumulation of clay gyttja, and gyttja superimposed the sandy layer. Many of the ponds and lakes in Forsmark are very shallow, often less than 1 m waterdepth and will have only a short duration as a lake before the basin will be filled in and developed into a wetland. The basins are all in the process of infilling with sediment and peat, hence a strict classification as lake or mire is only representing the present situation. Clay gyttja and gyttja clay are frequent in the surface of the wetlands located at low altitudes, e.g along the shores of Lake Fiskarfjärden and Lake Gällsboträsket. *Gyttja sediments* consist of high proportion of organic material formed in lakes and consist mainly of remnants from plants that had grown in the lake. In areas with calcareous soils, such as the Forsmark area, calcareous gyttja forms when lime saturated ground water enters the lake and/or by biological precipitation by algae. In this model clay gyttja and gyttja are represented by L3 lens.

Peat consists of remnants of dead plants, which are preserved in areas where the prevailing wet conditions prevent the breakdown of the organic material. In the geological map, peatlands are often subdivided into fens and bogs. The vegetation in the fens gains nutrients from the groundwater whereas a bog gains nutrient mainly from precipitation. The bogs are therefore poor in nutrients and are characterised by a coherent cover of Sphagnum-species. The peatlands identified in the Forsmark area are both fen and bogs. The bogs however are few and still young while rich fens are the dominating type. Peat is found most frequently in the south western part of the model area, i.e. the most elevated areas that has been above the sea level long enough for infilling of basins and peat to form. Stenrösmossen and the mire at Rönningarna are two examples of mires which at least partly are developed into bogs. In this model, peat is represented by Z2. Additional to actual peat, many of the young wetlands in Forsmark are covered with clay gyttja in the surface, thus not included in Z2.

3 Methodology

3.1 Conceptual model

The regolith depth model (RDM) is geometrical and 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 (Chapter 2.2 and /Hedenström and Sohlenius in prep/).

The principle for the definition of the layers and lake sediment lenses is illustrated in Figure 3-1. Note that the layer thicknesses are shown in a principle way in the figure.

The model is subdivided into seven layers and three lenses according to the conceptual understanding of the Forsmark site, Figure 3-1. The layers are named Z1–Z6 and the lake sediment lenses L1–L3. The lenses can be regarded as sub-models where the lacustrine sediments in some of the lakes have been modelled separately and only exists within the lake area. The model presents the geometry of the lower level for each layer, presented as elevation above sea level (RH 70). The model has a spatial resolution of 20×20. The lower level for Z5 was interpolated from the data set of information of depth of regolith and the distribution of bedrock outcrops. Thus the lower level of Z5 represents the bedrock surface regardless if it is covered by regolith or not. The bottom layer, Z6, represents a transition zone between the bedrock and the regolith. This layer has a constant thickness of 0.6 m and is intended to represent the uppermost fractured bedrock and is thus not a part of the regolith. The layer is included in the Forsmark RDM since a layer with high hydraulic conductivity has been recorded in the contact zone between bedrock and regolith /e.g. Werner and Johansson 2003/.

In many of the lakes, the stratigraphical information regarding the spatial distribution of the lake sediments was sufficient for modelling of three separate sub-models, here referred to as lenses, L1–L3. However, the lenses are only modelled below eight lakes in the area, see Figure 3-2. In the areas where these lenses appear they replace the occurrence of Z1, Z2, Z3, Z4a and Z4b. Therefore, below the lenses either Z5 or Z6 (or both) exist, if the total depth of the lenses are > 0.6. In the mires the information was not sufficient for modelling of lenses. It should be noted that the geological units representing L1–L3 are the same as the input to the layers Z1–Z4b.

All layers and lenses, except Z6, may have thickness zero. The layers in the model are summarized and explained in Table 3-1.

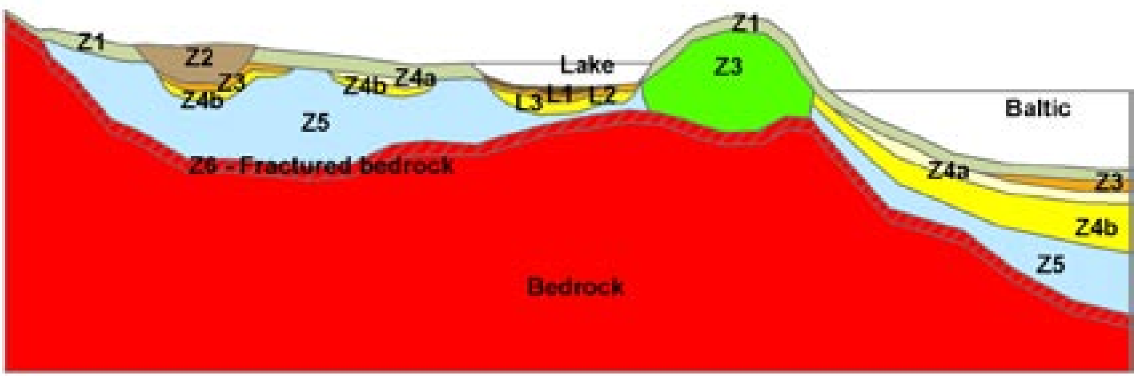


__Figure 3-1.__ Conceptual model used for the regolith depth model. The principle of the seven layers and three lenses modelled in the area, for description of the layers, see Table 3-1.

Table 3-1. Deposits, simplified codes and occurrence for the seven layers and three lenses. All lenses are interpreted from corings in lakes /Hedenström 2003/.

Description of layer/lens	Simplified code	Description/occurrence
Gyttja (algal gyttja, calcareous gyttja, clay gyttja-gyttja clay), Peat	L1	Present inside the boundary of the lakes. When peat is present as surface layer within the lake area, this is included in the L1 lens. The sediment in L1 and Z4a partly consist of the same geological units.
Postglacial sand and/or gravel	L2	Present inside the boundary of the lakes. The sediments in L2 and Z3 consist of the same geological unit.
Clay (glacial and postglacial)	L3	Present inside the boundary of the lakes. The sediments in L3 and Z4a and Z4b consist of the same geological unit.
Surface layer	Z1	The layer is affected by surface processes, e.g soil forming processes in the terrestrial parts or sedimentation/transport/ersion in the limnic/marine parts. This layer is present within the entire modelled area, except where the surface is covered by peat or where the model has a lens (under lakes). On bedrock outcrops, the layer is 0.1 m and 0.6 m in other areas. If the total modelled regolith depth is less than 0.6 m, Z1 will be the only layer. The layer can be connected to a GIS application such as the map of Quaternary deposits or soiltype map and assigned properties in accordance to the properties of the deposits.
Peat	Z2	This layer is only present where peat is presented in the QD map. Calculated average depths are used for the layer since too few observations are available for interpolating. The average depth is used for peat above and below the 5 m.a.s.l. contour line ,1.4 m and 0.4 m respectively. Postglacial sand (Z3) always underlie Z2. If peat is intersecting glacial clay or sand on the QD map, Z4b underlie Z3.
Postglacial sand/gravel, glaciofluvial sediment and artificial fill	Z3	The layer is only present where the surface layer consists of postglacial sand/gravel, glaciofluvial sediment or artificial fill. The layer geometry is interpolated from input data and average values. This may result in a discrepancy between the modelled Z3 a and the marine geological map. In the the terrestrial parts, Z3 is assigned average depth values for postglacial sand and artificial fill and glaciofluvial sediment. The glaciofluvial sediment and artificial fill are modelled to always be situated directly on bedrock. Z3 as sand is always present under peat (Z2).
Postglacial clay including gyttja clay	Z4a	Z4a is present in the marine area where postglacial clay is the surface layer. In the marine areas, the layer geometry is interpolated from input data and average values. This may result in a discrepancy between the modelled Z4a and the marine geological map. When average values are used, Z4a is always underlain by Z4b.
Glacial clay	Z4b	Z4b is present where glacial clay is the surface layer. Additionally, Z4b is present under Z3 when peat is located next to sand or glacial clay and when sand is located next to glacial clay. In the marine area, the layer geometry is based on interpolation from input data and average values. In the terrestrial area, the layers are assigned calculated average depth values. In the marine are, interpolated Z4b values > 0.5 m are rejected in areas where the geological map shows till or glaciofluvial sediment. This may result in a discrepancy between the modelled Z4b and the marine geological map.
Till	Z5	This layer is present in a major part of the model area. The thickness of the layer is based on interpolation from input data and average values. Z5 is 0 at bedrock outcrops, if the total QD depth is < 0.6 m or if the layers/lenses are located directly on the bedrock surface. The lower limitation of Z5 represents the bedrock surface, i.e. Z5 represents a Digital Elevation Model for the bedrock surface.
Fractured bedrock	Z6	This layer has a constant depth of 0.6 m and represents the bedrock upper part, calculated from the interpolated Z5.The layer represents a high conductive zone that have been observed in many of the hydraulic tests within Forsmark.

Figure 3-2. The eight lakes in the Forsmark area where lake sediment lenses have been modelled.

3.2 Interpolation and usage of data

3.2.1 Usage of seismic and sediment echo sounding data

Only observation points with a complete layer of postglacial sand/gravel, glaciofluvial sediment or artificial fill, i.e. the mentioned deposits is underlain by another layer, have been used by the interpolation of Z3.

Only observation points with a complete layer of postglacial clay, i.e. the clay is underlain by another layer, have been used by the interpolation of Z4a.

Only observation points with a complete layer of glacial clay, i.e. the clay is underlain by another layer, have been used by the interpolation of Z4b.

3.2.2 Usage of wells from SGUs well archive

An extract from the SGUs well archive over the Forsmark area was made 7/4 2006 /SGU 2007/. The quality of the coordinates in the well archive is varied and the uncertainty for the X- and Y-coordinate can be up to 250 m. Therefore only the 7 wells from the archive that have been surveyed by SKB were used.

3.2.3 Data not reaching bedrock

The depth values from the observations not reaching bedrock were used for calculation of average depth of the individual layers and lenses. Some observation points don't reach the bedrock surface, but give valuable information regarding minimum regolith depth. The depth of each observation point was compared with the average depth of the sub-domain. Only points resulting in lower bedrock surface than obtained using the domain value was included in the interpolation of the bedrock surface.

3.2.4 Average values for depth of Quaternary deposits

Since there are large parts of the modelling area with low density of data, the model is built up mostly from average values of different deposits, calculated from input data (Table 3-2). The average values are then assigned to different areas in the model in relation to the map of QD according to the conceptual model and over all stratigraphic understanding of the Forsmark area /cf Hedenström and Sohlenius in prep/. Table 3-3 shows the total average values applied in each domain.

Table 3-2. The average values of different Quaternary deposits used for the calculation of regolith depth for the sub domains in Figure 3-3.

Quaternary deposit/ domain no/ layer	Average value of depth (m)	Standard deviation of average value of depth (m)	n	Source for calculating average values
Terrestrial area				
Peat above/ below 5 m.a.s.l./ sub-domain 7/ layer Z2/	1.4/0.4	To small data set for calculating standard deviation	12/82	/Fredriksson 2004, Lokrantz and Hedenström 2006/
Sand in terrestrail area/ layer Z3	0.2	± 0.24	350	/Hedenström 2004/
Postglacial clay in terrestrail area/ layer Z4a	0.15	–	63	/Hedenström 2004/
Glacial clay in terrestrial area	0.35	–	63	/Hedenström 2004/
Artifical fill	3	–	1	Assumed from site characterisation
Glaciofluvial sediment/ sub-domain 9/ layer Z3	6.5	–	3	/Werner et al. 2004/
Total regolith/ sub-domain 5/ dominated by till, layer Z5	3.6	± 2.2	9,264	Table 2-1
Total regolith/ sub-domain 6/ dominated by clayey till layer Z5/	5.8	± 2.7	319	Table 2-1
Marine area				
Till in marine area/ sub-domain 1/ layer Z5	6.2	± 4.3	1,106,862	/Elhammer and Sandkvist 2005/
Glacial clay and clay in marine area/ sub-domain 2/ layer Z4b	3.2	± 2.6	738,659	/Elhammer and Sandkvist 2005/
Postglacial sand and gravel/ sub-domain 3/ layer Z3	1.7	± 0.5	358,349	/Elhammer and Sandkvist 2005/
Postglacial clay and clay gyttja/ sub-domain 4/ layer Z4a	0.9	± 0.95	25,684	/Elhammer and Sandkvist 2005/

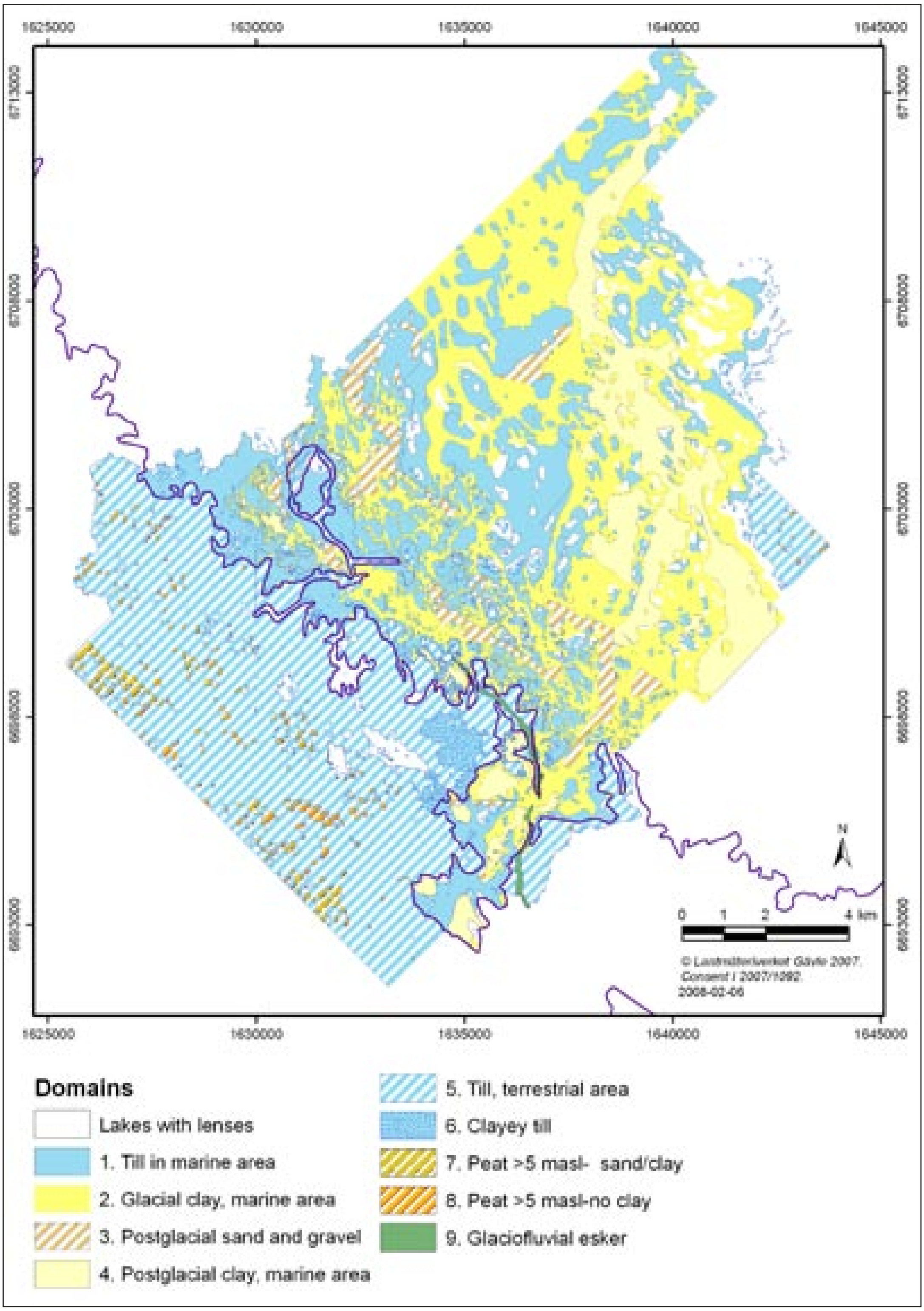


Figure 3-3. *The model area classified into the sub-domains used for assigning average QD depth values when primary observations are missing. The white areas north east of the coastline represents bedrock.*

Table 3-3. The different sub-domains used for ascribing average QD depth values in areas without primary observation points. The distribution of the sub-domain areas is showed in Figure 3-3.

Domain		Quaternary deposit	Layes included in the domain	Sub sums	Total depth (m)
1	Marine area	Till	Z5	6.2	6.2
		Clayey till or boulder clay			
		Till with thin surface layer of sand or clay			
2	Marine area	1) Clay	Z5+Z4b	6.2+3.2	9.4
		2) Glacial clay with thin surface layer of postglacial sand			
3	Marine area	1) Postglacial fine sand	Z5+Z4b+Z3	6.2+3.2+0.9	10.3
		2) Postglacial sand			
		3) Postglacial sand-gravel			
4	Marinearea	1) Clay gyttja with thin surface layer of postglacial fine sand	Z5+Z4b+Z4a	6.2+3.2+0.9	10.3
		2) Clay gyttja with thin surface layer of postglacial silt			
		Clay gyttja			
		Gyttja			
5	Terrestrial	All QD in terrestrial area, exept those included in domains 6–9 or areas where lenses are modelled.	Z5	3.56	3.6
6	Terrestrial	Clayey till with low boulder frequency	Z5	5.76	5.8
7	Terrestrial	Peat > 5 m.a.s.l. intersecting to sand, gravel or glacial clay	Z5+Z4b+Z3+Z2	3.56+0.5+0.2+1.4	5.7
8	Terrestrial	Peat > 5 m.a.s.l., not intersecting sand, gravel or glacial clay	Z5+Z3+Z2	3.56+0.2+1.4	5.2
9	Marine/ Terrestrial	Glaciofluvial esker	Z3	5.76	5.8

3.3 Construction of databases used for interpolation of raster surfaces

Data used for interpolation of raster surfaces for bedrock surface (Z5), lenses in lakes (L1–L3), postglacial clay (Z4a), glacial clay (Z4b), and sand/gravel (Z3) used in regolith depth model version 2.3 are of different origin and quality (Table 2-1). In order to generate a good result by the interpolation, 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 judgment 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 are described in Table 3-1.

The seismic and sediment echo sounding measurements performed by the Geological Survey of Sweden, SGU /Elhammer and Sandkvist 2005/ (Table 2-1) are divided in a detailed and regional area (Areas 4 and 5, Figure 2-3). The density of measurement points along the transect lines are much higher in the detailed area compared to the regional area. In order to receive approximately the same point density in the two areas, only each 8th point from the detailed area was included in the Z5 database.

Since measurements from the detailed area are of higher resolution than measurements from the regional area /Elhammer and Sandkvist 2005/, all measurement points from the regional area within 100 m from measurement points from the detailed area were not included in the Z5 database.

All pixels in the 20 m DEM /Strömgren and Brydsten in prep/, that were intersected by bedrock outcrops from the QD map /Hedenström and Sohlenius in prep/, were converted to points and included in the Z5 database (Figure 3-4a). These points are given regolith depth zero (i.e. 0.1 m) in the model. However, a different methodology was used for bedrock points situated inside the surface of the lakes were lake sediment lenses were modelled (Figure 3-4b). The reason for this is that the lake sediment lenses were constructed for the RDM2.2 model version and not changed for the 2.3 RDM.

All observation points of lower ranking number (Table 2-2) within a distance of 30 m from observation points of higher ranking number were not included in the Z5 database. In the marine area, a buffering distance of 100 m was used between the measuring lines in the detailed marine geological area and between the two marine geological data sets. The data points are referred to as data reaching or data not reaching the bedrock surface in Table 3-4.

The DEM /Strömgren and Brydsten in prep/ were converted to points. All points within the domains described in Table 3-3, 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. However, the elevation levels for the average values of QD depths in lakes where lenses were modeled were calculated from the lowest level of the lenses.

Table 3-4. Database used for interpolation of the bedrock surface (Z5).

Data	No of points
Average QD depth values	283,529
Seismic and sediment echo sounding data (detailed area)	128,296
Seismic and sediment echo sounding data (regional area)	18,855
Bedrock outcrops	88,945
Observation points reaching bedrock	8,119
Observation points not reaching bedrock	3
Total no of points	**527,747**

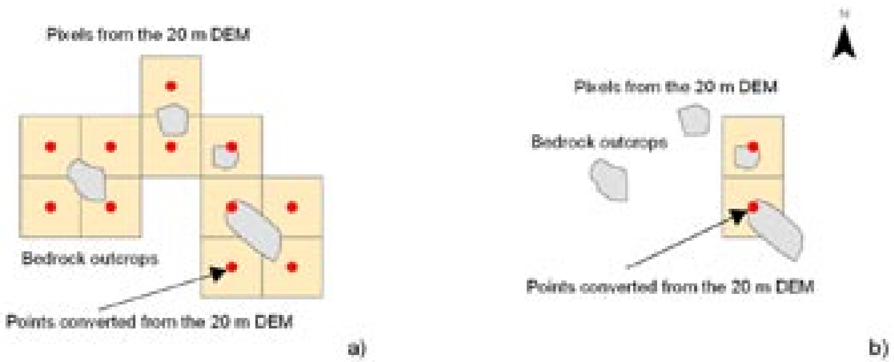


Figure 3-4. *a) The methodology for how points corresponding to bedrock outcrops were chosen and included in the Z5 database. b) In lakes where lake sediment lenses were interpolated, only points corresponding to bedrock outcrops situated inside bedrock outcrop surfaces were included in the Z5 database.*

All average QD depth values, except for areas within 100 m from the marine seismic and sediment echo sounding data and within 30 m from all other data were included in the Z5 database. In areas where lake sediment lenses were interpolated, points with average QD depth values within 30 m from all other data in these lakes were excluded from the Z5 database.

Databases used for interpolation of lenses (L1–L3) were created for the eight lakes presented in Figure 3-2.

The proportions of different input data for these databases are described in Table 3-5.

Observation points (stratigraphical information from lakes) were included in the lens databases. Unfortunately, there were too few observation points for generating a good result by the interpolation. Therefore, points named supporting points in Table 3-5 had to be included in the lake sediment lens databases. This was done according to certain rules described below:

- Pixels from the 20 m DEM /Strömgren and Brydsten in prep/ inside these 8 lakes were converted to points. Supporting points were placed in the north, east, south and west direction, around observation points lacking surrounding observation points in these directions within the pixels from the 20 m DEM, and given the same elevation levels as the observation point (Figure 3-5a).
- In case two or more observation points were situated in the same 20 m pixel (Figure 3-2b), lacking other observation points in the north, east, south and west direction, the surrounding supporting points were given the mean values for the observation points (Figure 3-5b).
- In case one observation point, for example, lacking surrounding observation points in the east direction and another observation point lacking surrounding observation point in the north direction and the nearest surrounding point (from the 20 m DEM) is the same for both points, this supporting point was given the elevation level from the nearest observation point (Figure 3-5c).
- No supporting points were included in the databases where pixels were occupied by points corresponding to till or bedrock outcrop.

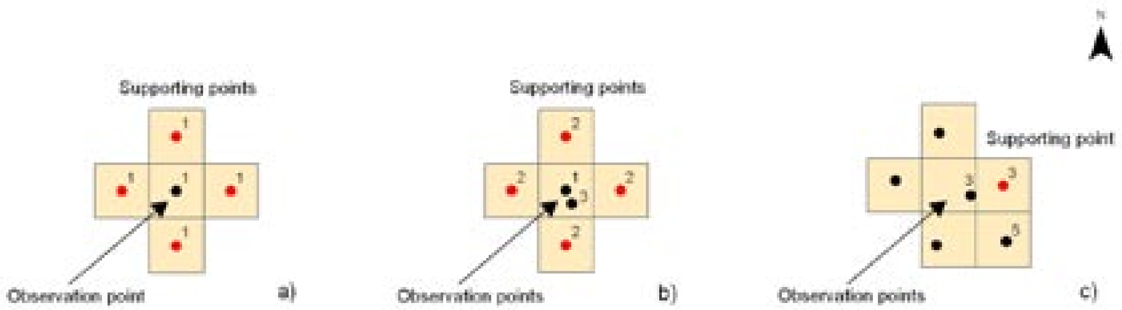


Figure 3-5. Examples of how supporting points were included in databases used for interpolation of lenses in lakes. a) An observation point lacking other observation points in the north, east, south and west direction were assigned 4 supporting points. These supporting points were given the same elevation level as the observation point. b) Two observation points occupying the same 20 m pixel and lacking other observation points in the north, east, south and west direction were assigned 4 supporting points. These supporting points were given the mean elevation level for the two observation points. c) An observation point lacking other observation point in the east direction and an observation point lacking other observation point in the north direction. In these cases the supporting point was given the elevation level from the nearest observation point.

Table 3-5. Databases used for interpolation of lake sediment lenses in 8 lakes.

Lake	Lens	Observation points	Till/or bedrock outcrops	Supporting points	Extension points	Adjusted points	Total no of points
Bolundsfjärden	L1	55	301	196	57	285	894
	L2	33	301	111	57	–	502
	L3	13	301	32	57	–	403
Eckarfjärden	L1	23	31/1	68	32	158	313
	L2	12	32	57	32	–	133
	L3	11	32	53	32	–	128
Fiskarfjärden	L1	23	139/1	74	34	508	779
	L2	15	140	71	34	–	260
	L3	13	140	63	34	–	250
Puttan	L1	10	48	43	10	13	124
	L2	8	48	32	10	–	98
	L3	4	48	12	10	–	74
Stocksjön	L1	6	8	26	7	6	53
	L2	3	8	22	7	–	40
	L3	1	8	5	7	–	21
Vambörsfjärden	L1	5	17	22	8	28	80
	L2	5	17	22	8	–	52
	L3	3	17	14	8	–	42
Gällsboträsket	L1	7	29	24	8	176	244
	L2	5	29	19	8	–	61
	L3	6	29	17	8	–	60
Lillfjärden	L1	15	45	60	18	28	166
	L2	12	45	46	18	–	121
	L3	10	45	36	18	–	109

Points inside till or bedrock outcrops according to the geological map /Sohlenius et al. 2004/ were given elevation levels from the 20 m DEM /Strömgren and Brydsten in prep/ and included as the bottom substrate in the databases used for interpolation of the L1–L3 lenses. Two points inside bedrock were identified and are included in the column named till or bedrock outcrops in Table 3-5.

Points referred to as extension points in Table 3-5 were used as the limitation for the lenses and distributed with even distances along the shoreline of the lakes. The distances between extension points are different for the lakes depending on the size of the lakes, and the number of observation points within the lakes.

Observation points, supporting points and extension points, and points representing till or bedrock outcrops were merged to databases. Test interpolations of raster surfaces with a resolution of 20 m were made for the L1-lenses only. The interpolated surfaces were compared to the DEM /Strömgren and Brydsten in prep/. Pixels with elevation level above the DEM (except for pixels were bedrock outcrops were assigned) were converted to points. These points were adjusted downward and lowered 1.4 m compared to the DEM in Lake Eckarfjärden (the only lake located above the 5 m a.s.l. isoline) and 0.4 m compared to the DEM in all other lakes, and included in the databases used for interpolation of the L1-lenses in the 8 lakes. These points are referred to as adjusted points in Table 3-5.

Databases used for interpolation of raster surfaces for the lower boundaries of glacial clay (Z4b), postglacial clay (Z4a) and sand/gravel (Z3) were constructed. The proportions of different data in these databases are described in Table 3-6.

Table 3-6. Databases used for interpolation of glacial clay (Z4b), postglacial clay (Z4a), and sand/gravel (Z3) raster layers in the marine area.

Datasource (number of points)	Layer	Z3	Z4a	Z4b
Average QD depth values within domain 2–4		2,646	38,133	108,165
Seismic and sediment echo sounding data (detailed marine area)		18,918	2,130	85,520
Seismic and sediment echo sounding data (regional marine area)		596	4,764	16,031
Observation points		1	1	8
Extension points		3,032	4,189	23,675
Total no of points		**25,193**	**49,217**	**233,399**

Measurement points from the seismic and sediment echo sounding data performed by SGU /Elhammer and Sandkvist 2005/ corresponding to glacial clay (Z4b), postglacial clay (Z4a) and sand/gravel (Z3) were included in the databases. Data from domain 3 was included in the Z3 database, data from domains 2 and 2–4 was included in the Z4a and Z4b databases respectively (Table 3-6, Figure 3-3).

Average QD depths for these layers were given in areas between the measurement points (Table 3-6). Points were converted from the DEM. 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 in sub-domain 2–4, within a buffering distance of 100 m from the seismic and sediment echo sounding data /Elhammer and Sandkvist 2005/ and within a buffering distance of 30 m from other observation points were excluded from the databases. The boundary of sub-domains 2–4 were divided in points, every 30 m. These points, named as extension points in Table 3-6, were given values from the 20 m DEM and included in the Z3, Z4a, and Z4b databases.

3.3.1 Kriging interpolation

Raster surfaces for the lower levels of Z5, Z4b, Z4a, Z3 and the lover level of the L1–L3 lenses 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 for "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 choosing of the semivariogram model and the parameters scale, length and nugget effect was done with the Geostatistical Analyst extension.

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 standardize root-mean-square prediction errors were not calculated for all models.

The kriging parameters and the models used for interpolations are presented in Appendix 3.

3.4 Adjustments and combining of interpolated and calculated surfaces

Below follows a description of the adjustments made when importing all the raster layers and lenses into Arc GIS 9.1, Spatial Analyst. The adjustments of layers and lenses are presented in the order they were performed. Except the adjustment described below all layers have been cut inside the model area. The layers and lake sediment lenses are described in Table 3-1 and a generalised profile is presented in Figure 3-1.

3.4.1 Lake sediment lenses

The interpolated lower levels of the three lake sediment lenses are adjusted in the following ways:

- The lower level of L1 is adjusted not to exceed the topography of the DEM. In case of till or bedrock outcrops areas, L1 is adjusted to ensure a thickness of 0.1 m.
- The lower level of L2 is adjusted not to exceed the lower level of L1. In case of till or bedrock outcrops areas, L2 is adjusted to ensure a thickness of 0 m.
- The lower level of L3 is adjusted not to exceed the lower level of L2. In case of till or bedrock outcrops areas, L3 is adjusted to ensure a thickness of 0 m.

Finally, the three lens layers were adjusted to just contain values inside the boundary of the eight lakes, see Figure 3-2. In areas outside the lake boundaries the lens layers have the same value as the DEM, i.e. the thicknesses of the lenses are 0 m in those areas. The adjustments were exclusively made in ArcGIS 9.1, with the extension Spatial Analyst.

3.4.2 Layer Z5

The interpolated lower level of Z5 is adjusted not to exceed the DEM topography and L3. In areas with bedrock outcrops Z5 is adjusted to ensure a thickness of 0.1 m (this was included by discrete points in the interpolation but was adjusted to be exactly 0.1 m in areas where the interpolation showed a slightly smaller or larger Z1 depth). This thin layer on bedrock outcrops corresponds to organic material that can affect the surface runoff in the area.

In some areas where the QD map does not show bedrock outcrop the interpolated bedrock surface lied very close to DEM (less than 0.1m below the DEM), since input data indicate there should be a regolith depth in these areas the bedrock surface was adjusted as described below.

- In case where this appears in areas without lake sediment lenses the bedrock surface was lowered 0.6 m below the DEM.
- In case where this appears in areas with lake sediment lenses the bedrock surface was treated in one of three different ways:
  a. If thickness of Z5 is larger or equal to 0.1 m the bedrock surface was left untouched.
  b. If lower level of Z5 exceeds the lower level of L3 and the total thickness of the lake sediment lens is larger than 0.1 m, the lower level of Z5 was lowered below L3.
  c. If lower level of Z5 exceeds the lower level of L3 and the total thickness of the lake sediment lens is less than 0.1 m, the bedrock surface was lowered 0.6m below the DEM.

3.4.3 Layer Z6

Z6 is actually located beneath the regolith and is intended to represent the upper part of the bedrock. The lower level of Z6 has not been interpolated. It has been calculated as 0.6 m beneath Z5, i.e. Z6 has a constant thickness of 0.6 m in the whole area.

3.4.4 Layer Z2

Z2 only exists in the terrestrial area. Z2 is shown as the average thickness of peat, and is not produced from interpolations. Within lakes, the lower level of Z2 was adjusted not to appear below L3. In those cases Z2 was set to 0.

3.4.5 Layer Z1

Z1 is cowers the whole model area, except in areas with peat (Z2) or lake sediment lenses (L1–L3) with a total thickness of more than 0.6 m. If the total lens depth is less than 0.6 m, Z1 is allowed under the lens. Z1 has a depth of 0.6 m in all areas except for bedrock outcrops where the depth is 0.1 m.

3.4.6 Layer Z3

Z3 consist of postglacial sand and gravel, glaciofluvial sediment or artificial fill. After interpolation, the lower level of Z3 in the marine area was adjusted to appear only where the geological map shows postglacial sand or gravel. Z3 is adjusted not to exceed the lower level of Z1 and not to be below the lower level of Z5 (i.e. bedrock surface).

In the terrestrial area, the average depth values of each deposit were used, hence Z3 is not produced by interpolation.

Z3 landing the terrestrial areas only exist where the QD map shows sand, artificial fill, glaciofluvial sediment or under peat.

Starting from the QD geological map, cells corresponding to sand where selected in the Z1 layer and lowered 0.2 m below Z1 and cells that contain artificial fill was lowered 3 m. Cells with glaciofluvial sediment were lowered 5.8 m with the glaciofluvial sediment always located directly on the bedrock surface. Cells corresponding to peat were lowered 0.2 m under Z2. The rest of the cells were given the same value as Z1, i.e. in those areas the thickness of Z3 is 0 m. Finally, the terrestrial and marine parts of Z3 were joined together.

3.4.7 Layer Z4a

Z4a corresponds to postglacial clay and clay gyttja and the lower level of the layer is interpolated from observation points and average depth values in the marine area and calculated from average values over land parts.

Areas with postglacial clay as the main deposit in the marine part of the QD map are used as outer boundary of the interpolation in that way that points along the spot boundaries assigned the thickness 0 m is used together with the input data for the interpolation of Z4a. Remaining areas, not corresponding to postglacial clay, are assigned values equal to the marine part of Z3.

Z4a in the terrestrial areas exist only where the QD map shows postglacial clay or clay gyttja. Starting from the map of QD, cells corresponding to postglacial clay or clay gyttja was selected in the Z1 layer and lowered 0.15 m. The rest of the cells were given the same value as Z3, i.e. in those areas the thickness of Z4a is 0 m.

In the terrestrial areas, Z4a was adjusted not to subside the lower level of Z5 and not to appear under lenses.

Finaly, the terrestrial and marine parts of Z4a were joined together and adjusted not to exceed the lower level of Z3 and not to reach below the lower level of Z5 (i.e. the bedrock surface).

3.4.8 Layer Z4b

Z4b corresponds to glacial clay and the lower level of the layer is interpolated from observation points and average values in the marine area and calculated from average values in the terrestrial area.

Glacial clay is interpolated over the whole sea floor area. In areas with bedrock, till or glaciofluvial sediment on the QD map, the thickness of Z4b is set to 0 m if the interpolated thickness is larger than 0.5 m. When the thickness is less than 0.5 m the layer is not adjusted since it is common with a thin clay layer in spots on top of till in the Forsmark area. Z4b was adjusted not to exceed the lower level of Z4a and not to be below the lower level of Z5.

Z4b in the terrestrial area only exist where the QD map shows glacial clay or peat and sand adjacent to glacial clay. Starting from the map of QD, cells corresponding to glacial clay, peat and sand adjacent to glacial clay were selected and lowered 0.35 m below Z3. When the QD map shows clay gyttja, the corresponding cells were lowered 0.35 m below Z4a and at glacial clay, the corresponding cells were lowered 0.35 m below Z1. The rest of the cells were given the same value as Z4a, i.e. in those areas the thickness of Z4b is 0 m.

Finally, the terrestrial and marine parts of Z4b were joined together.

3.5 Import of the layers into the GeoModel tool

The program used for the final stage of the modelling and visuilisation of regolith depths is the GeoModel, 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 stratigraphical Acsess database was compiled for the RDM 2.2 model version, containing generalised stratigraphical profiles from all corings and excavations. The stratigraphical database was used in the GeoModel for viewing the information stored for each observation point. Additionally the GeoModel is used for extracting profiles of geological formations for a general understanding of the geology in the area. The stratigraphical profiles can be included in the profiles (see Chapter 4 and Appendix 1).

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 Forsmark 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 and Figure 4-2 shows the total modelled regolith depth in the whole model area and in the central area respectively. The regolith depth within the model varies between 0.1 and 42 m. Areas with thin regolith and frequent bedrock outcrops are e.g. the coastal zone and the islands, including the shoreline close to Gräsö Island. Generally, the regolith is deeper in the marine area where the average regolith depth is c. 8 m while the average total depth is approximately 4 m (cf. Table 5-2).

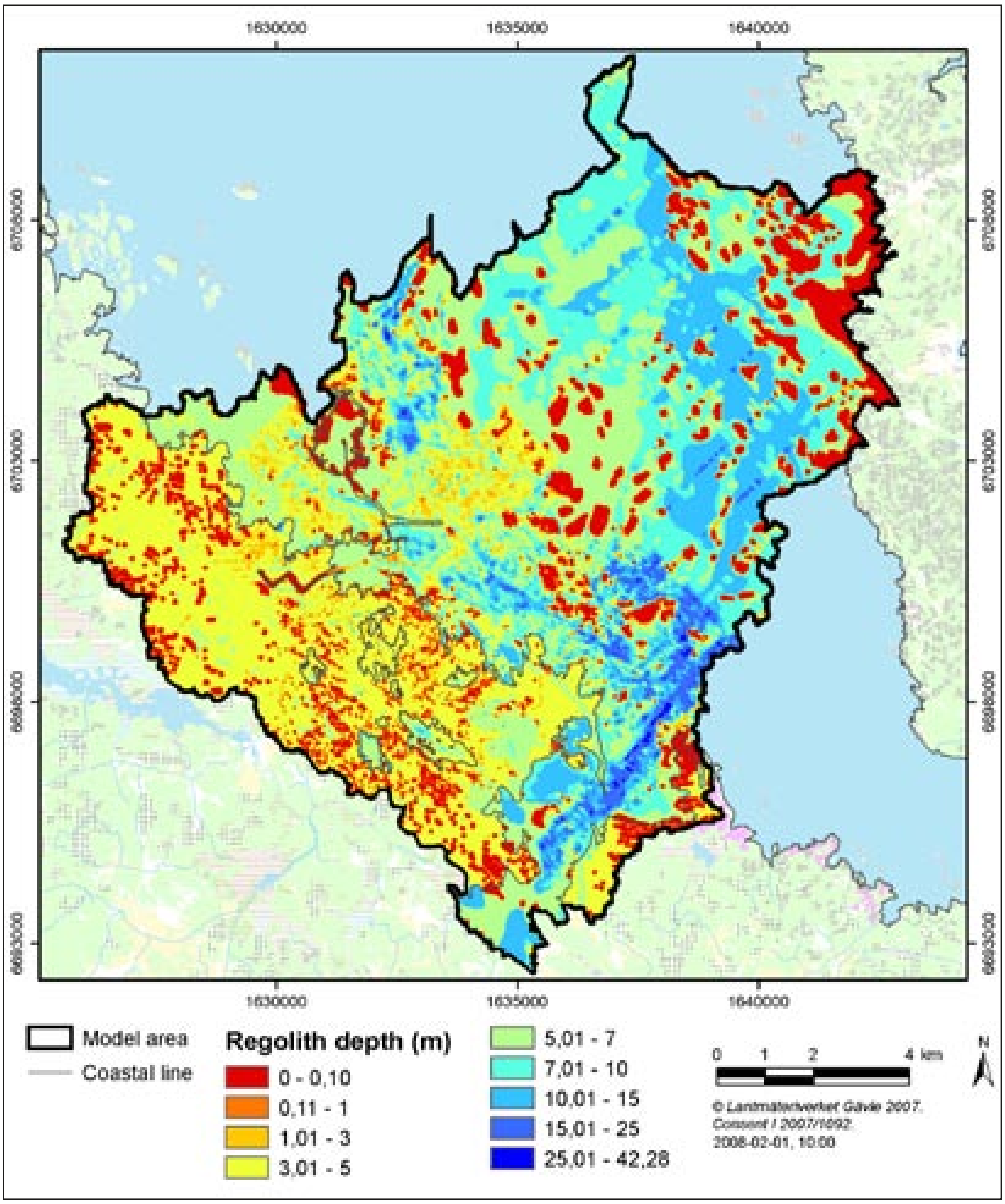


Figure 4-1. *Total modelled regolith depth.*

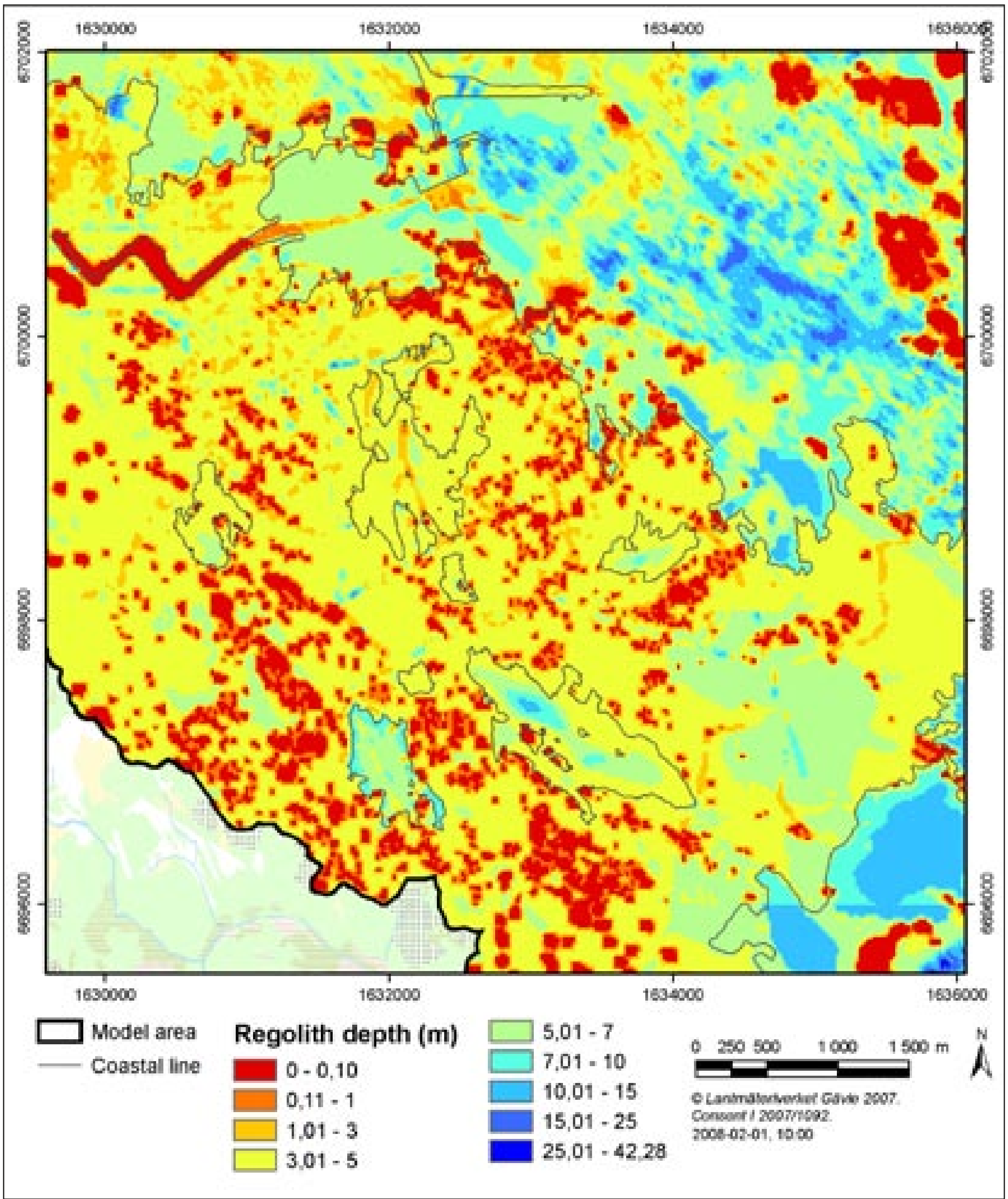


Figure 4-2. *Total modelled regolith depth in the central area.*

Within the terrestrial area, the area covered with clayey till has a generally deeper regolith than the reminding terrestrial area. A zone with relatively deep regolith and few bedrock outcrops in the terrestrial area can be followed from the inlet of Lake Fiskarfjärden, including the lake basin and further to the NW. This depression in the bedrock has the same direction as several of the major bedrock lineaments in the Forsmark area, however no interpreted lineament is located through the bottom of lake (Figure 6-2).

The maximum regolith depth in the model is about 42 m, recorded in the southwest-northeast groove outside the entrance to Kallrigafjärden. The majority of the observations with regolith depth > 20 m are located within the coastal area. The average and median regolith depth of the interpolated and adjusted model is shown in Table 4-1.

Table 4-1. Average and median total 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)	5.63	4.07	5.68
Whole model except bedrock outcrops	6.51	3.67	6.09

Table 4-2 below shows the average value and median regolith depth, based on input data from the different data sources. Generally, input data shows slightly lower average and median regolith depths than those derived from the interpolated surfaces where also the bedrock outcrops (i.e. a QD depth of 0.1 m) are included. The average depth from the model excluding bedrock outcrops agree approximately with the average values from the input data.

4.2 Vertical profiles

A number of vertical profiles within the model area are presented in this chapter and Appendix 1. To generate such profiles the GeoModel tool was used, see Chapter 3.5. The profiles presented here are selected to include representative examples from the model. Any other profile may be generated using the GeoModel tool. Profiles from which results are shown below and Appendix 1, are shown in Figure 4-3. The corresponding profiles are presented for the RDM 2.2, see Appendix 2.

It should be noted that the profiles are drawn along manually defined lines, see Figure 4-3, from which the modelled regolith depths in each grid point are illustrated. The profiles show the observation points that fall within a 200 m band width of the line. This means that boreholes and observation points situated up to 100 m from the line in either direction, where the topography and layer elevations are illustrated, will be included in the graph. In some of the illustrated profiles, the elevations of observation points and depths of geological units may therefore differ from the modelled layers displayed in the profiles. Below follows two illustrative profiles through the area.

Table 4-2 Average, median and maximum regolith depth calculated from different sources of input data.

Type of data	Number of observations	Average QD depth (m)	Median QD depth (m)	Maximum QD depth (m)
Corings and excavations				
Organic and in-organic sediment mapping, peat land mapping, Ocean sediment core sampling	1	5.47	5.47	5.47
Quaternary deposit mapping and stratigraphic observations, Neotectonic stratigraphic observation	23	3.95	3.46	11.64
SGU's archive of wells	5	2.13	1.56	12.02
Cored, percussion and probing boreholes, monitoring well in soil	116	4.84	4.22	16.01
Geophysical data				
Refraction seismic measurement data	6,853	3.98	3.64	29.88
Ground penetration radar measurement data	439	3.38	3.12	8.79
Continuous Vertical electrical soundings (CVES)	264	6.25	5.84	18.60
Seismic and sediment echo sounding data	147,151	8.65	6.93	43.78
Reflexion seismic	421	3.46	2.75	11.11
Total	**155,273**	**8.41**	**6.65**	**43.78**

The profile that describes the stratigraphical distribution of the layers and lake sediment lenses in Lake Bolundsfjärden is presented in Figure 4-4. The lenses containing the water laid sediments are barely visible. This is partly the result of the elongated profile but it also reflects the fact that the organic sediments are thin in this basin /cf Hedenström 2004/.

The profile crossing the glaciofluvial esker is displayed in Figure 4-5. A comparison with the conceptual model (Figure 3-1) shows a discrepancy in the shape of the bedrock under the glaciofluvial esker. Since too few observations are available, average depth values are used, resulting in a profile where the bedrock topography follows the ground elevation. In fact, it is most probably that the glaciofluvial sediments are thicker at the crest and gradually thinner at the edges. The presented shape of the esker and bedrock surface is the result of the concept of using average depth values for all areas where glaciofluvial sediment is presented in the geological map.

In Appendix 1, additional profiles are presented. The observation points are included in the illustrated profile and the geological layers are listed in the legend. The frame surrounding the profile line shows the 200 m zone for including bore holes in the graph. It should be noted that the observation points displayed in the profiles are before buffering, thus all the observations are not used in the final model. For presentation reason in areas with many corings, some stratigraphical profiles are not displayed in the profiles.

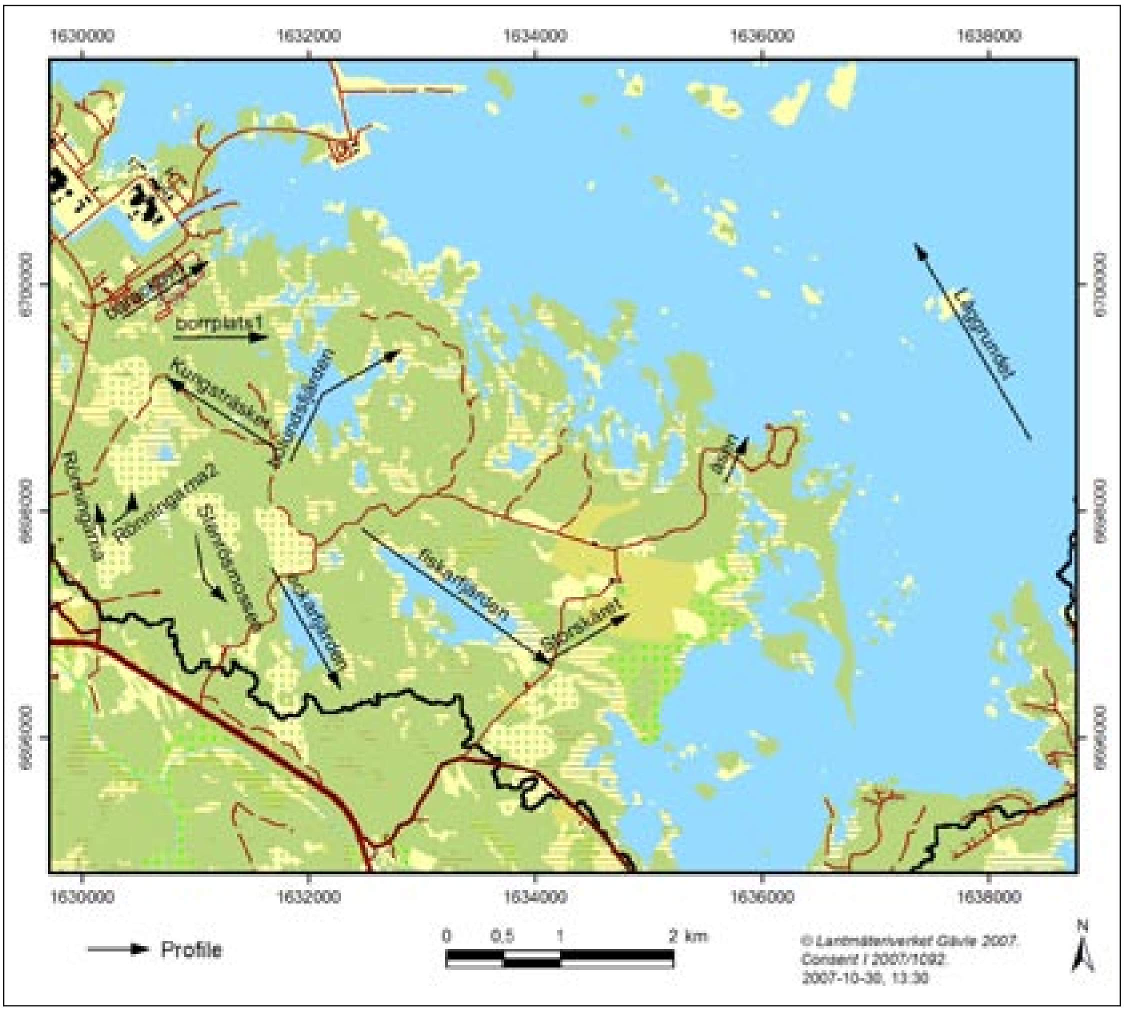


__Figure 4-3.__ The location of the profiles presented. The names of the profiles refer to the profile names shown in Chapter 4.1 and Appendix 1. The corresponding profiles generated from the RDM 2.2 are presented in Appendix 2.

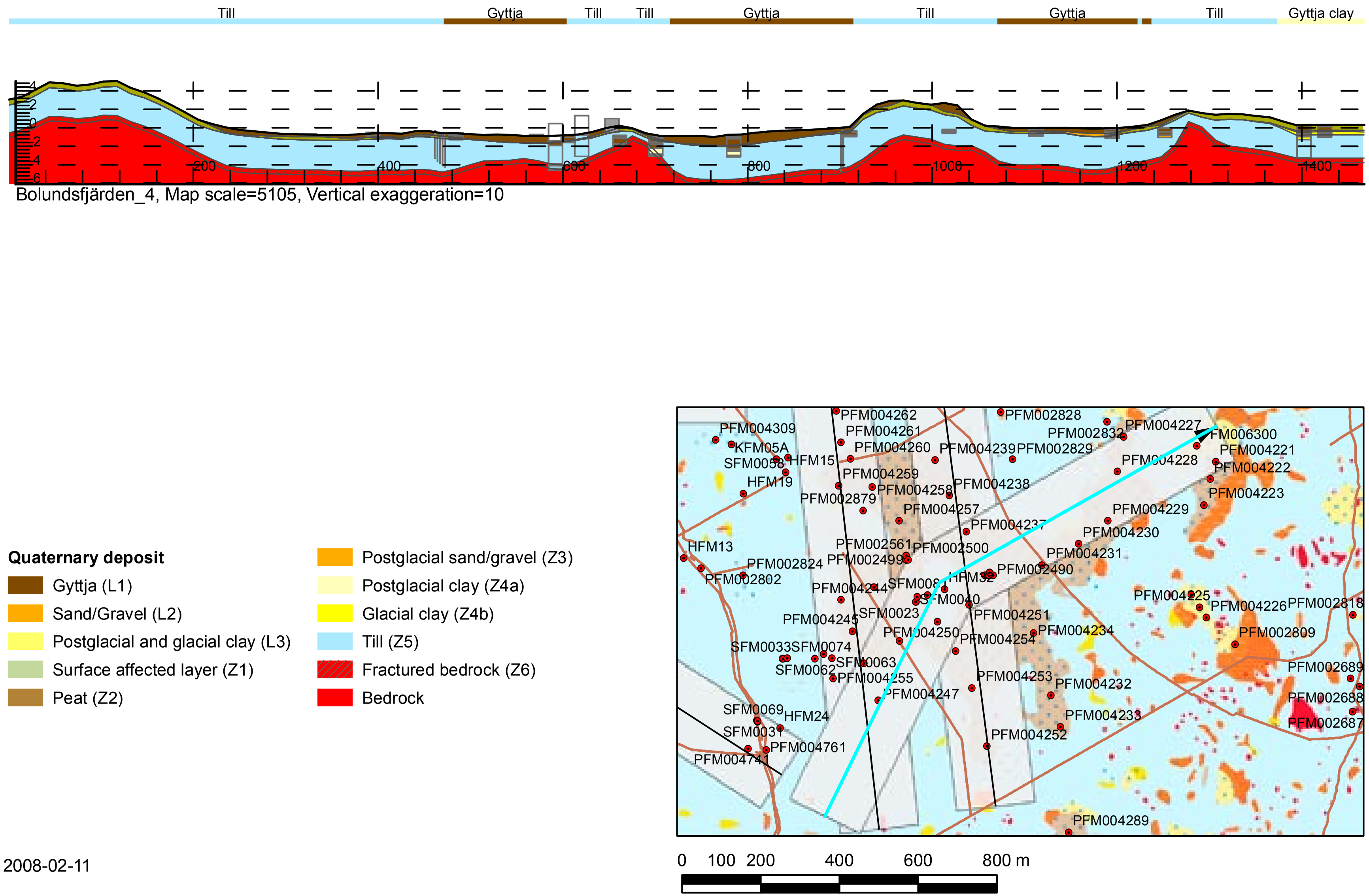


Figure 4-4. Stratigraphical section along the Bolundsfjärden profile. For location of the profile, see Figure 4-3.

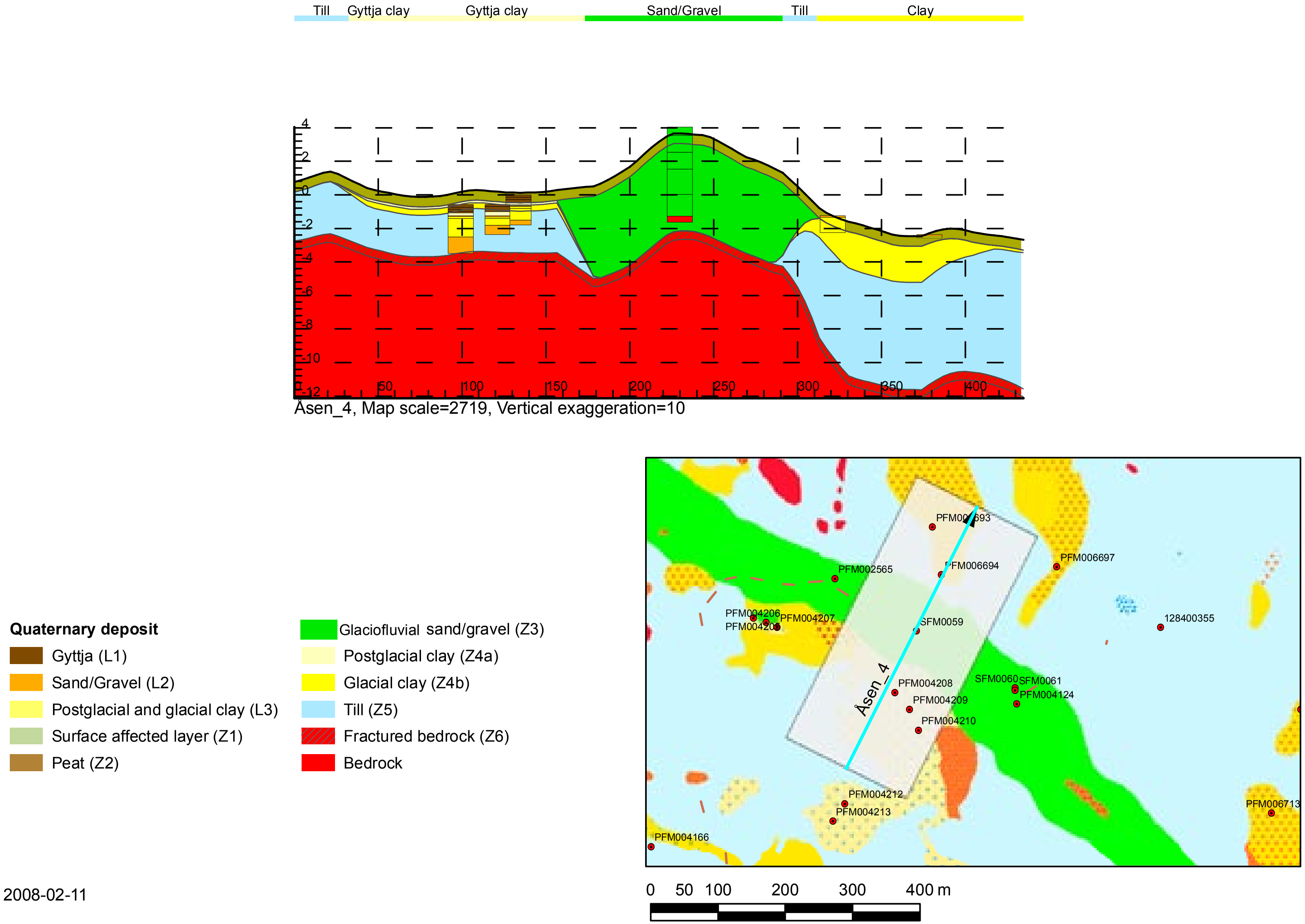


Figure 4-5. *Stratigraphical section along the Börstilåsen profile. For location of the profile, see Figure 4-3.*

4.3 Resulting files

The dataset is to be found in the SKB's GIS database and consist of the layers SDEADM.POS_FM_GEO_5903 -- SDEADM.POS_FM_GEO_5909 under the reference ID C148. The total regolith depth is stored under SDEADM.POS_FM_GEO_5920. The stratigraphical database compiled for the RDM 2.2 model version is stored as Acsess file ORGGeoModel_Source.mdb.

5 Anomalies in the regolith thickness

The evaluation in this chapter only concerns the sub-model consisting of the total regolith thickness, i.e. the thickness between the regolith surface and the bedrock surface. This sub model will be referred to as regolith thickness model (RTM) and the main model, including all the individual layers and lenses is referred to as regolith depth model, (RDM). The regolith surface is defined as the digital elevation model (DEM) with a resolution of 20 metres, and consequently any errors in the DEM will be present in the (RTM) as well. The quality check of the DEM is in progress and is expected to be completed during spring 2008. In that report also a quality check of the RTM will be included. This evaluation is therefore restricted to the anomalies that can be seen in different RTM displays while the mathematical and statistical analyses will be presented in the later report /Strömgren and Brydsten in prep/.

The digital data accessible for the evaluation are

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

(ii) a DEM with the same extension and resolution as the Z6 raster layer, and

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

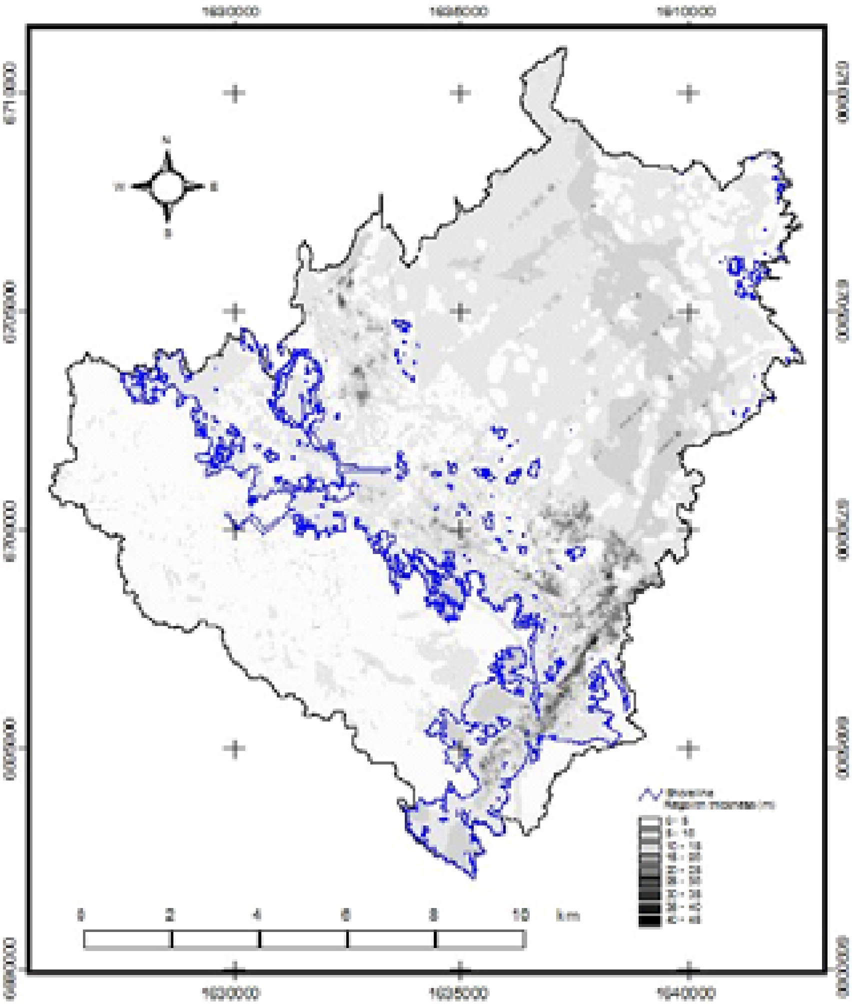


Figure 5-1. *The regolith thickness model (RTM) over the Forsmark area computed as the difference between the digital elevation model (DEM) and the bedrock surface model (the Z5 layer). The sea shoreline (blue) is displayed to make it easier to navigate on the map.*

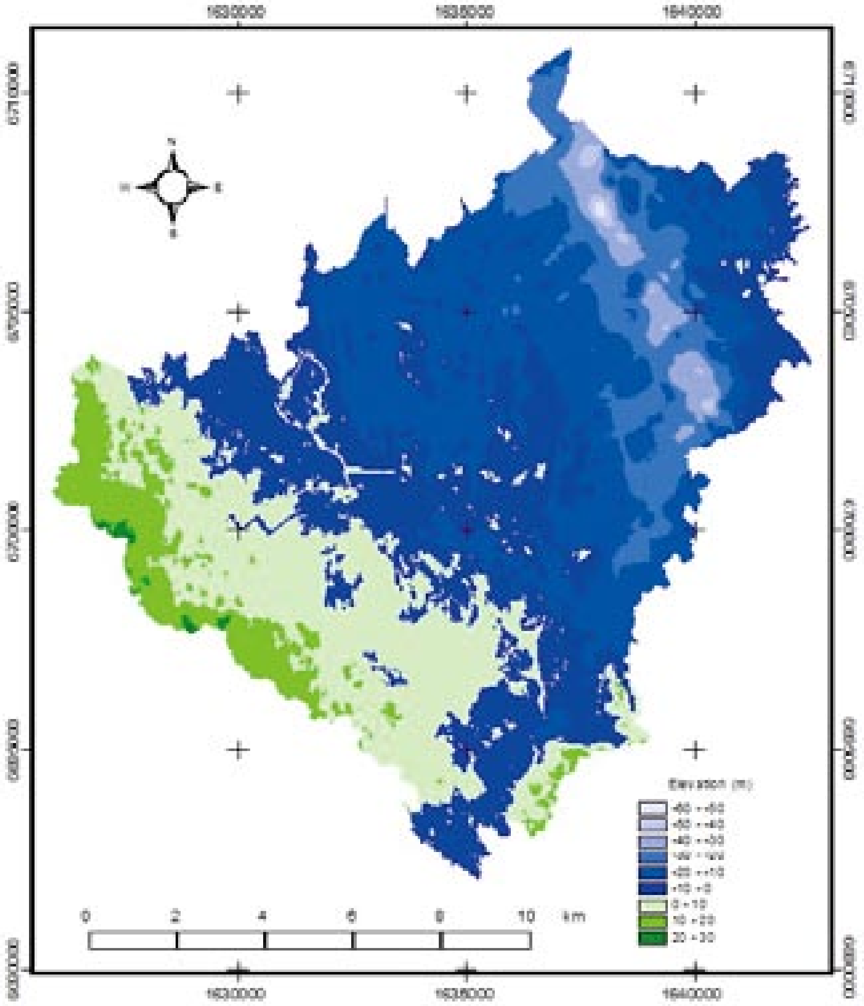


Figure 5-2. *The digital elevation model (DEM) for the Forsmark area with a resolution of 20 metres.*

The regolith thickness model (RTM) was computed as the difference between the DEM and the Z6-layer and the subsequent check will be done on this new layer. The GIS analyses are performed on the Z6 layer while the tables and regolith thickness are calculated from the contact between Z5 and Z6.

The value range in the RTM is 0.1–42 metres. Very thick regolith (> 20 metres) is to be found only in the sea close to the mainland. The largest regolith thickness (42 metres) is located in the south-east part of the model domain (see Figure 5-3). For large areas the regolith is less than 5 metres thick (see Figure 5-4), and on land the regolith thickness is mainly small.

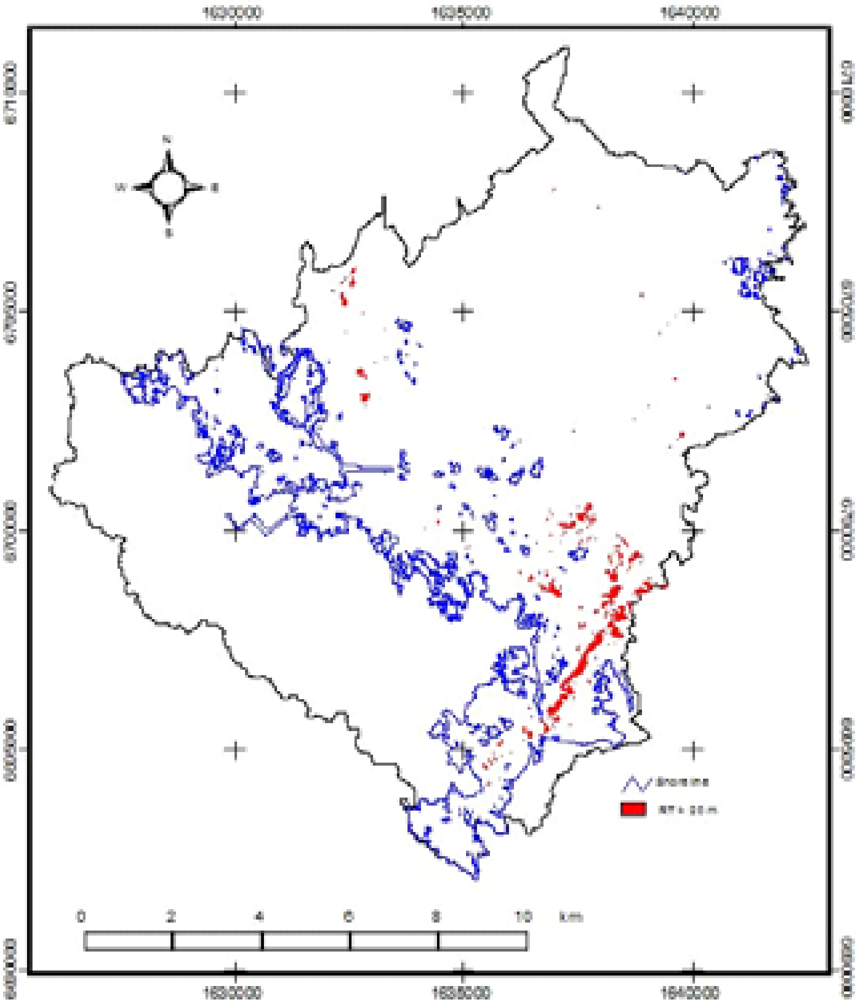


Figure 5-3. *Areas with a regolith thickness greater than 20 metres (including Z6).*

The RTM shows a number of linear structures (lineaments), predominantely in NW-SO and NO-SW directions. The most conspicuous lineaments are marked in Figure 5-5. Some of these are probably based on geological grounds while other indicate some errors, either in lack of raw data/unfavourable distribution of the data points or a result of chosen interpolation parameters.

One real cause to the marked lineaments in the RTM might be existing lineaments in the bedrock, for example a fracture, fissure or fault in the bedrock. The fractured 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.

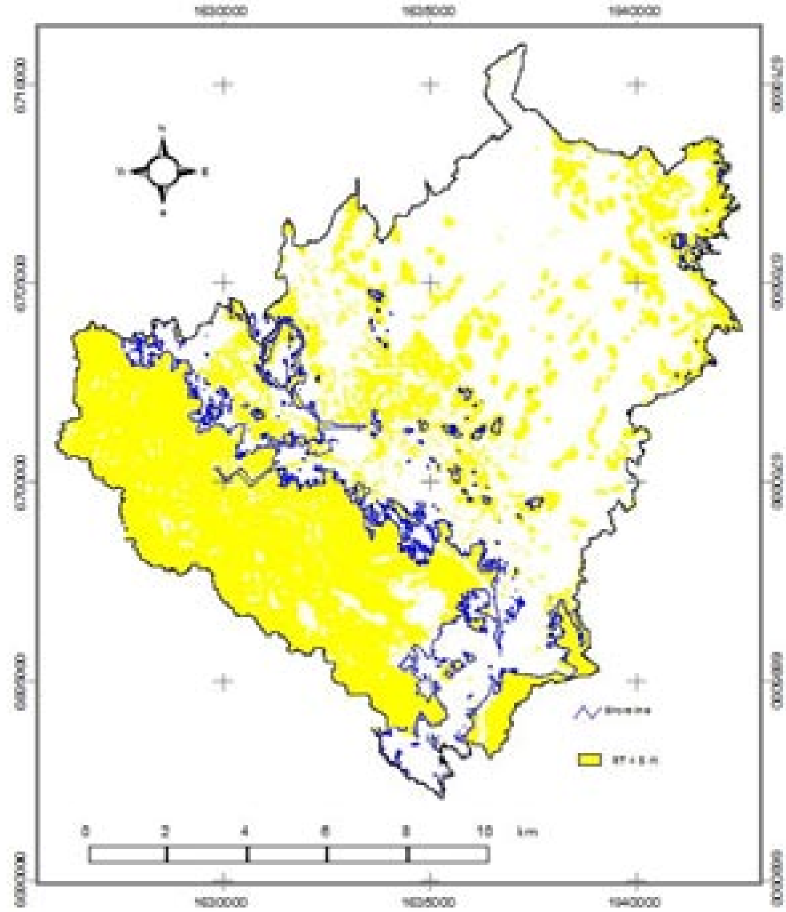


Figure 5-4. *Areas with regolith thickness less than 5 metres (including Z6).*

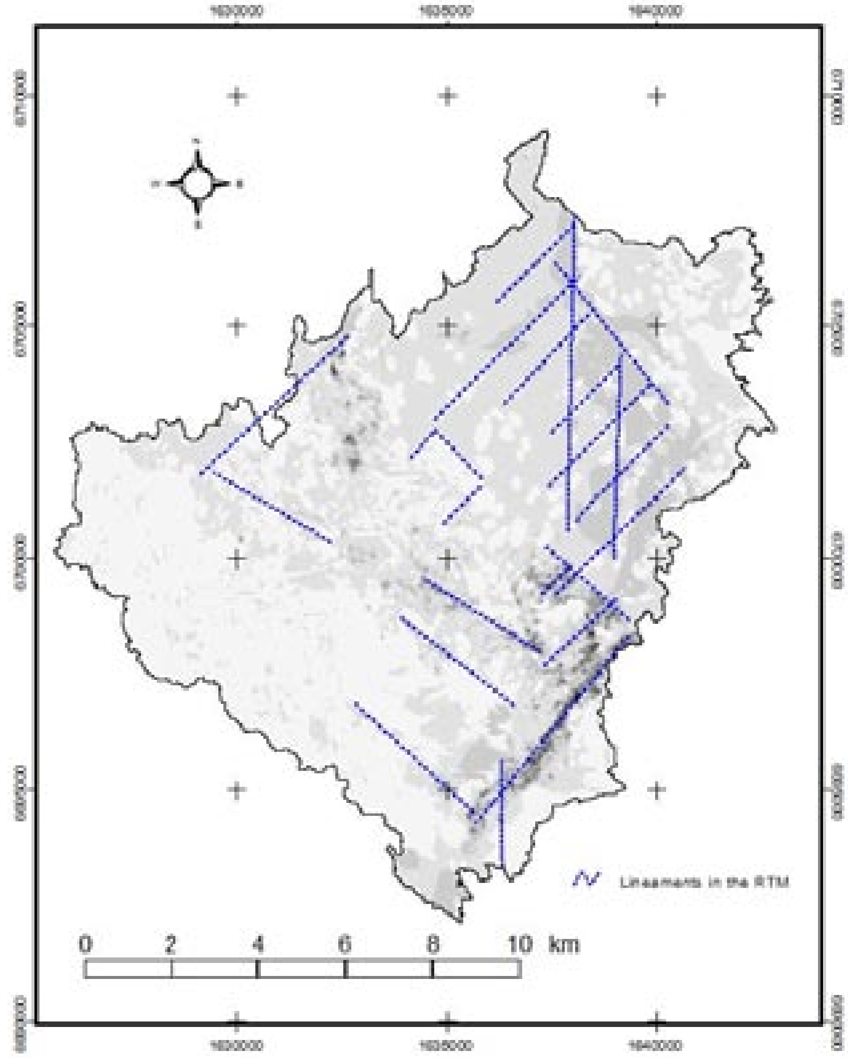


Figure 5-5. *Clearly marked lineaments in the regolith thickness model (RTM) are marked with blue dots.*

Figure 5-6 is the same as Figure 5-5 with the addition of lineaments in the bedrock displayed in red (SKB GIS Layer (SDEADM.POS_FM_GEO_5032)). As shown in the figure, several of the RTM lineaments (blue dashed line) coincide with bedrock lineaments (red unbroken line). Furthermore, areas with large regolith thickness (see Figure 5-3) also seem to coincide with bedrock lineaments.

Note that bedrock lineaments which do not coincide with ridges in the RTM, i.e. one N-S directed lineament in the NE part of the model (1 in Figure 5-6) domain and one NW-SE directed located in the central part of the domain (2 in Figure 5-6), however seems to coincide with threshold features in the RTM.

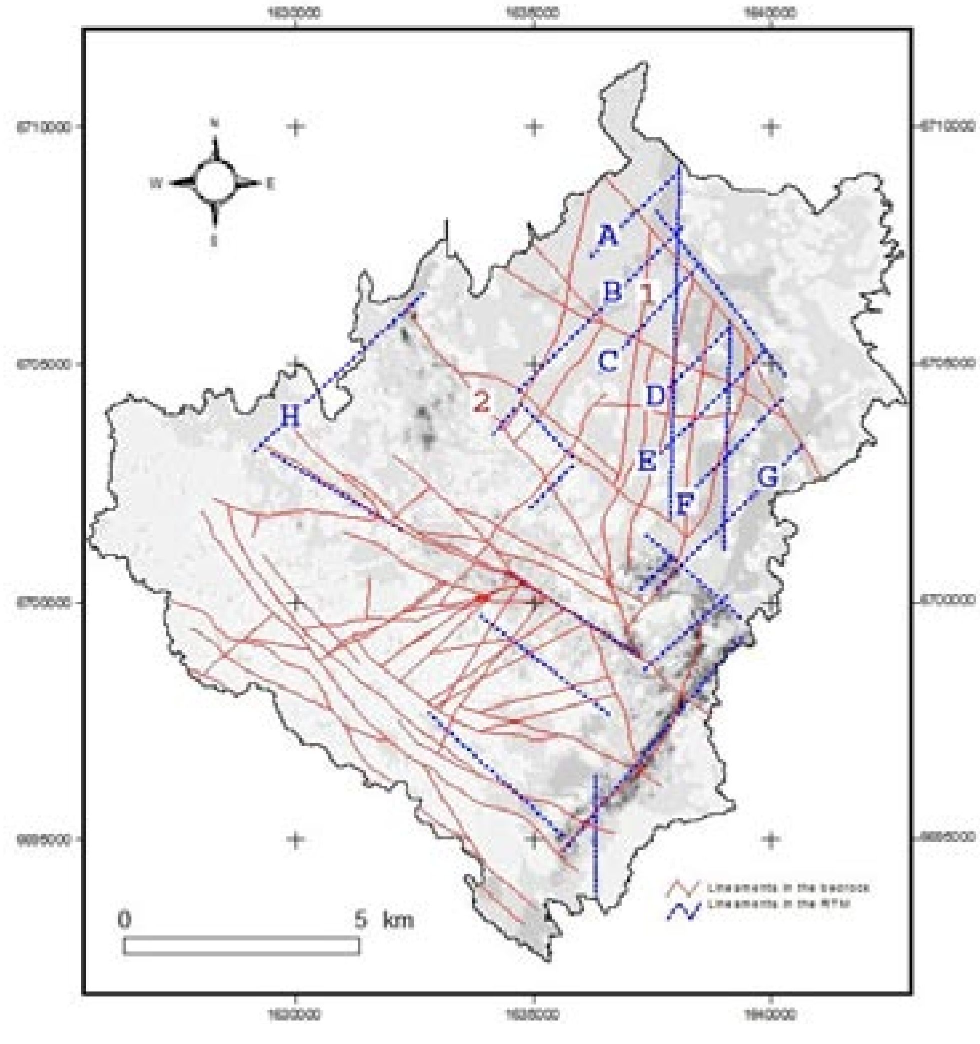


Figure 5-6. Clearly marked lineament in the RTM (blue) and lineament in the bedrock (red).

A number of lineaments in the RTM that could not be explained by features in the bedrock remains. The lineaments with NE-SW direction, especially those located in the NE part of the model (A–G in Figure 5-6). These lineaments coincide exactly with initial raw data from the marine geological survey (Elhammer and Sandkvist 2005) thus the lineaments reflect transects of the survey vessel (see Figure 5-7). The distance between transects are approximately 1 km whereas the distance between raw data points along transects are approximately 3 metres. This distribution of the input data results 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 Chapter 2 and 3, a number of virtual points have been added in areas between the transects where there are no measured data. These virtual points have been assigned values that corresponds to the average value of regolith thickness in the area. So, these NE-SW lineaments in the sea are thus due to errors in the virtual data used between the transects.

The NE-SW lineament in the RTM which is located close to the NW border of the model (H in Figure 5-6) is due to a third cause. This lineament coincides with the outer border of the marine geological survey, thus the density of the raw data is much lower in the area NW of that line which means that the quality of the RTM is considerably lower here.

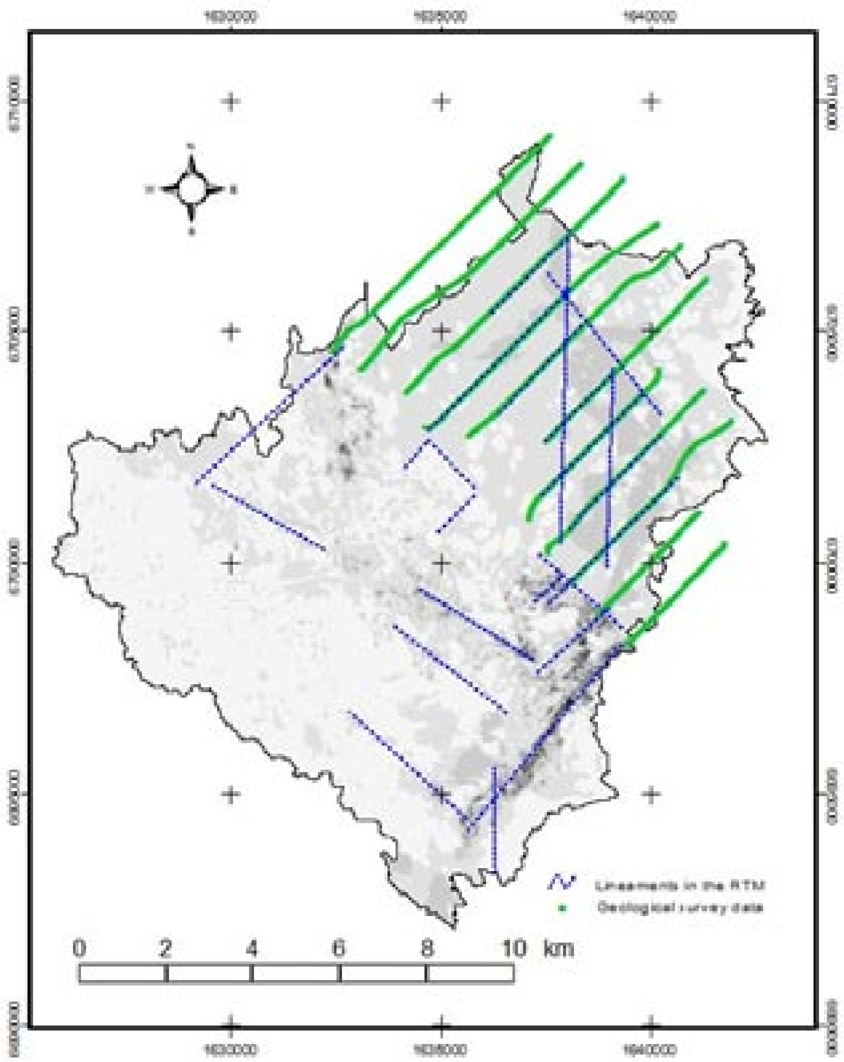


Figure 5-7. *Clearly marked lineament in the RTM (blue dots) and positions for raw data from the regional marine geological survey (green lines).*

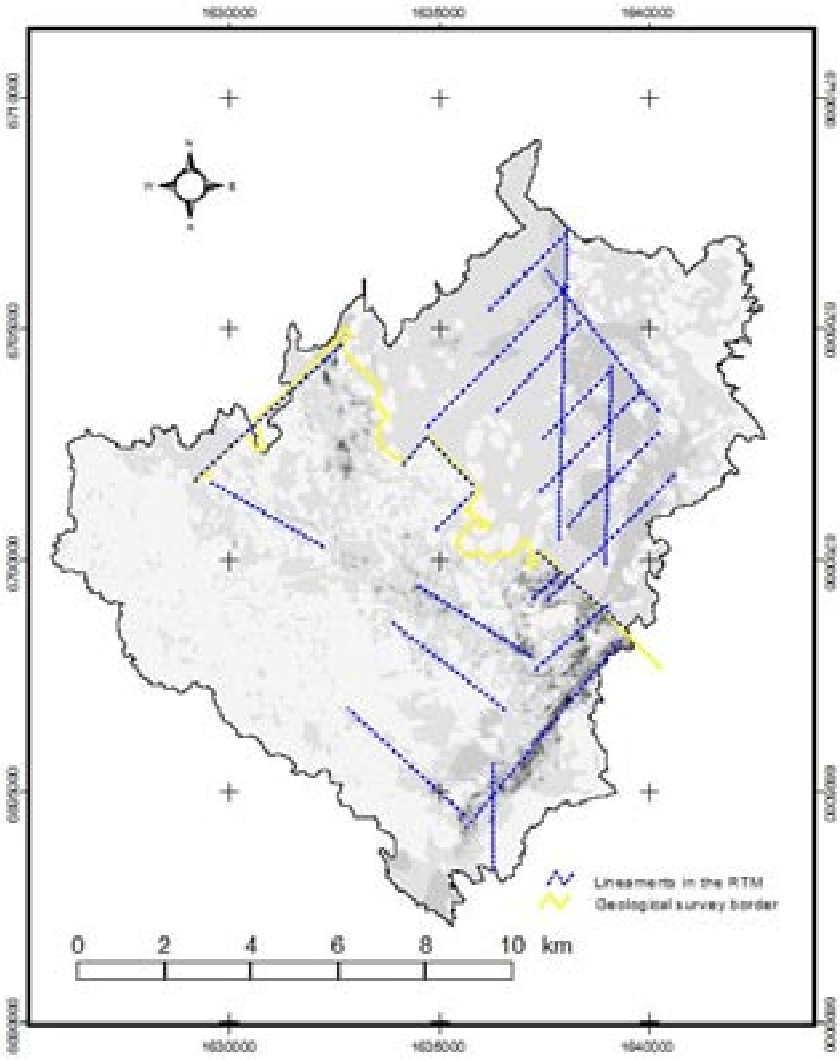


Figure 5-8. *Clearly marked lineament in the RTM (blue dots) and the border between the detailed and regional marine geological survey (yellow line).*

In a hillshade view from 315 degrees the appearance of objects elongated in approximately NE directions will be exaggerated, i.e. the azimuths in Figures 5-9 and 5-10 are chosen so that phenomenon associated with 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 5-9 with a yellow line and the sea shoreline with a blue line.

In Figure 5-9 it is clearly showed that the resolution of the raw data from the marine geological surveys have a high impact on the final shaping of the RTM. The pattern in the RTM 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. In the marine area close to Gräsö (eastern part of the model domain) the regolith thickness is distributed in a somewhat intermediate pattern between land areas and deep sea areas.

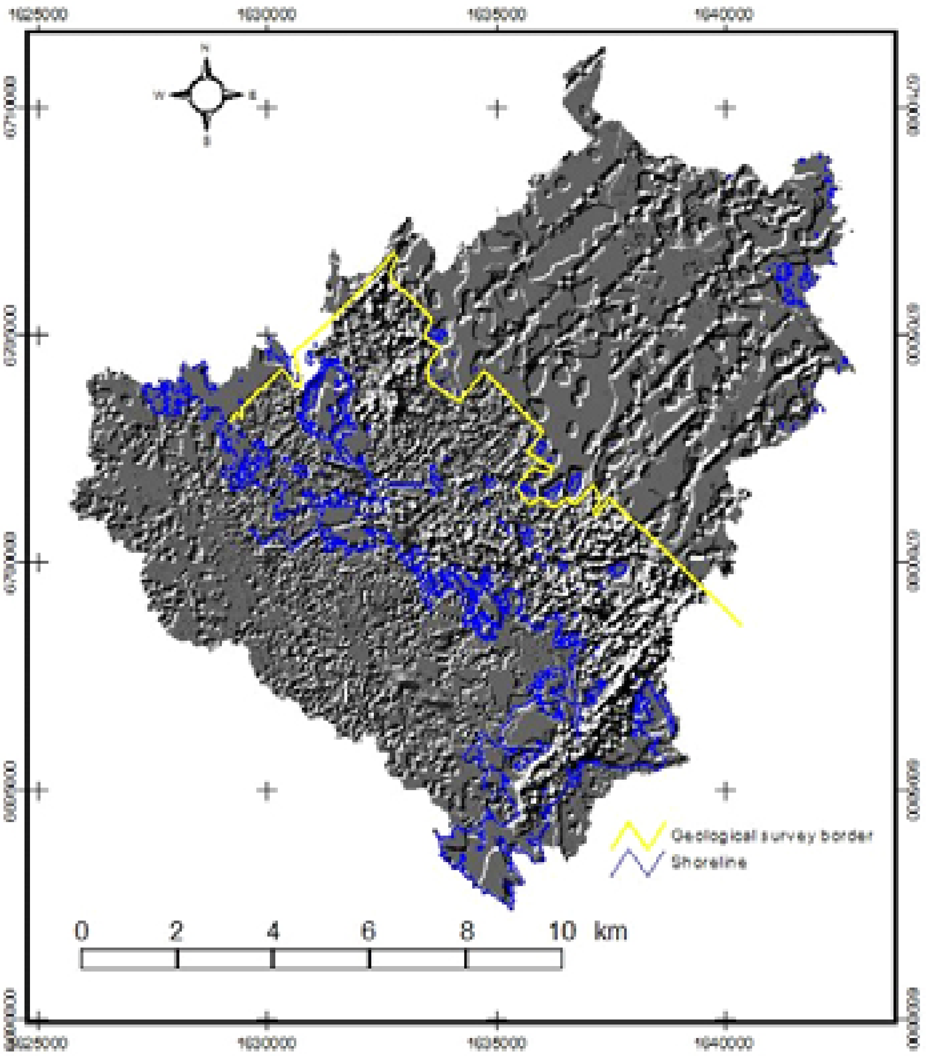


Figure 5-9. *A hillshade view of the RTM with a sun azimuth from 315 degrees and with a sun altitude of 45 degrees.*

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

Since the densities of raw data point and the density of the virtual points to the RTM differs between the central deep sea area and the area close to Gräsö, the point density or the assigned values of the virtual points are the only explanations to the different RTM topography between these areas.

Figure 5-10 shows the same area and the same light characteristics as for Figure 5-9 but for the DEM. The same pattern stands out as for the RTM which indicates that the unrealistic pattern that appears in the central part of the RTM is due to errors in the DEM. During the compilation 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 RTM between the deep sea and the shallow sea close to Gräsö.

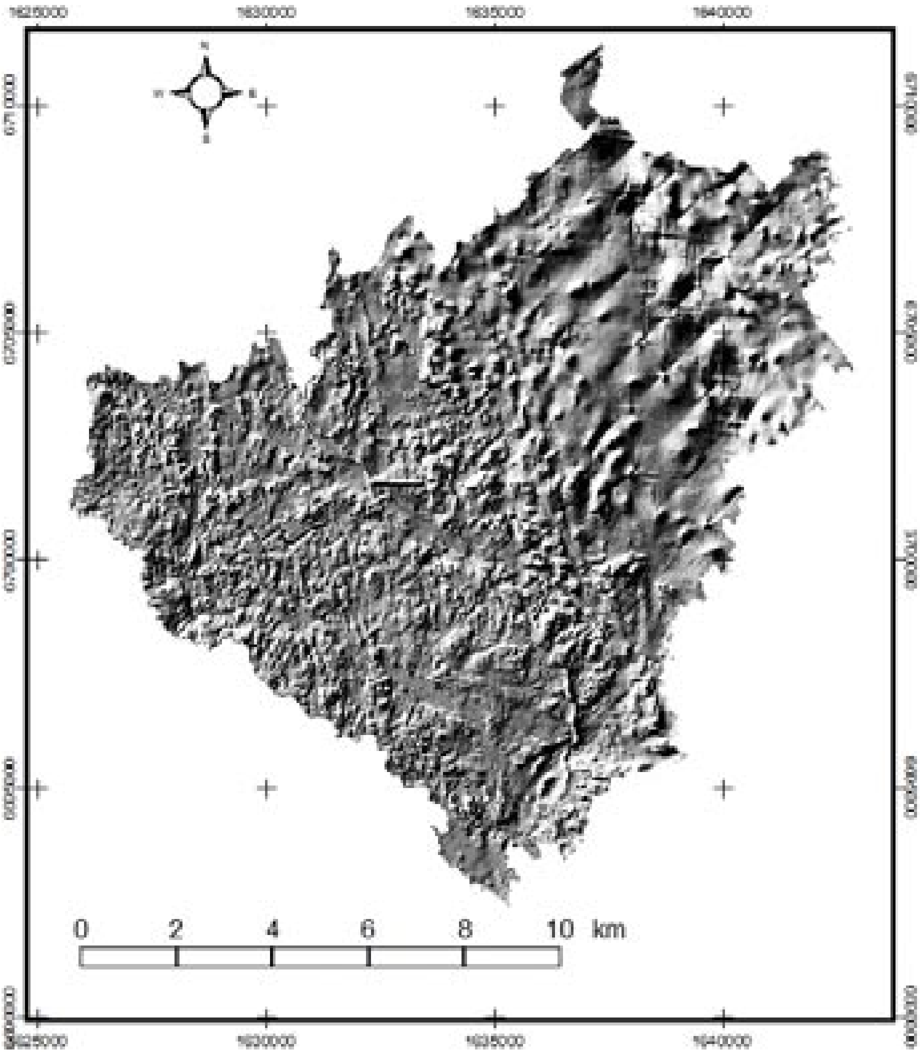


Figure 5-10. *A hillshade view of the DEM with a sun azimuth from 315 degrees and with a sun altitude of 45 degrees.*

Figure 5-11 shows a hillshade for the RTM where the light flows from SW (225 degrees) and therefore objects elongated in the NW direction are accentuated. The clearly marked lineament number 3 coincide well with one of the major bedrock lineaments (see Figure 5-6), which indicates that the RTM here describe a real geological anomaly. Locations of the additional three lineaments marked in the figure can however not be explained by features in the bedrock. Lineament number 1 is located exactly on the border between the two marine geological survey areas and the reason for the distinct visibility of the lineament is that the regolith depth decreases abruptly from the south-westerly to the north-easterly side of the border. The similar phenomenon can also be seen at the same border at the central part of the domain. These anomalies are questioned in more detail later

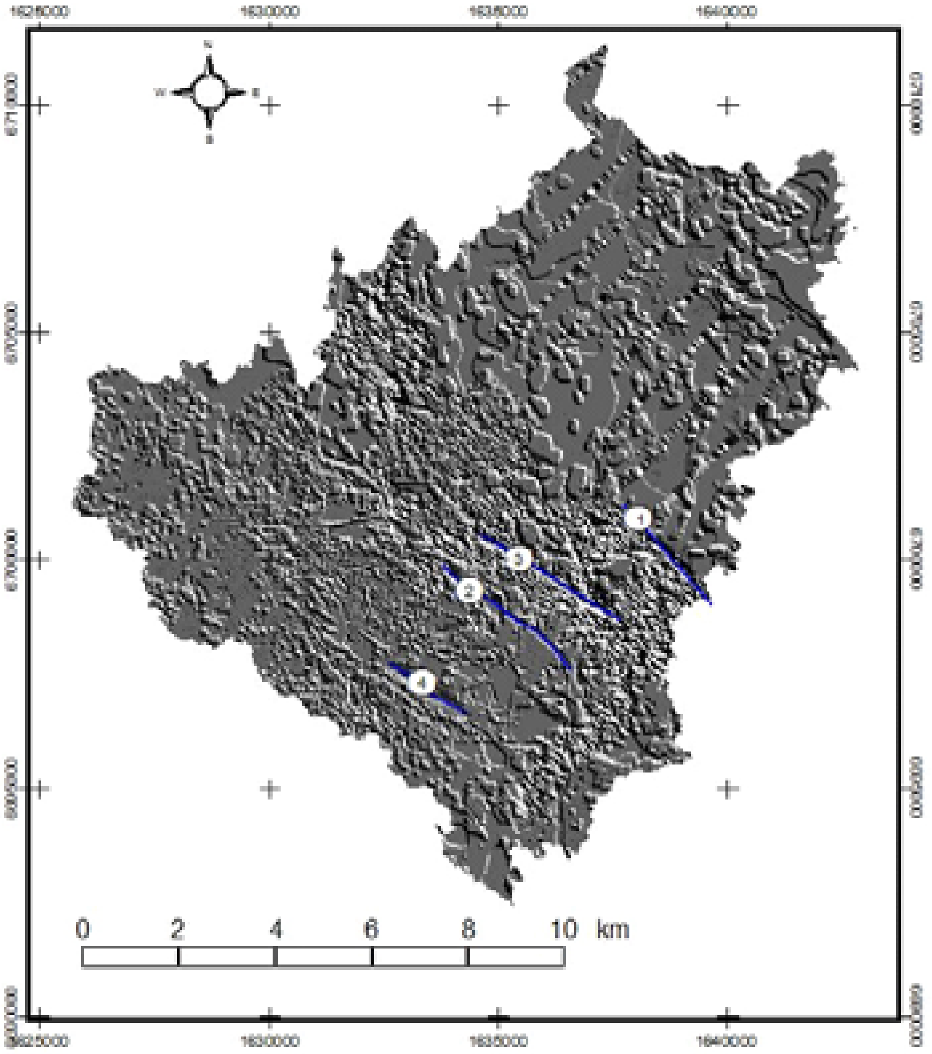


Figure 5-11. *A hillshade view of the RTM with a sun azimuth from 225 degrees and with a sun altitude of 45 degrees.*

Lineament number 4 in Figure 5-11 represents a depression in the RTM following the distribution of Lake Fiskarfjärden. The structure is standing out because the regolith thickness is greater beneath the lake as compared to its surroundings. The phenomenon is logic; the location of the lake is due to a depression in the bedrock which often in turns is due to some weakness in the bedrock. Thick layers of till often occur in those locations which in addition is superimposed with lacustrine sediments that together gives a great total regolith thickness. High regolith thickness can also be found beneath other lakes within the model domain but is not so accentuated in the 225 degree hillshade since these lakes are elongated in a different direction than Lake Fiskarfjärden.

A third method to visually check the quality of the RTM is to compute the slope of the RTM. The slope gradient varies among 0–33 degrees with an average value of 2.1 degrees.

In the RTM slope model, completely different patterns occur in the south-westerly part (mostly land) and the north-easterly part (mostly sea) of the model domain. Different structures within the regional marine geological survey area, which is already discussed, also occur in the slope model; transects in the NE-SW direction and the lineaments in the bedrock in the NW-SE direction. Flat areas (blue areas in Figure 5-12) coincide with areas with a high share of virtual points, which is logic.

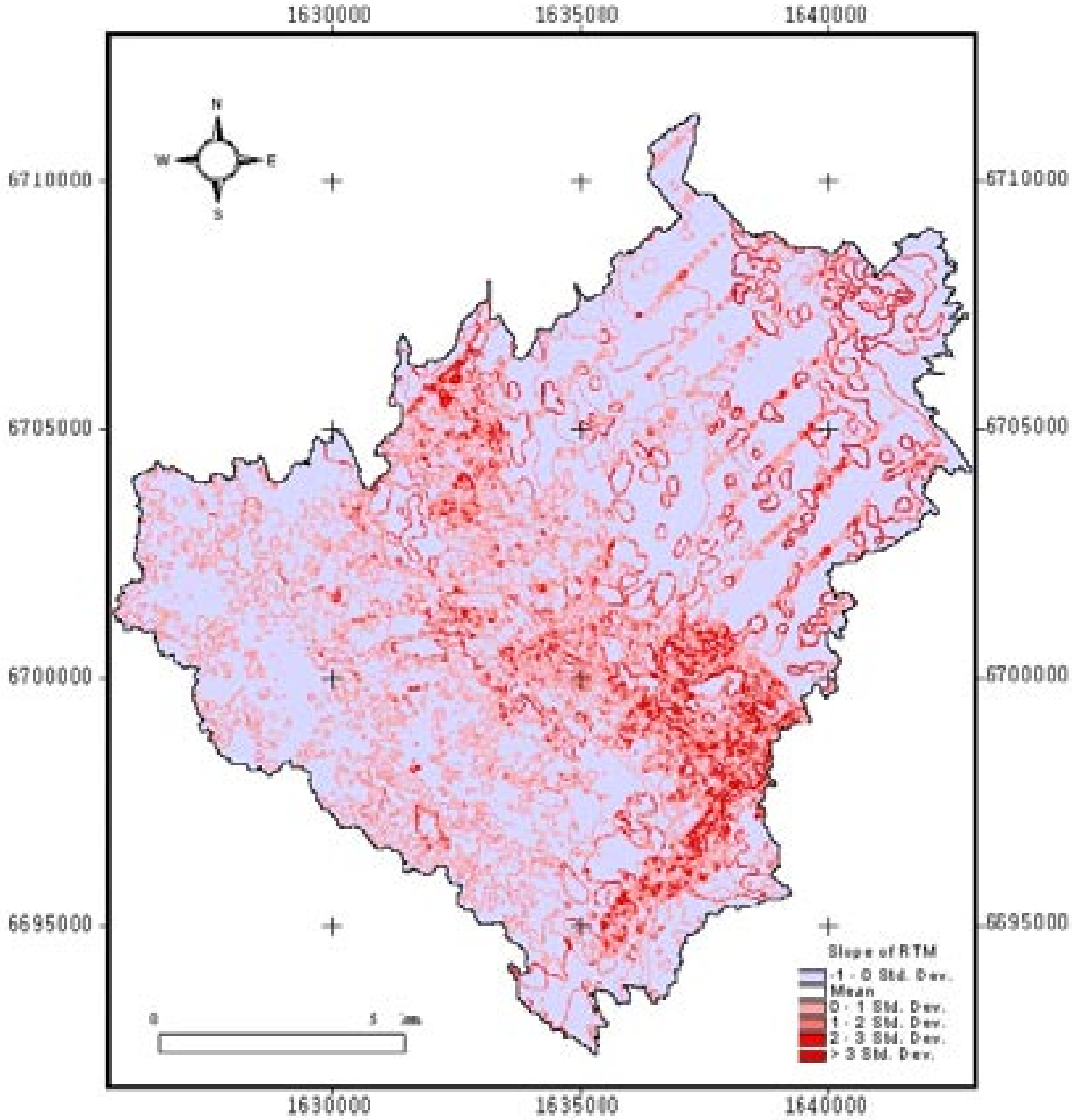


Figure 5-12. *A slope gradient map calculated from the RTM shown ith standard deviation classes. Blue areas have a slope less than the average slope (2.1 degrees).*

Figure 5-13 shows areas with slope gradients greater than 8 degrees (2.5% of the domain area). When the slope gradient is displayed as in Figure 5-13, it is evident that a difference in patterns occurs between the three areas (the detailed and regional marine geological survey areas and the land area), especially in the eastern part of the model domain. In the detailed survey area, many places with high slope gradients occur (high differences in regolith thickness at short distances) while this phenomenon almost totally lacks in the regional survey area. The different patterns between the detailed survey and the regional survey area could be the result of the difference in methods used in the two marine geological survey areas /Elhammer and Sandkvist 2005/.

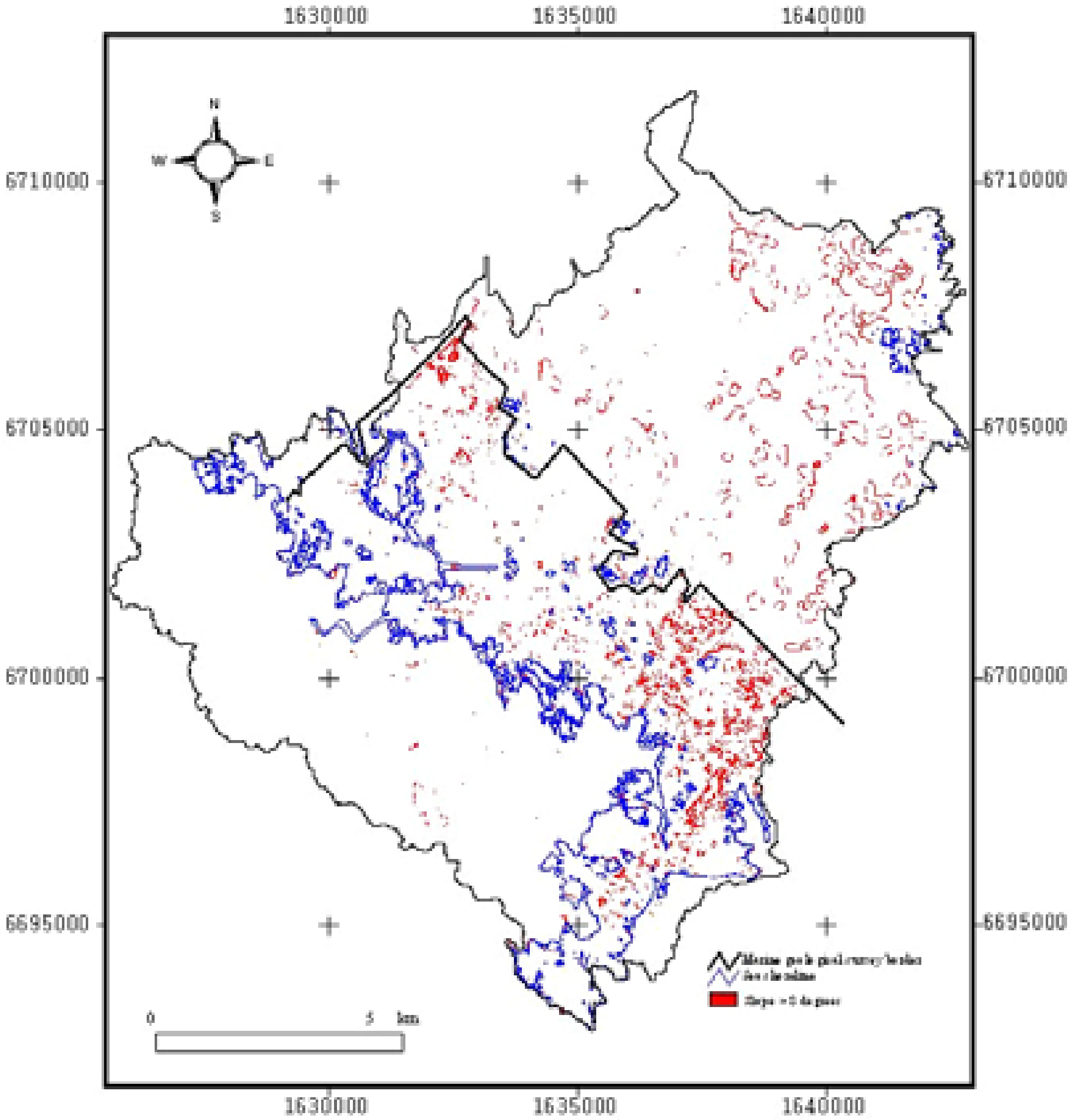


Figure 5-13. *Areas with a high regolith thickness slope (> 8 degrees) are marked with red colour. The blue line is the sea shore and the black line shows the border between the detailed and regional marine geological survey areas.*

The marine geological survey in the two areas is overlapping at some transects. The overlaps make it possible to analyse if any differences in geological interpretation occur between the two areas. Figure 5-14 shows one of the areas with overlap. The transects are parallel with a distance of less than 2 metres.

Since the spatial resolution is higher for the measuring points in the detailed transect, each point in the regional transect was matched with the closest point in the detailed transect. The point can then be pair wise analysed.

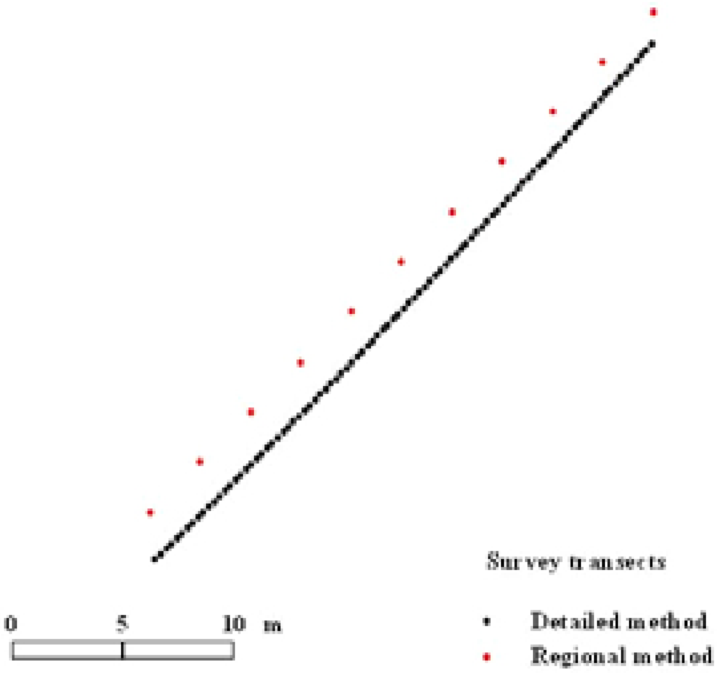


Figure 5-14. *Positions for survey points from the regional transect 21 (red dots) and detailed transect 119 (black dots) in the marine geological survey.*

The bedrock levels differ approximately 10 metres at all 11 points with a lower located bedrock surface for the detailed survey transect. As shown in the table, the explanation for the difference is that the till is not present in the regional transect and the till surfaces have wrongly been interpreted as a bedrock surface. As a logical consequence of this the regolith thickness has been underestimated within the regional survey area which shows up as high slope gradients at the border between the two survey areas. In the RTM the phenomenon is shown as a threshold with a shallower thickness in the regional area. Both these phenomena occur along the border between the two survey areas, however most clearly in the south-east part of the domain from which we have taken the figures to Table 5-1. If this method discrepancy occurs (wrongly interpreted till surfaces as bedrock surfaces) also in other parts of the regional area, can not be excluded.

One indication of the possible extent of the misinterpretation is the share of points from the marine geological surveys that have an occurrence of regolith but no strata with till. The stratification at these locations is often glacial clay placed directly on top of the bedrock, a phenomenon that exists but must be considered as rather unusual. Within the regional survey area, 26% of the points with such properties while corresponding stratigraphy within the detailed survey area is only 1%. This difference in share could indicate a widespread interpretation error within the regional survey area.

The seismic sounding equipment used in the detailed survey area generally has a higher resolution, but poorer penetration depth, as compared to the equipment used in the regional survey area. This is mainly due to the frequency spectrum of the different sound sources used. Also the fact that the detailed survey area is generally shallower than the regional survey area makes it more difficult to interpret the seismograms since a lot of extra sideechoes are introduced. This together may have caused an overall underestimation of the regolit depth, especially till, in the regional area and also an overestimation in the detailed area (oral communication, Bernt Kjellin, SGU 2007).

In Figures 5-1 and 5-4 it is evident that the regolith thickness is less in the terrestrial area compared to the sea, and that a distinct border seems to be located along the present sea shoreline. Figure 5-15 shows the RTM domain divided into three regions; land, detailed and regional marine geological survey areas. Table 5-2 shows calculated average values of regolith thickness in these three regions for modelled values from the RTM, raw data points and raw measured data points (virtual points excluded) used in the interpolation of the RTM.

Table 5-1. Regolith characteristics at survey points along two overlapping transects (see Figure 5-14). All units are in metres.

id	Bedrock level regional transect	Bedrock level detailed transect	Water depth regional transect	Water depth detailed transect	Total soil thickness regional transect	Total soil thickness detailed transect	Till thickness regional transect	Till thickness detailed transect
1	22.18	32.18	16.40	16.67	5.70	15.51	0.08	10.75
2	22.31	32.21	16.41	16.71	5.90	15.50	0.08	10.91
3	22.53	32.61	16.42	16.75	5.11	15.86	0.08	11.52
4	22.75	33.15	16.43	16.81	5.32	16.34	0.08	12.29
5	22.90	34.11	16.44	16.86	5.49	17.25	0.08	13.46
6	22.80	35.22	16.45	16.90	5.35	18.32	0.08	14.74
7	22.74	35.60	16.51	16.93	5.23	18.67	0.08	15.19
8	22.64	35.62	16.55	16.96	5.09	18.66	0.08	15.28
9	22.54	35.63	16.58	16.99	5.96	18.64	0.08	15.36
10	22.45	35.65	16.62	17.02	5.83	18.63	0.08	15.45
11	22.36	34.78	16.68	17.05	5.69	17.73	0.08	14.64

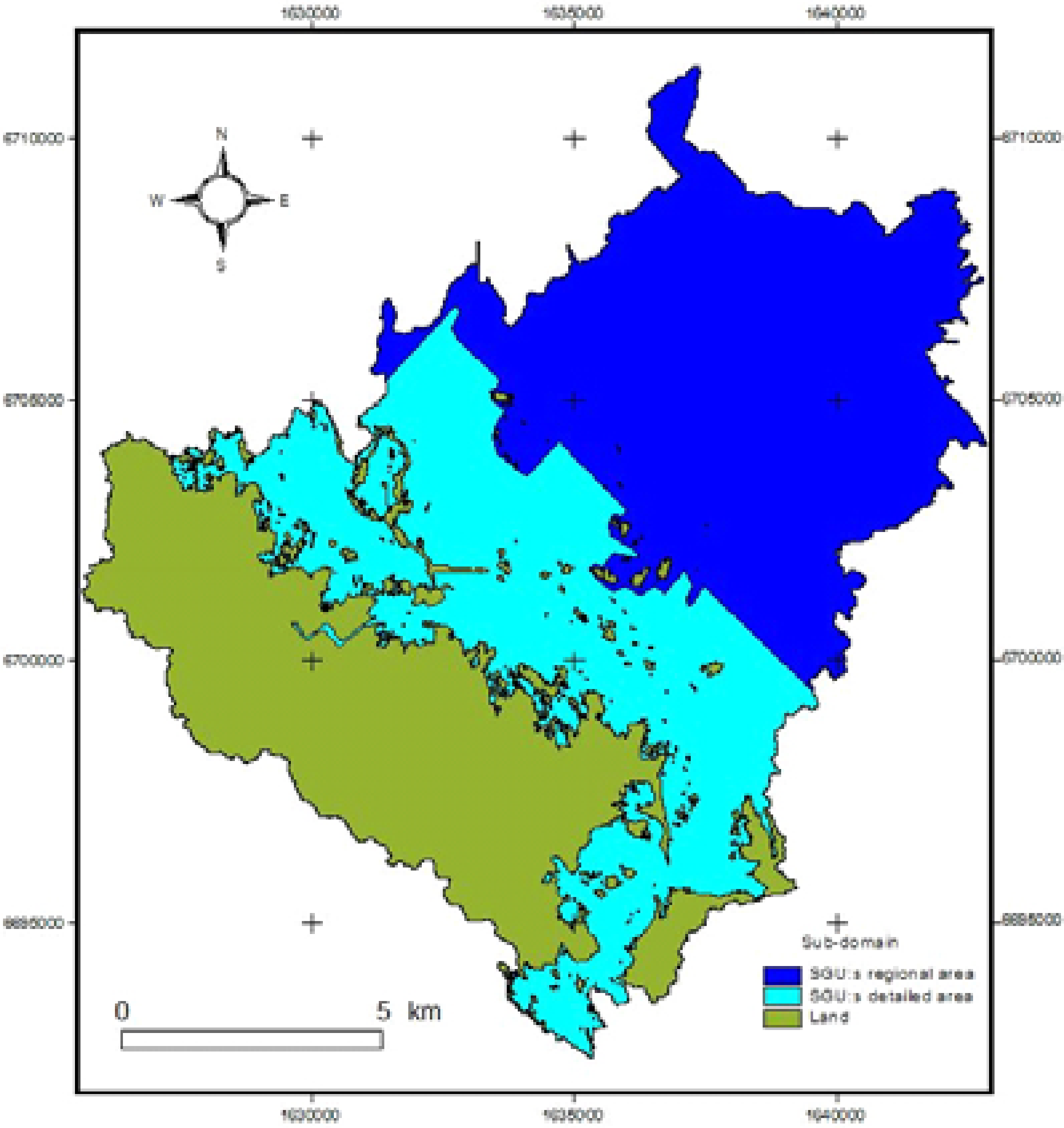


Figure 5-15. The RTM domain divided into three sub-domains used in the calculation of average regolith thickness (see Table 5-2); land and the regional and detailed marine geological survey areas

The average regolith thickness is approximately twice as large within the sea regions as compared to the land region and this is not caused by the values assigned the virtual points (see Table 5-2). Theoretically, the regolith thickness should be shallower over land since wave generated processes in the sea will erode loose deposits when these sediments due to positive shore displacement are located on shallow bottoms. A comparison of extensions of Quaternary deposits between the land and sea gives that postglacial fine-grained deposits (clayey and silty fractions) are eroded before the sea bottom becomes land. The same seems to be valid also for glacial clay. Table 5-3 shows average thickness of different geological strata for data from the marine geological surveys.

The average thickness of the post-glacial fine-grained strata is only one centimetre in the detailed region and 47 centimetres in the regional area, so even if all post-glacial sediments can be eroded, it can not be the only explanation for the difference in the average total regolith thickness between land and sea. The thickness of the glacial clay strata is 3.59 metres in the regional area and 2.01 metres in the detailed area, so the erosion of glacial clay can not explain the difference in regolith thickness. It is possible that the differences in total regolith thickness between the land and sea are due to the difference in density of raw data (approximately 300 points km^{-2} on land compared too approximately 1,300 point's km^{-2} within the marine area), the quality of the raw data or both. This can hopefully be cleared out in the more mathematical and statistical quality check of both the DEM and the RTM that will be published later /Strömgren and Brydsten in prep/.

A part of a hillshade of the RTM slope gradient layer is shown in Figure 5-16. Areas that seem to rise in the 2-dimensional figure are areas with high slope gradients. Many of the structures already questioned stand out on the map and in addition, a number of circular structures of which some have “crater appearance.”

Since also the marine geological survey transects are visible in the figure, it can be seen that circular structures are located between the transects and therefore, no raw data for regolith thickness are located close to the circular structures. The explanation to these structures is also here to be found in the DEM. At the largest circular structure on the map, there are two concentric rings with water depth values from the digital chart (lines for 10 and 15 metres water depths) which have given a corresponding circular structure in the DEM. Since all regolith thickness values in the close vicinity to the circular structures are virtual points with the same value, the error in the DEM is mirrored to the RTM.

Table 5-2. Average regolith thickness (m) in three subareas; land and the regional and detailed marine geological survey areas. The RTM-values are modelled and raw data are the Z-values used for interpolation of the RTM. In measured raw data the virtual points are excluded.

	Selection	Land	Sea Det.	Sea Reg.
RTM	All	3.5	7.6	8.0
Raw data	All	3.9	8.0	8.3
	Measured	4.2	8.3	8.2

Table 5-3 Average thickness of different quaternary deposits in raw data from the marine geological surveys.

	All points	Detailed area	Regional area
Post-glacial clay-silt	0.02	0.01	0.47
Glacial clay	2.02	2.01	3.59
Till	5.94	6.02	4.58
Total	**8.32**	**8.30**	**9.10**

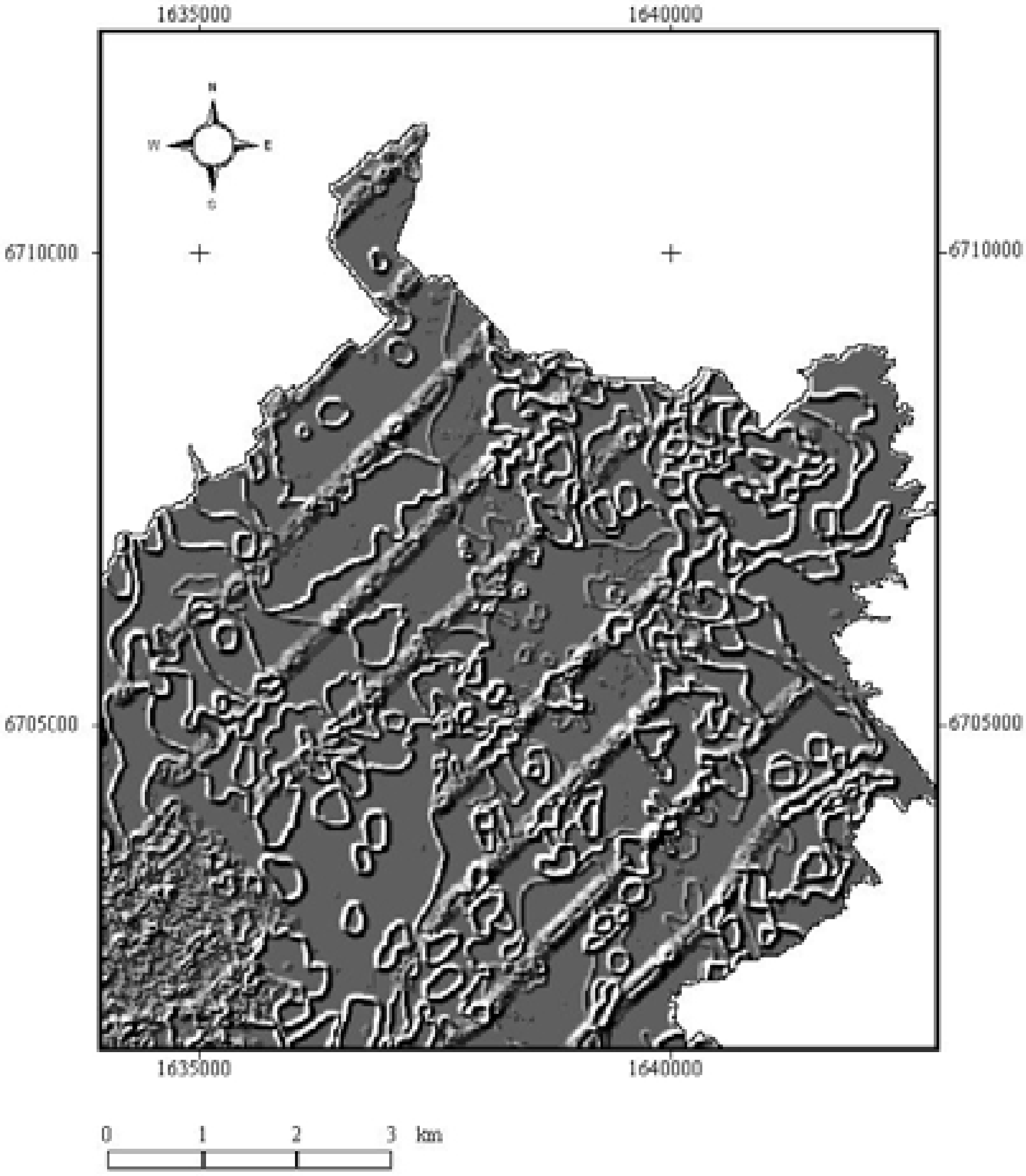


Figure 5-16. *A hillshade map calculated from the slope gradients map. Areas that seem to rise in the 2-dimensional figure are areas with high slope gradients.*

6 Summary and discussion

The present model describes the geometrical distribution of the regolith at Forsmark, subdivided into seven layers and three lenses. The layers and lenses are constructed according to a conceptual model of the Quaternary geology of the Forsmark site. This means that the layers and lenses are constructed to represent the spatial distribution of different Quaternary deposits. It should be noted that the model is pure geometrical and the properties are assigned by the user.

The total modelled regolith depth varies between 0.1 and 42 m. Generally, the regolith is deeper in the marine area while the terrestrial areas contain the majority of the exposed bedrock. To model regolith depth and stratigraphy is by nature affected by large uncertainties and the presented results in this report should be regarded as a general geometrical model of the area on a landscape level. The vast majority of the input data used in this model is based on interpretation of geophysical measurements. Of the total number of 527,747 observation points used for interpolation of the bedrock surfaces other than outcrops, in fact only 141 are direct observations (corings or excavations) where the actual bedrock surface was identified. The same data set was then used for calculating the average values of the different sub-domains, representing 53% of the observations used for interpolating the bedrock surface. Thus, the model is very sensitive to the calculation of average values and interpretation of geophysical data.

The spatial resolution of the model is 20×20 m, thus in areas with detailed information, several observations may be located within the same pixel. When detailed studies of the bedrock surface has been performed in Forsmark, it was often reviled that a small scale topography characterises the bedrock surface, although the upper surface or the regolith is remarkably flat. For example, this small scale undulating bedrock topography was observed e.g. in the corings close to Drill site 1 and when excavating Drill site 5 /Leijon 2005/ but is not captured in this model.

When extracting the regolith from the DEM, the elevation of the bedrock surface is presented (Figure 6-1). A comparison with the > 3 km lineaments in Forsmark shows that at least the major lineaments, predominantly with a NV-SE strike, can be detected as depressions in the bedrock.

6.1 Areas with less confidence

Since the elevation of all points are derived from the DEM, the absolute depth at each observation point will be affected with an error due to the absolute difference between the actual elevation of the point and the elevation from the 20×20 m pixel in the DEM. The quality of the DEM will be evaluated by /Strömgren and Brydsten in prep/. In general, the quality in the terrestrial areas and along the measuring profiles in the marine area are better than between the measuring lines in the marine area, where the uncertainty is large. The problem with underestimated regolith depths occurs when the measured elevation at an observation point exceeds the interpolated DEM. In the same way, the total regolith depth can be overestimated when the measured elevation of an observation point is lower than the DEM.

Since all pixels that touch a bedrock outcrop are modelled as bedrock and buffered 30 m, areas with many small outcrops will have an over representation of bedrock. This phenomenon is especially obvious in the area where a detailed geological mapping has been performed and outcrops as small as 10 m were displayed on the map.

Large areas are represented by average depth values, mainly based on geophysical data. A comparison between depth values of geophysical information and corings in the terrestrial part shows deeper regolith observed in corings. This may indicate that the geophysical measurements

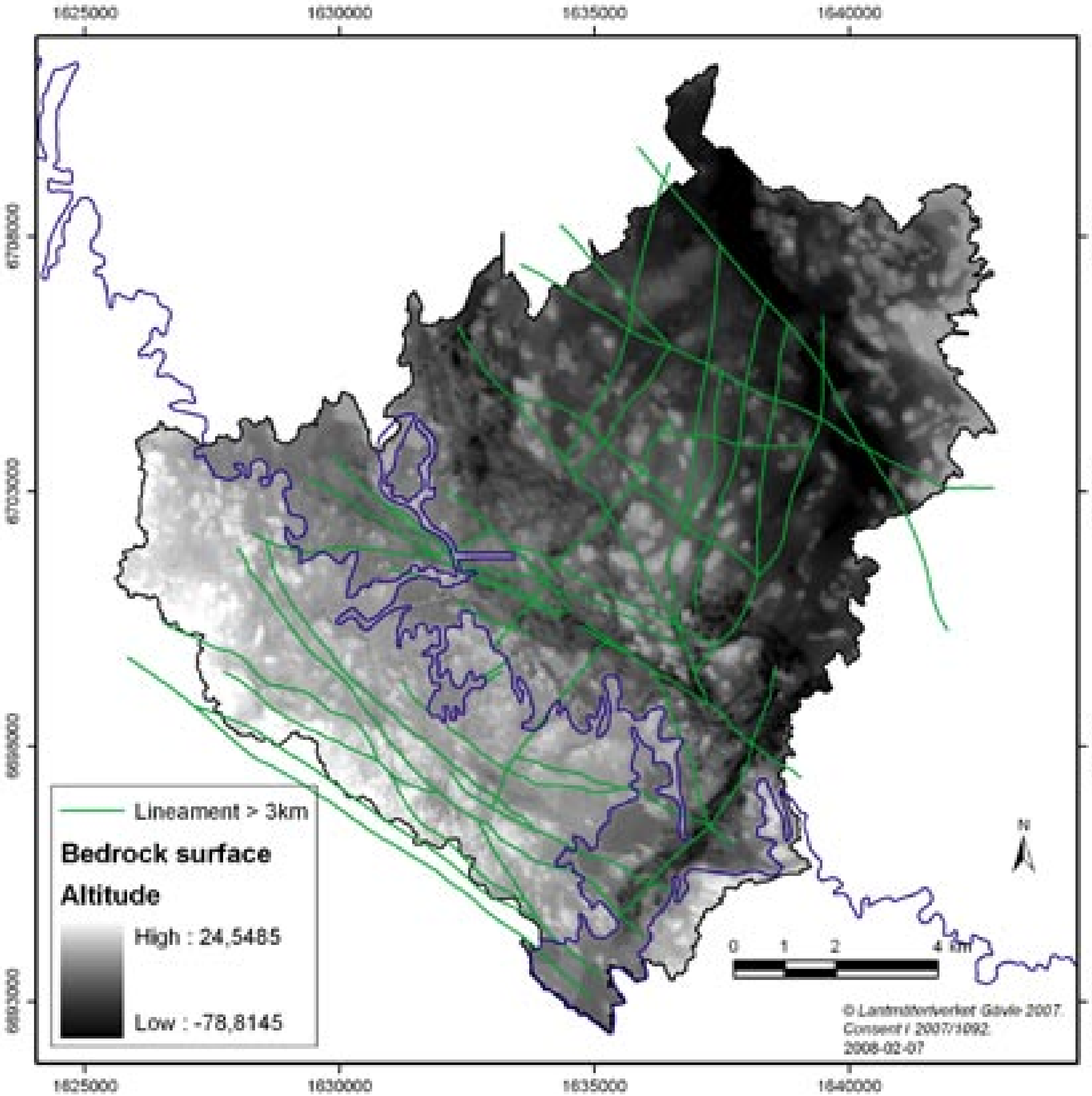


Figure 6-1. *The modelled bedrock surface with a resolution of 20 m. The green lines are lineaments longer than 3 km.*

may show a generally too shallow regolith. The discrepancy between the data sets may also be the result of a some what biased localisation of the coring sites to areas with deep regolith.

The concept of applying average depth values in areas with no observation points results in a regolith cover that follows the DEM. Thus, any errors in the DEM will be present also in the RDM. The transition between different sub-domains will be represented by a leap in the modelled regolith dept but most probably represented by a gradual transition in the terrain.

The difference between the two model versions was calculated by subtracting the 2.2 modelled depths from the 2.3 depth, see Appendix 2. The maximum difference between the two models is 28 m. The red to orange part of the scale indicates that the modelled regolith depth was deeper in the 2.2 version while the green to blue areas indicates that the 2.2 version presented a thinner regolith than the 2.3 version. The pale green/yellow areas on the map represents areas where the two model versions are equal, corresponding to the distribution of the observation points used in the two models. The largest discrepancy between the model versions is found e.g. in the coastal area where the 2.2 model have records of thick regolith on islands partly represented with bare bedrock. Additionally, in the marine area, between the observation points, the 2.3 model version shows deeper regolith.

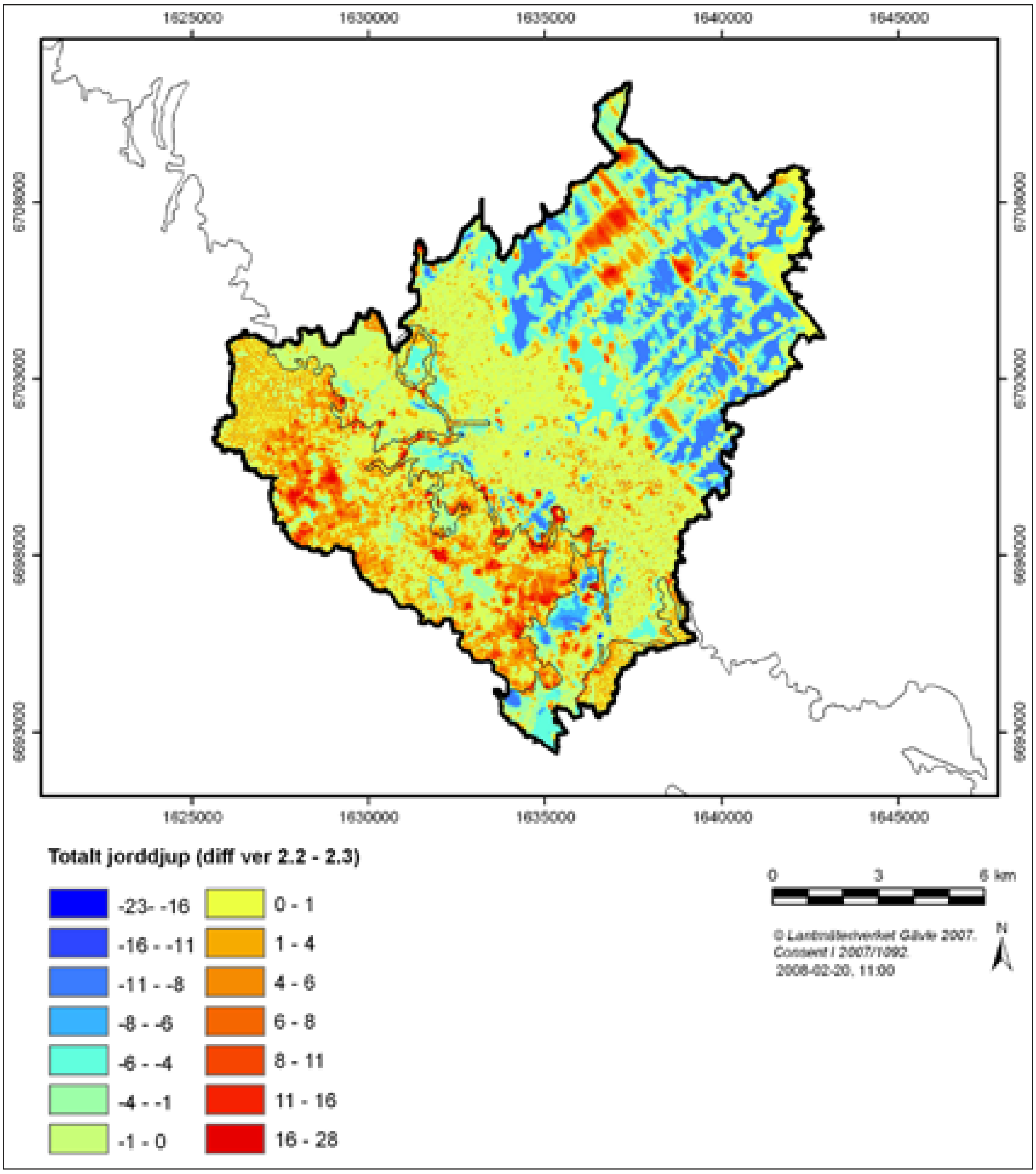


Figure 6-2. *The difference between the model version 2.2 and 2.3 presented in metres.*

7 References

Bergman B, 2004. Reflection seismics in the Forsmark area. Updated estimate of bedrock topography (previous report P-04-99). SKB P-04-158, Svensk Kärnbränslehantering AB.

Bergman B, Palm H, Juhlin C, 2004. Forsmark site investigation. Estimate of bedrock topography using seismic tomography along reflection seismic profiles. SKB P-04-99, Svensk Kärnbränslehantering AB.

Brydsten L, Strömgren M, 2004. Digital elevation models for site investigation programme in Forsmark. SKB R-04-70, Svensk Kärnbränslehantering AB.

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

DHI Water & Environment, 2008. MIKE GeoModel – User Guide. DHI Water & Environment, Hörsholm, Denmark.

Elhammer A, Sandkvist Å, 2005. Forsmark site investigation: Detailed marine geological survey of the sea bottom outside Forsmark. SKB P-03-101, Svensk Kärnbränslehantering AB.

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

Fredriksson D, 2004. Forsmark site investigations: Peatland investigation Forsmark. SKB P-04-127, Svensk Kärnbränslehantering AB.

Hedenström A, 2003. Forsmark site investigations: Investigation of marine and lacustrine sediments in lakes. SKB P-03-24, Svensk Kärnbränslehantering AB.

Hedenström A, 2004. Forsmark site investigations: Investigation of marine and lacustrine sediments in lakes. Stratigraphical and analytical data. SKB P-04-86, Svensk Kärnbränslehantering AB.

Hedenström A, Sohlenius G, Albrecht J, 2004. Forsmark site investigation. Stratigraphical and analytical data from auger drillings and pits. SKB P-04-111, Svensk Kärnbränslehantering AB.

Hedenström A, Sohlenius G, in prep 2008. Description of the regolith at Forsmark. Site descriptive modelling. SDM-Site Forsmark. SKB R-08-04, 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.

Ising J, 2005. Forsmark site investigation: Mapping of Quaternary deposits on the bottom of shallow bays outside Forsmark. SKB P-06-88, Svensk Kärnbränslehantering AB.

Johansson P-O, 2003. Forsmark site investigation. Drilling and sampling in soil. Installation of groundwater monitoring wells and surface water level gauges. SKB P-03-64, Svensk Kärnbränslehantering AB.

Keisu M, Isaksson H, 2004. Forsmark site investigation: Acquisition of geological information from Forsmarksverket, Information from the Vattenfall archive, Råcksta. SKB P-04-81, Svensk Kärnbränslehantering AB.

Lagerbäck R, Sundh M, Johansson H, 2004. Forsmark site investigation: Searching for evidence of late- and post-glacial faulting in the Forsmark region. Results from 2003. SKB P-04-123, Svensk Kärnbränslehantering AB.

Lagerbäck R, Sundh M, Svedlund J-O, Johansson H, 2005. Forsmark site investigation. Searching for evidence of late- and postglacial faulting in the Forsmark region. Results from 2002–2004. SKB R-05-51, Svensk Kärnbränslehantering AB.

Leijon B (ed), 2005. Forsmark site investigation: Investigations of superficial fracturing and block displacements at drill site 5. SKB P-05-199, Svensk Kärnbränslehantering AB.

Lokrantz H, Hedenström A, 2006. Forsmark site investigation: Description, sampling and analyses of Quaternary deposits in connection with groundwater monitoring wells, pumping wells and BAT filter tips. SKB P-06-92, Svensk Kärnbränslehantering AB.

Marek R, 2004a. Forsmark site investigation. Ground penetrating radar survey 2003. SKB P-04-78, Svensk Kärnbränslehantering AB.

Marek R, 2004b. Forsmark site investigation. A co-ordinated interpretation of ground penetrating radar data from the Forsmark site. SKB P-04-156, Svensk Kärnbränslehantering AB.

Persson C, 1985. Jordartskarta 12I Östhammar NO. Sveriges geologiska undersökning Ser Ae 73.

Persson C, 1986. Jordartskarta 13I Österlövsta SO/Grundkallen SV. Sveriges geologiska undersökning Ser Ae 76.

Rönning H J S, Kihle O, Mogaard J O, Walker P, Shomali H, Hagthorpe P, Byström S, Lindberg H, Thunehed H, 2003. Helicopter borne geophysics at Forsmark, Östhammar, Sweden. Forsmark site investigation. SKB P-03-41, Svensk Kärnbränslehantering AB.

SGU, 2007. brunnsarkivet. www.sgu.se. (Accessed 2007-04-07)

Sohlenius G, Hedenström A, 2003. Forsmark: Mapping of unconsolidated Quaternary deposits, Field data 2002. SKB R-03-11, Svensk Kärnbränslehantering AB.

Sohlenius G, Hedenström A, Rudmark L, 2004. Forsmark site investigation: Mapping of unconsolidated Quaternary deposits 2002–2003. Map description. SKB R-04-39, Svensk Kärnbränslehantering AB.

Strömgren M, Brydsten L, in prep 2008. Quality check of the 20 m DEM at Forsmark.

Sundh M, Sohlenius G, Hedenström A, 2004. Stratigraphical investigation of till in machine cut trenches. SKB P-04-34, Svensk Kärnbränslehantering AB.

Söderbäck (ed) in prep 2008. Geological evolution, palaeoclimatology and historic development in the Forsmark and Laxemar /Simpevarp areas. Site descriptive modelling. SDM-Site. SKB R-08-19, Svensk Kärnbränslehantering AB.

Thunehed H, Pitkänen T, 2003. Forsmark site investigation. Electric soundings supporting inversion of helicopterborne EM-data. SKB P-03-44, Svensk Kärnbränslehantering AB.

Thunehed H, 2005. Forsmark site investigation: Inversion of helicopter-borne electromagnetic measurements. SKB P-04-157, Svensk Kärnbränslehantering AB.

Toresson B, 2005. Forsmark site investigation: Seismic refraction survey 2004. SKB P-05-12, Svensk Kärnbränslehantering AB.

Toresson B, 2006. Forsmark site investigation: Seismic refraction survey 2005–2006. SKB P-06-138, Svensk Kärnbränslehantering AB.

Vikström M, 2005. Modelling of soil depth and lake sediment. An application of the GeoEditor at the Forsmark site. SKB P-05-07, Svensk Kärnbränslehantering AB.

Werner K, Johansson P-O, 2003. Slug tests in groundwater monitoring wells in soil. Forsmark site investigation. SKB P-03-65, Svensk Kärnbränslehantering AB.

Werner K, Lundholm L, Johansson P-O, 2004. Forsmark site investigation. Drilling and pumping test of wells at Börstilåsen. SKB P-04-138, Svensk Kärnbränslehantering AB.

Appendix 1

Profiles with interpreted geological layers

The location of the profiles is shown in the horizontal view in each profile, and in an overview in Figure 4-3. The observation points are included in the illustrated profile and the geological layers are listed in the legend. The frame surrounding the profile line shows the 200 m zone for including bore holes in the graph. It should be noted that the observation points displayed in the profiles are before buffering, thus all the observations are not used in the final model. For presentation reason in areas with many corings, some stratigraphical profiles are not displayed in the graphs.

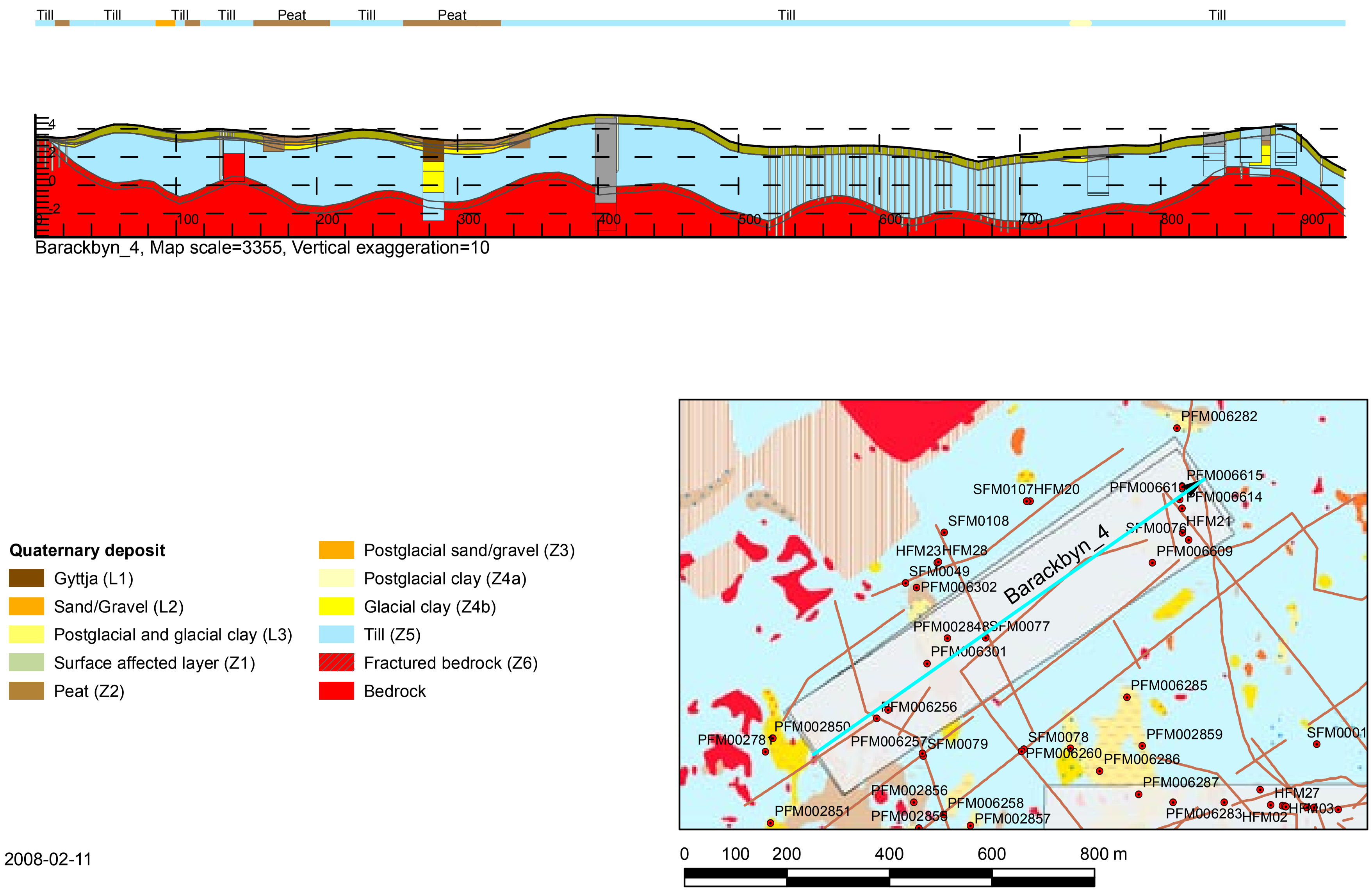


Figure A1-1. Vertical profile showing stratigraphy and total regolith depth along profile "Barackbyn". For location of the profile, see Figure 4-3.

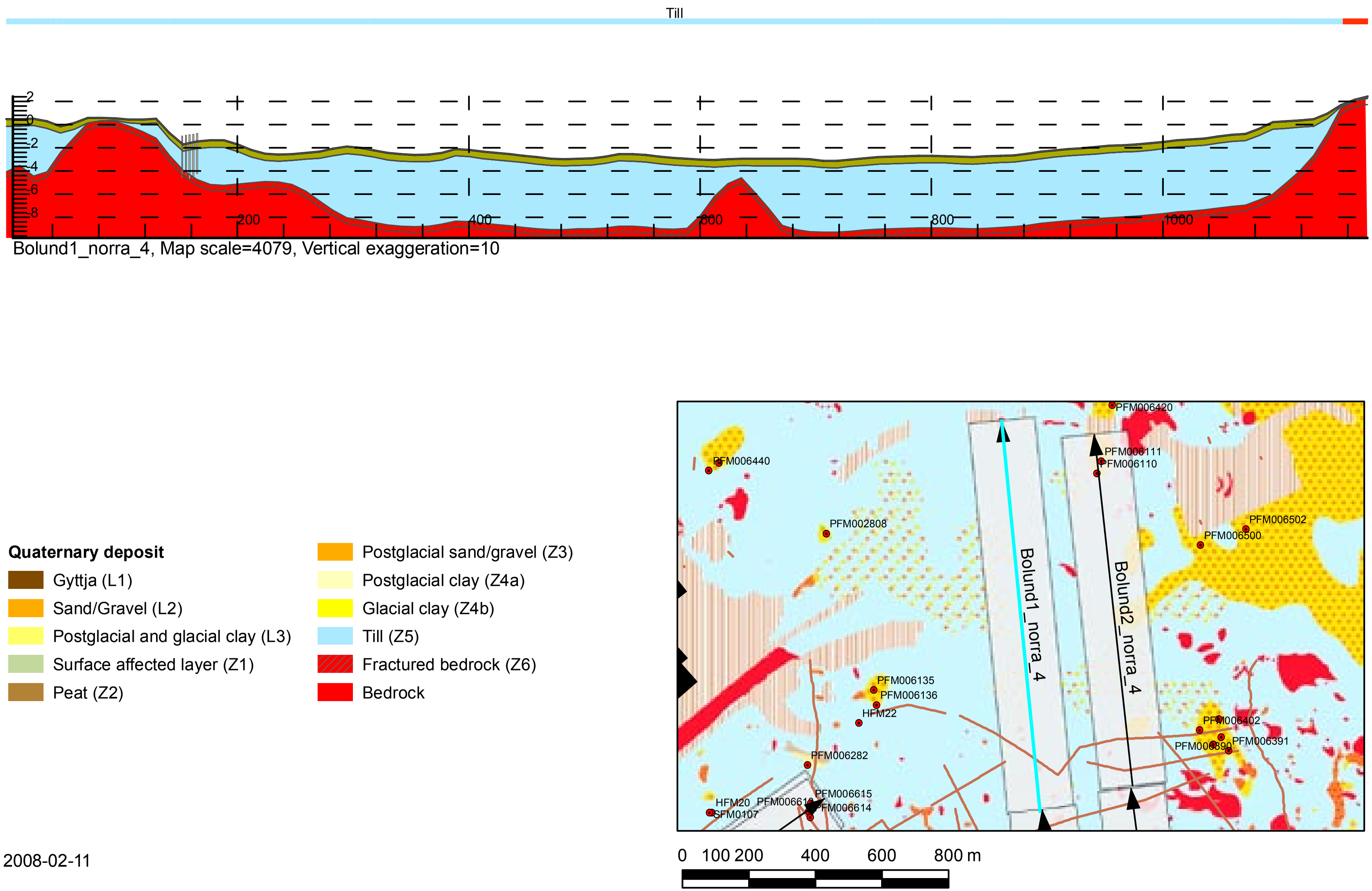
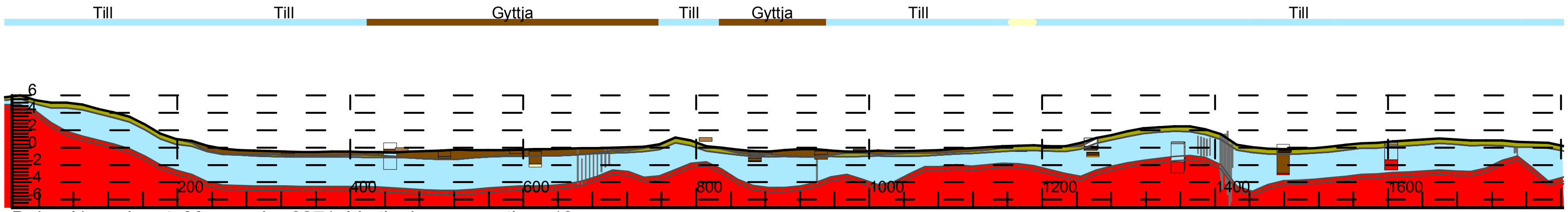
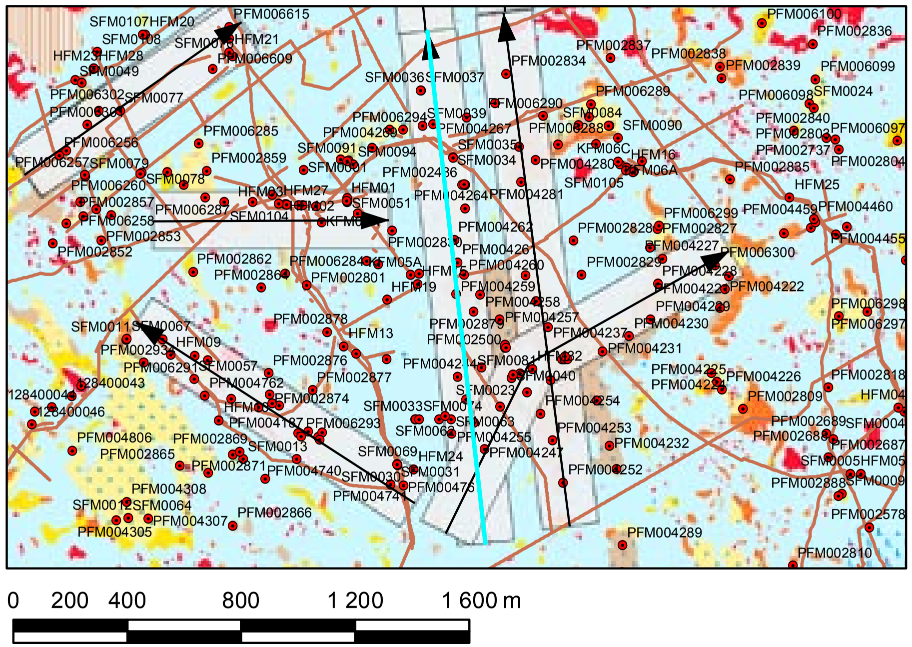


Figure A1-2. Vertical profile showing stratigraphy and total regolith depth along profile "Bolund1_norra".



Quaternary deposit

- Gyttja (L1)
- Sand/Gravel (L2)
- Postglacial and glacial clay (L3)
- Surface affected layer (Z1)
- Peat (Z2)
- Postglacial sand/gravel (Z3)
- Postglacial clay (Z4a)
- Glacial clay (Z4b)
- Till (Z5)
- Fractured bedrock (Z6)
- Bedrock



2008-02-11

Figure A1-3. *Vertical profile showing stratigraphy and total regolith depth along profile "Bolund 1_södra".*

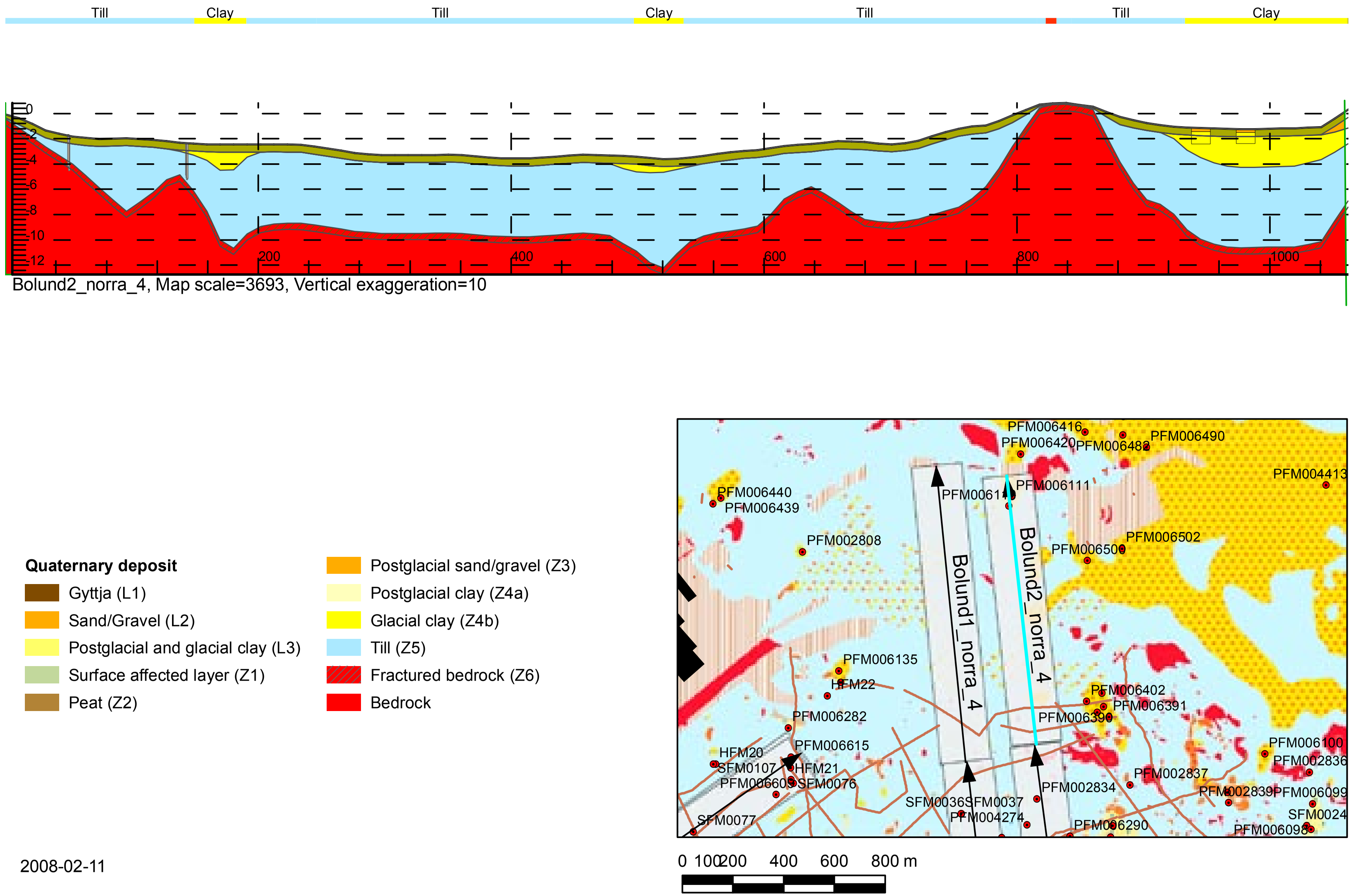


Figure A1-4. Vertical profile showing stratigraphy and total regolith depth along profile "Bolund2_norra".

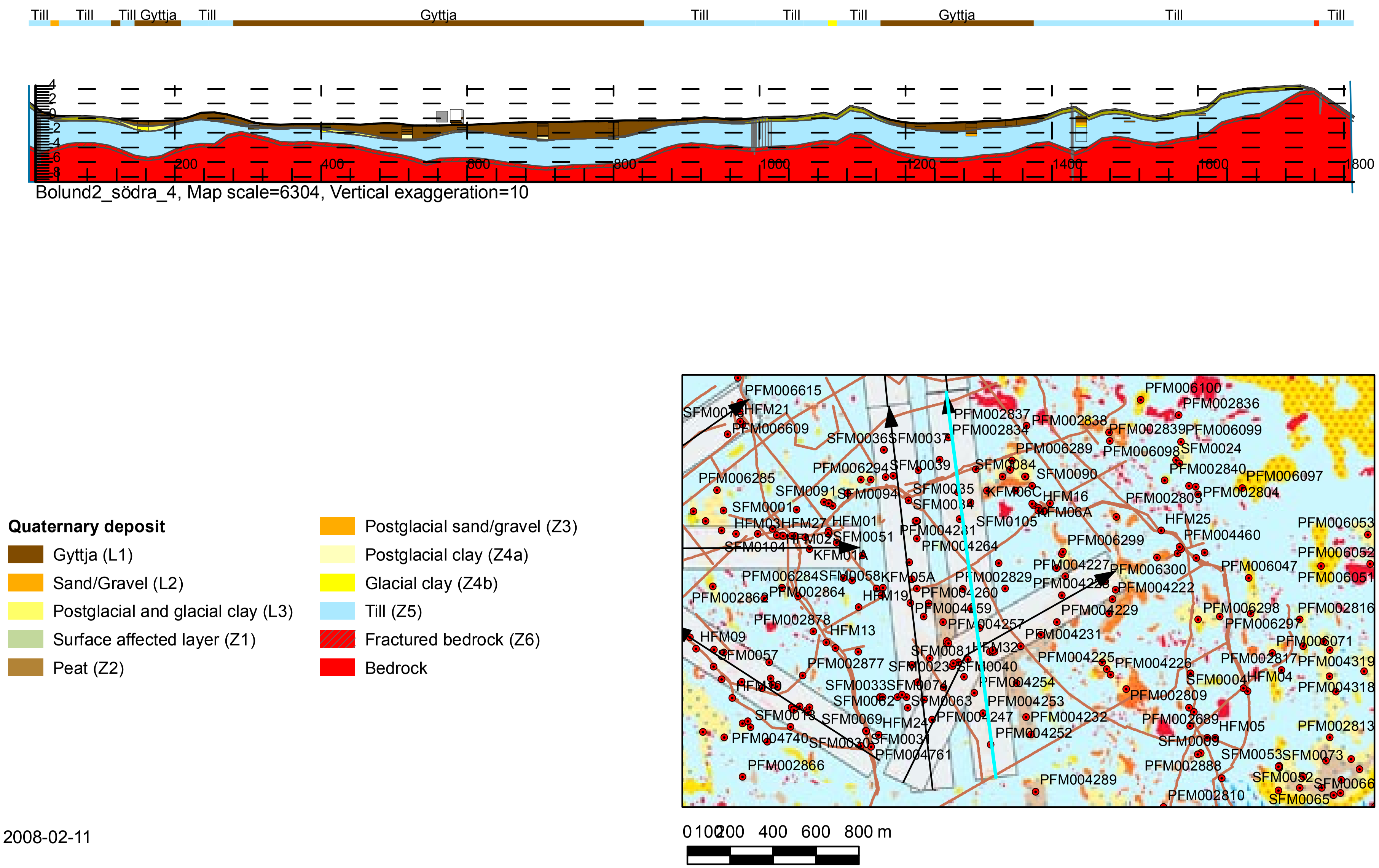


Figure A1-5. Vertical profile showing stratigraphy and total regolith depth along profile "Bolund2_södra".

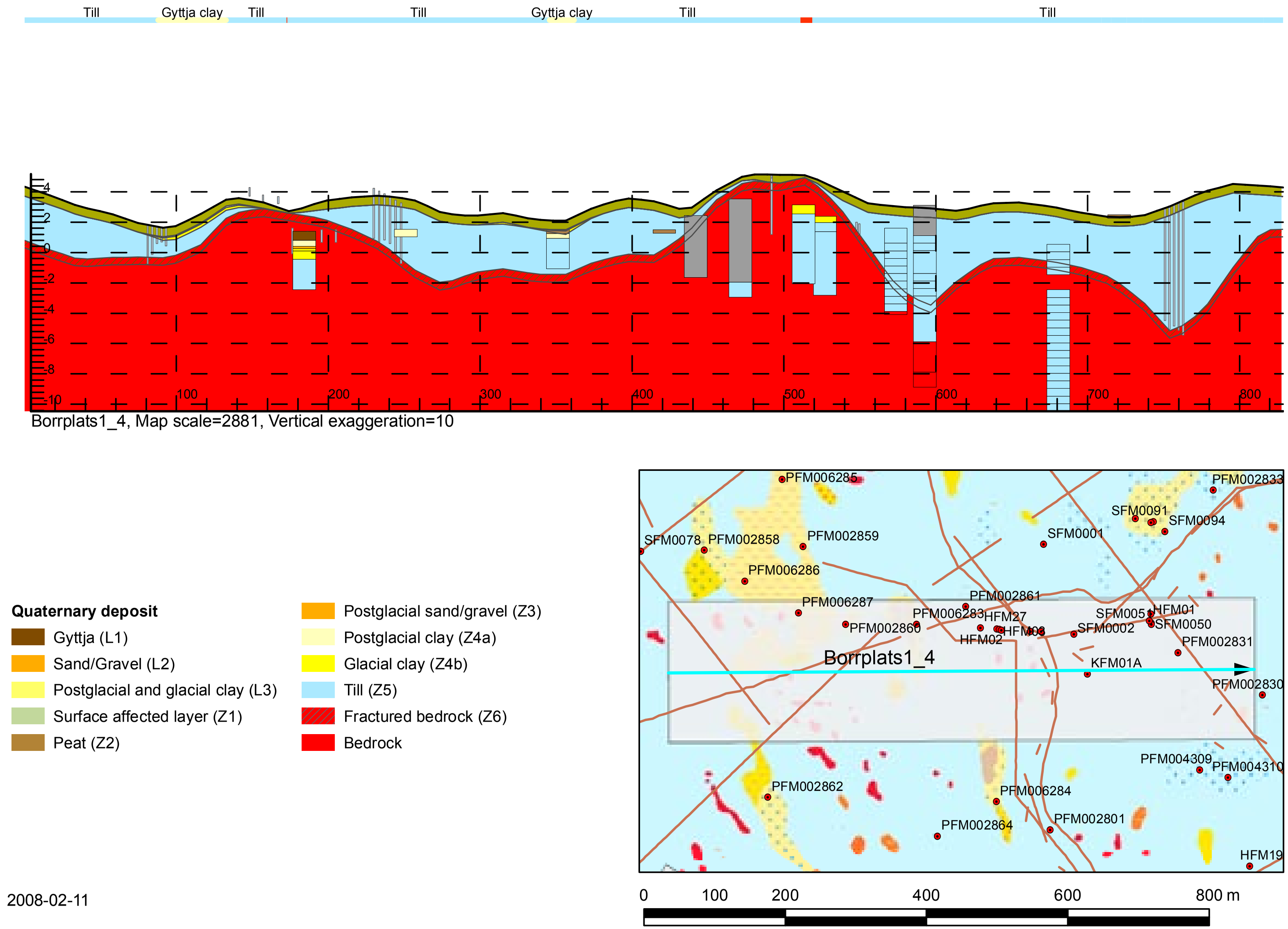


Figure A1-6. Vertical profile showing stratigraphy and total regolith depth along profile "Borrplats 1". For location of the profile, see Figure 4-3.

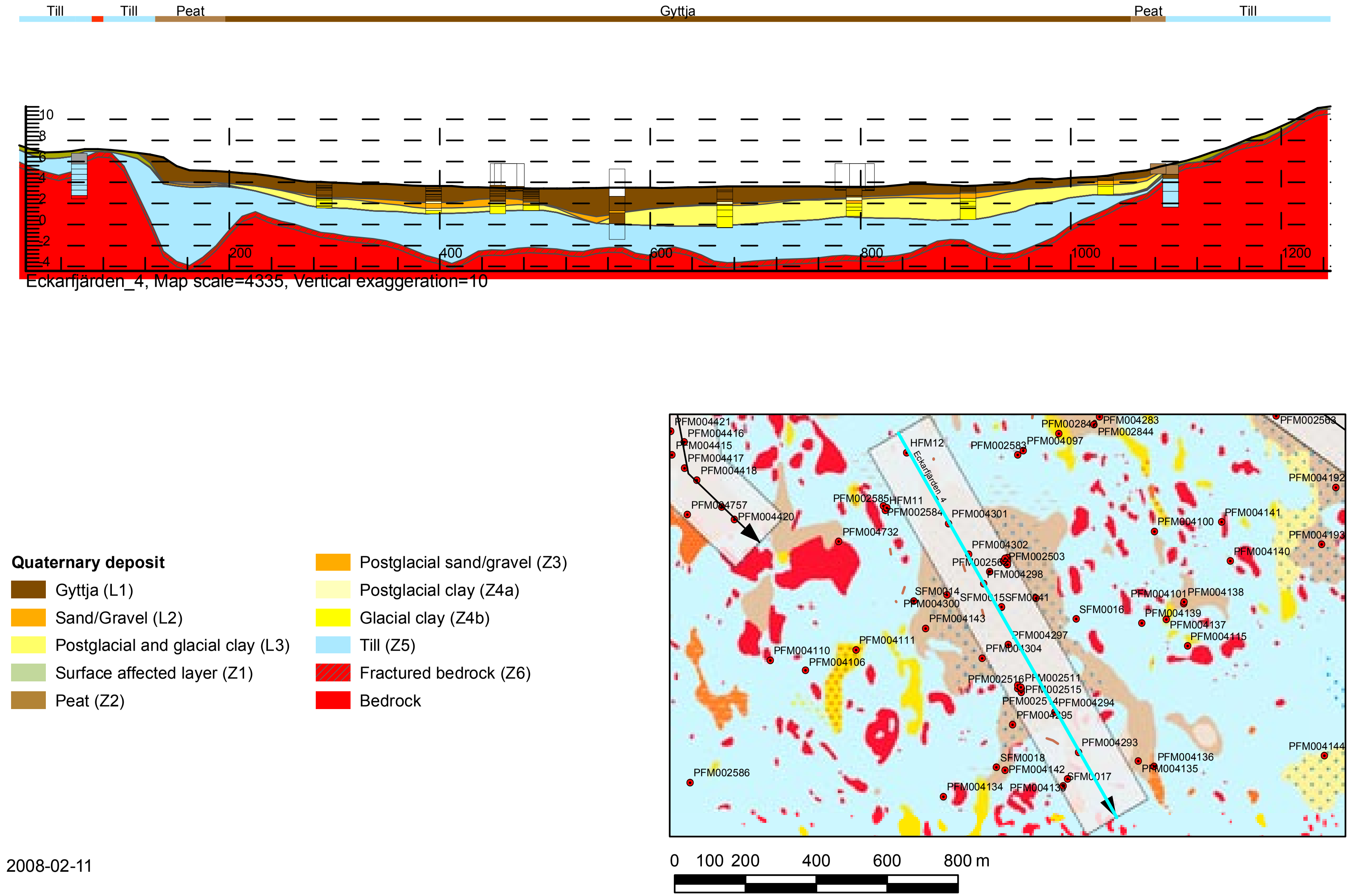


Figure A1-7. Vertical profile showing stratigraphy and total regolith depth along profile "Eckarfjärden". For location of the profile, see Figure 4-3.

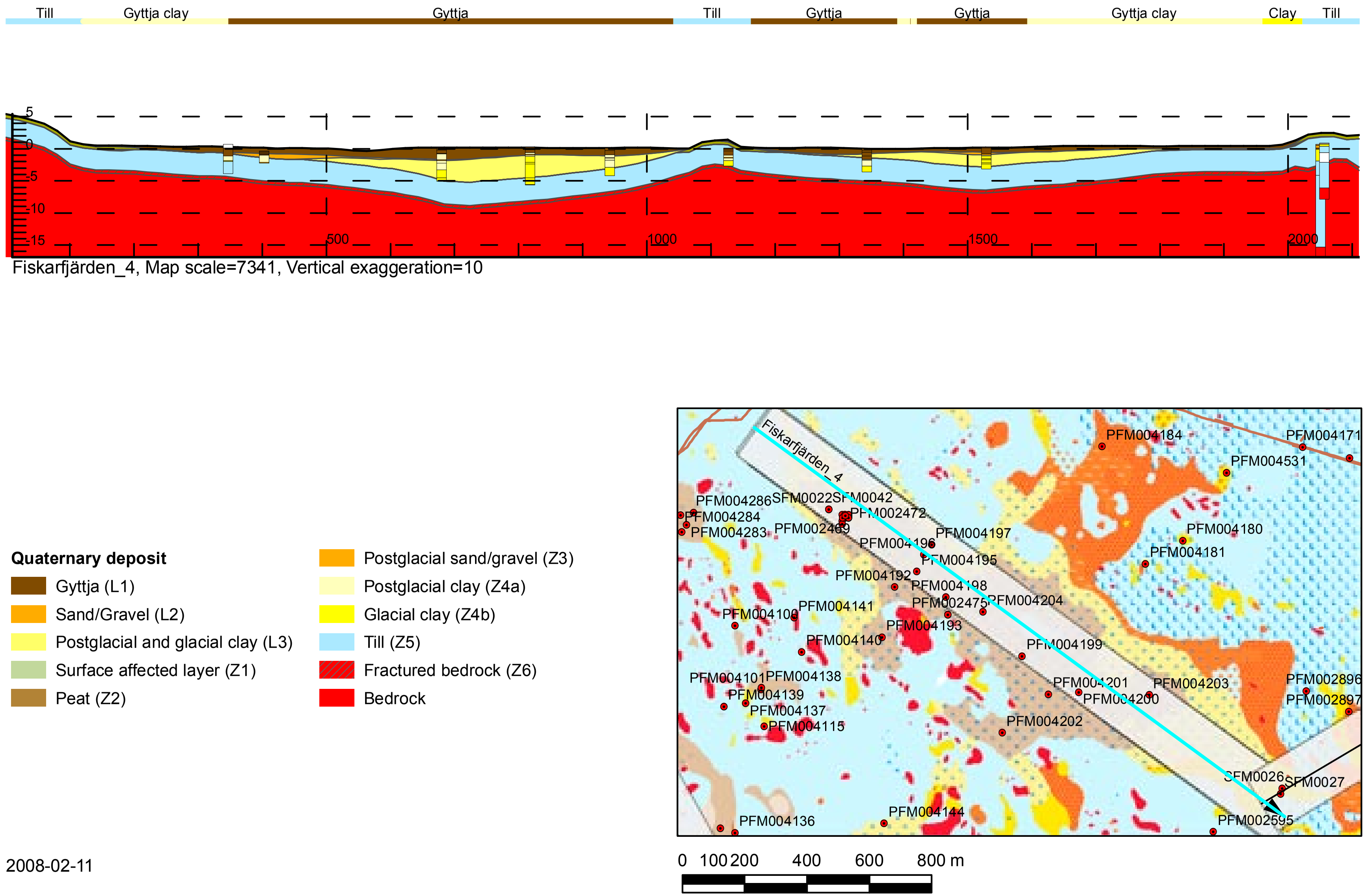


Figure A1-8. *Vertical profile showing stratigraphy and total regolith depth along profile "Fiskarfjärden". For location of the profile, see Figure 4-3.*

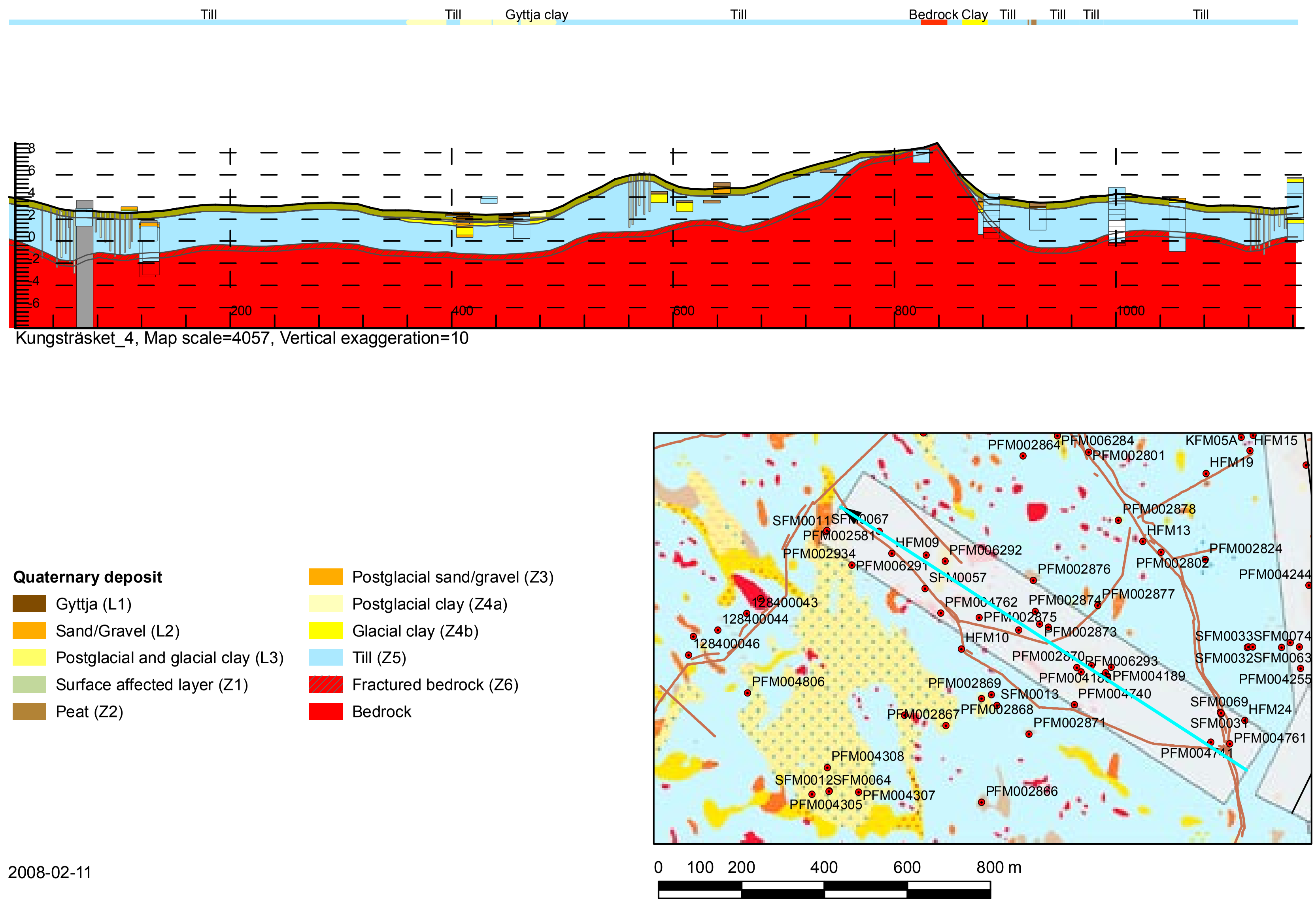


Figure A1-9. *Vertical profile showing stratigraphy and total regolith depth along profile "Kungsträsket". For location of the profile, see Figure 4-3.*

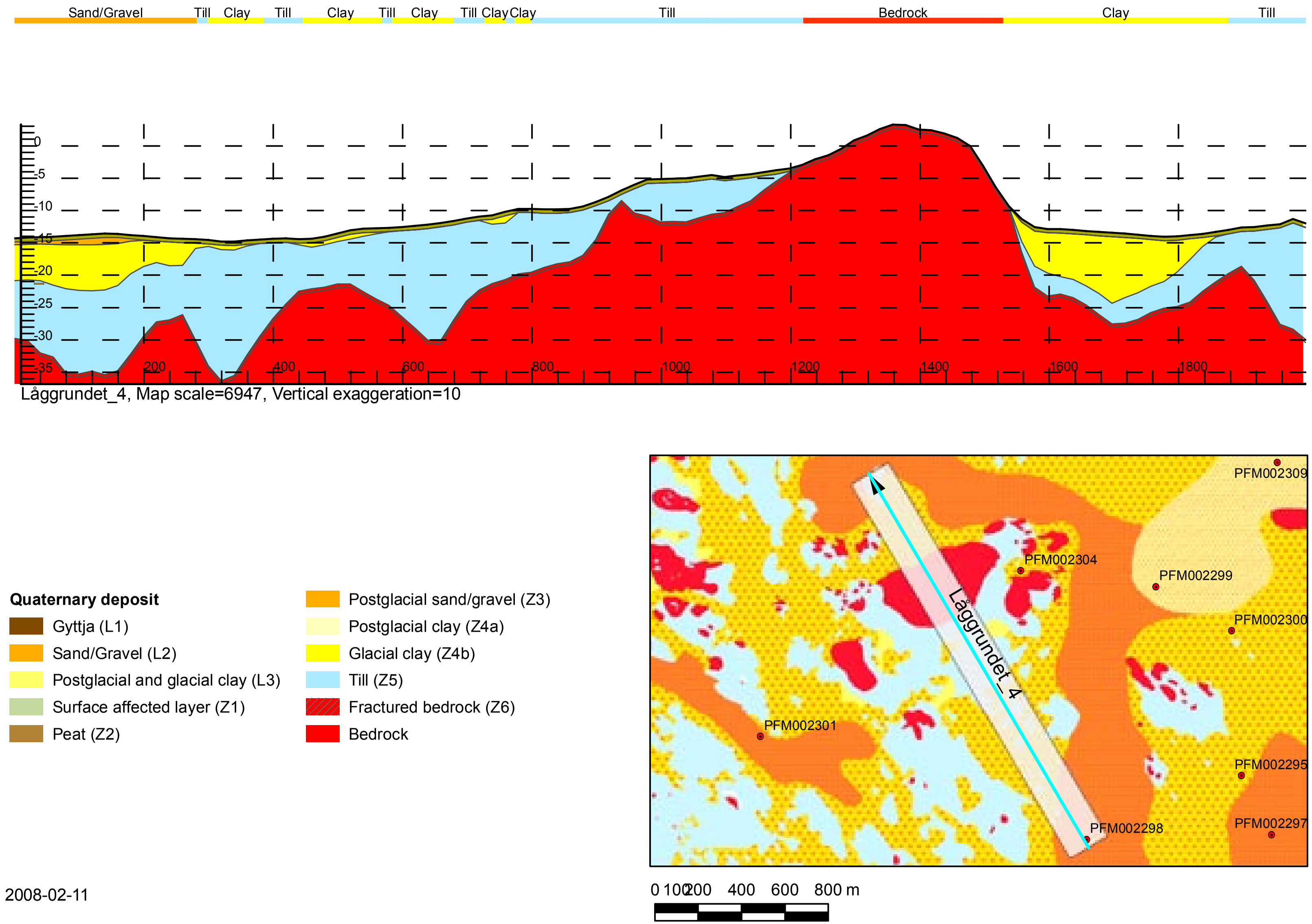


Figure A1-10. *Vertical profile showing stratigraphy and total regolith depth along profile "Långgrundet". For location of the profile, see Figure 4-3.*

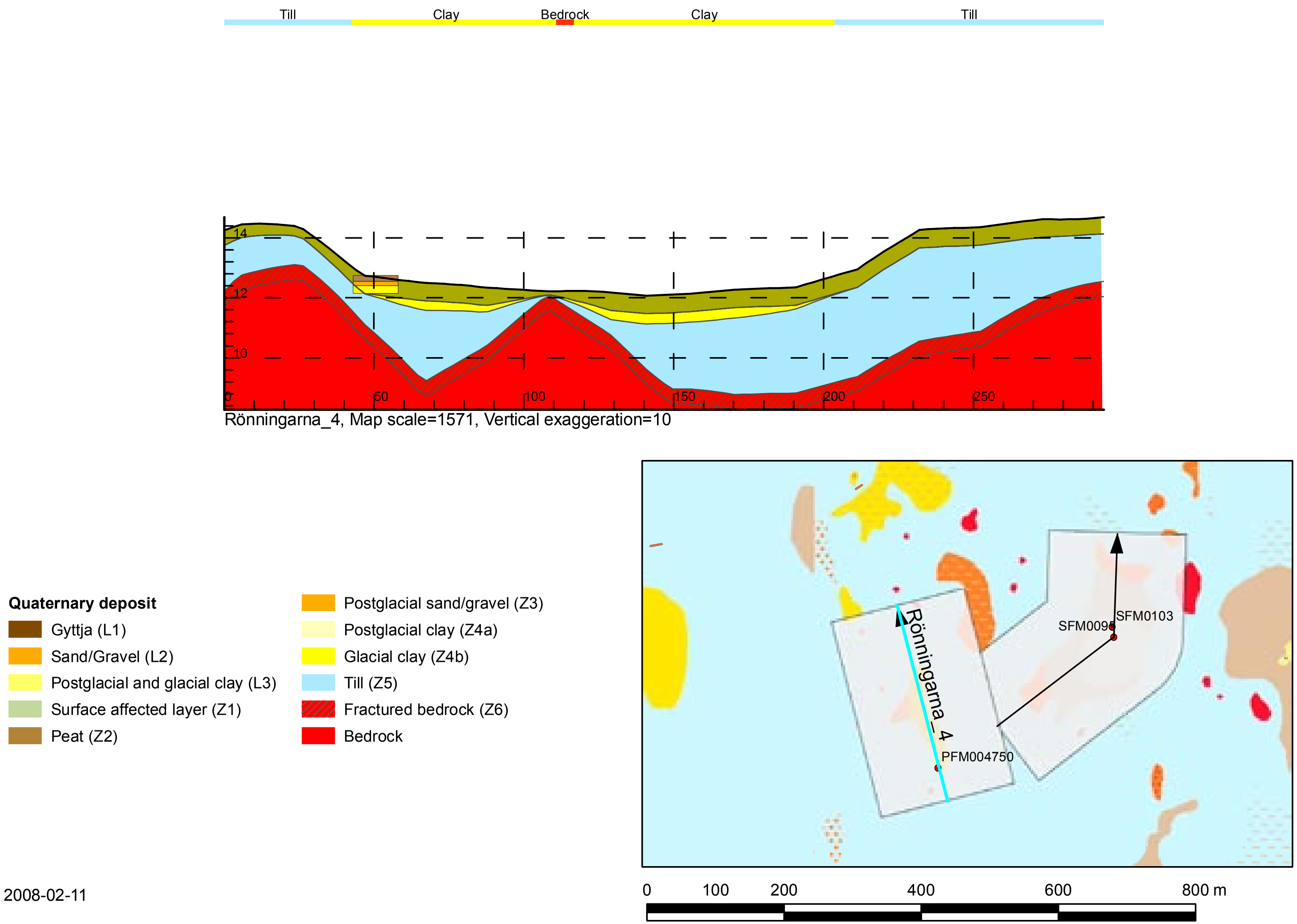


Figure A1-11. *Vertical profile showing stratigraphy and total regolith depth along profile "Rönningarna". For location of the profile, see Figure 4-3.*

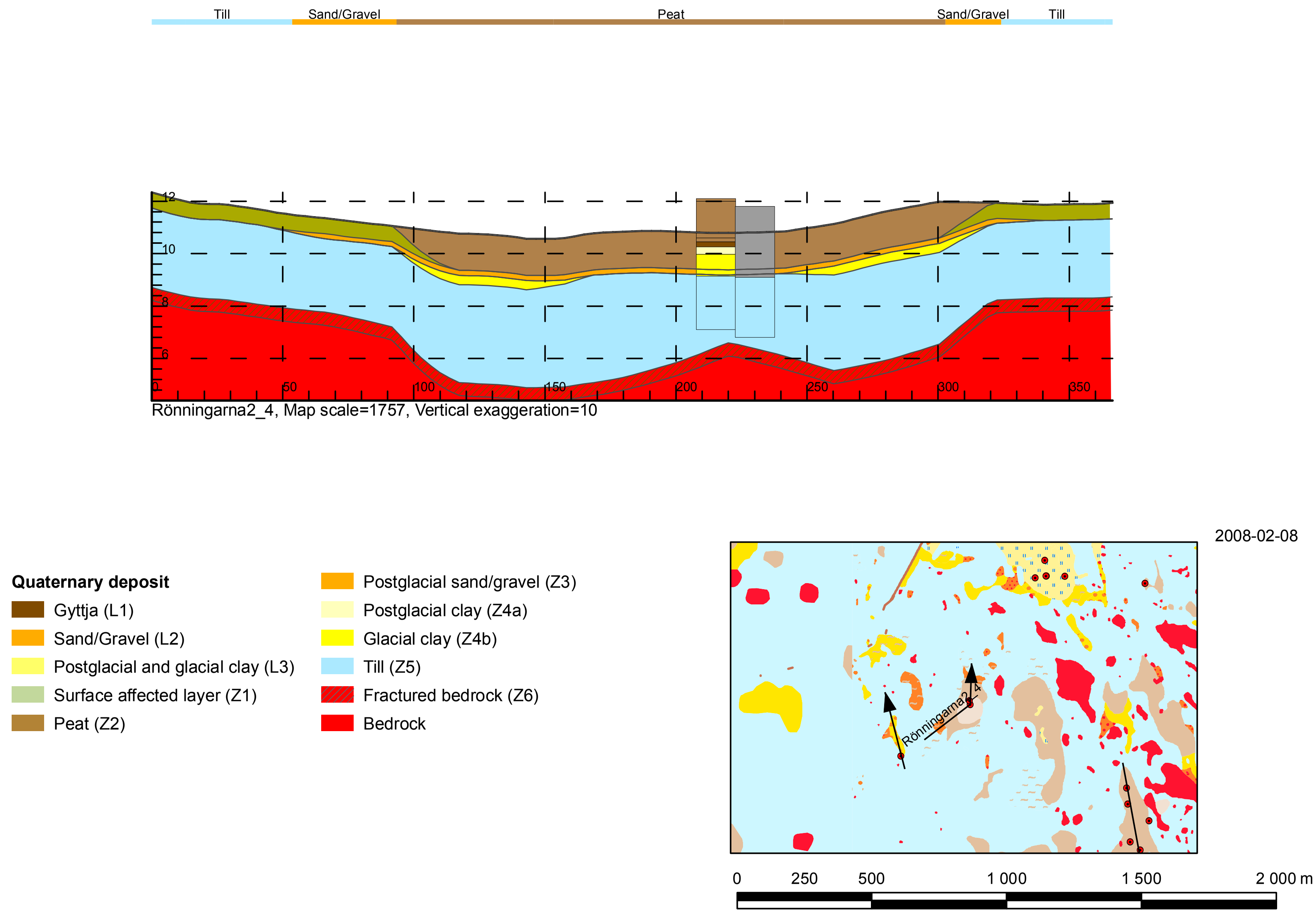


Figure A1-12. *Vertical profile showing stratigraphy and total regolith depth along profile "Rönningarna 2". For location of the profile, see Figure 4-3.*

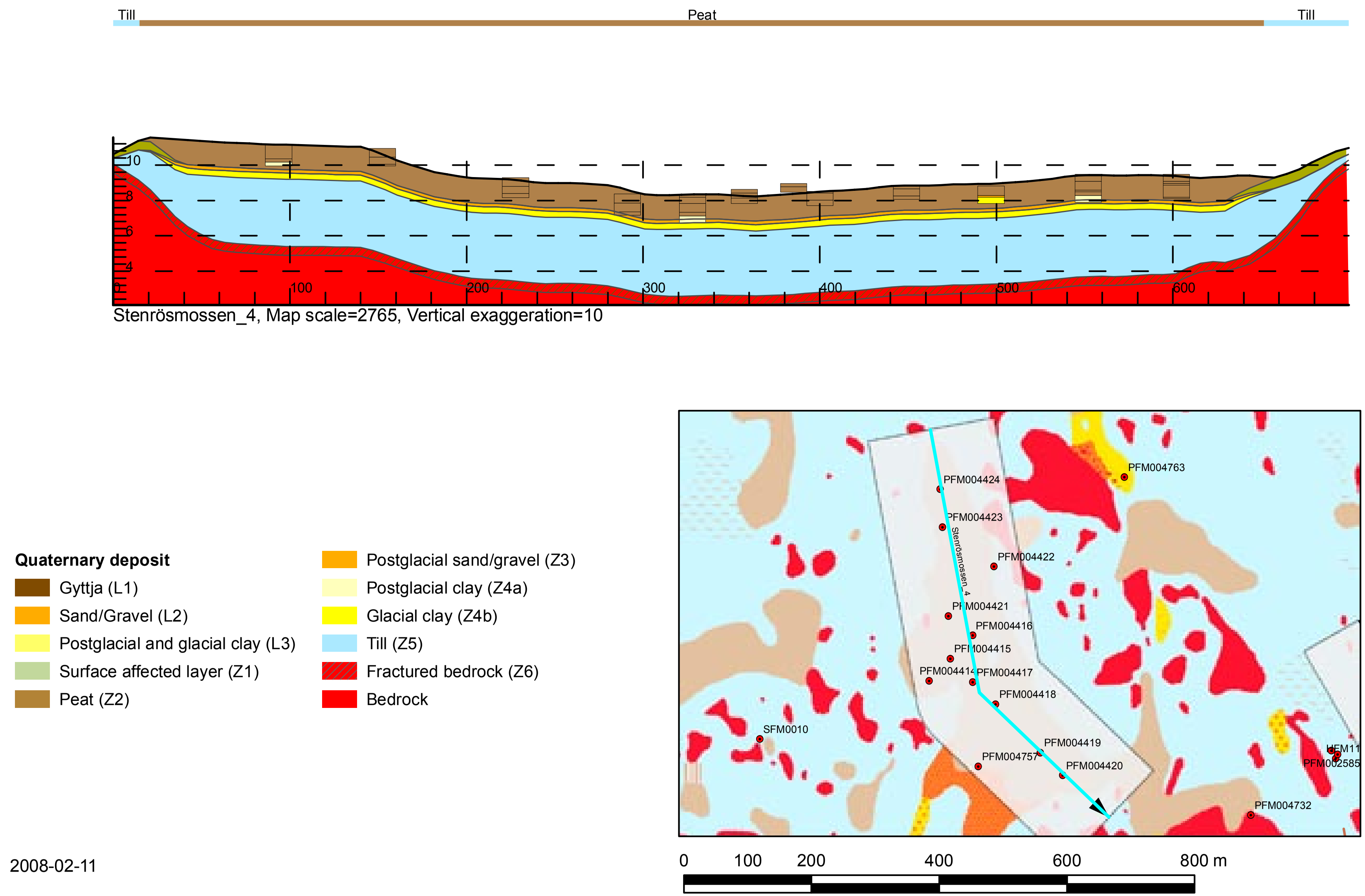


Figure A1-13. *Vertical profile showing stratigraphy and total regolith depth along profile "Stenrösmossen-". For location of the profile, see Figure 4-3.*

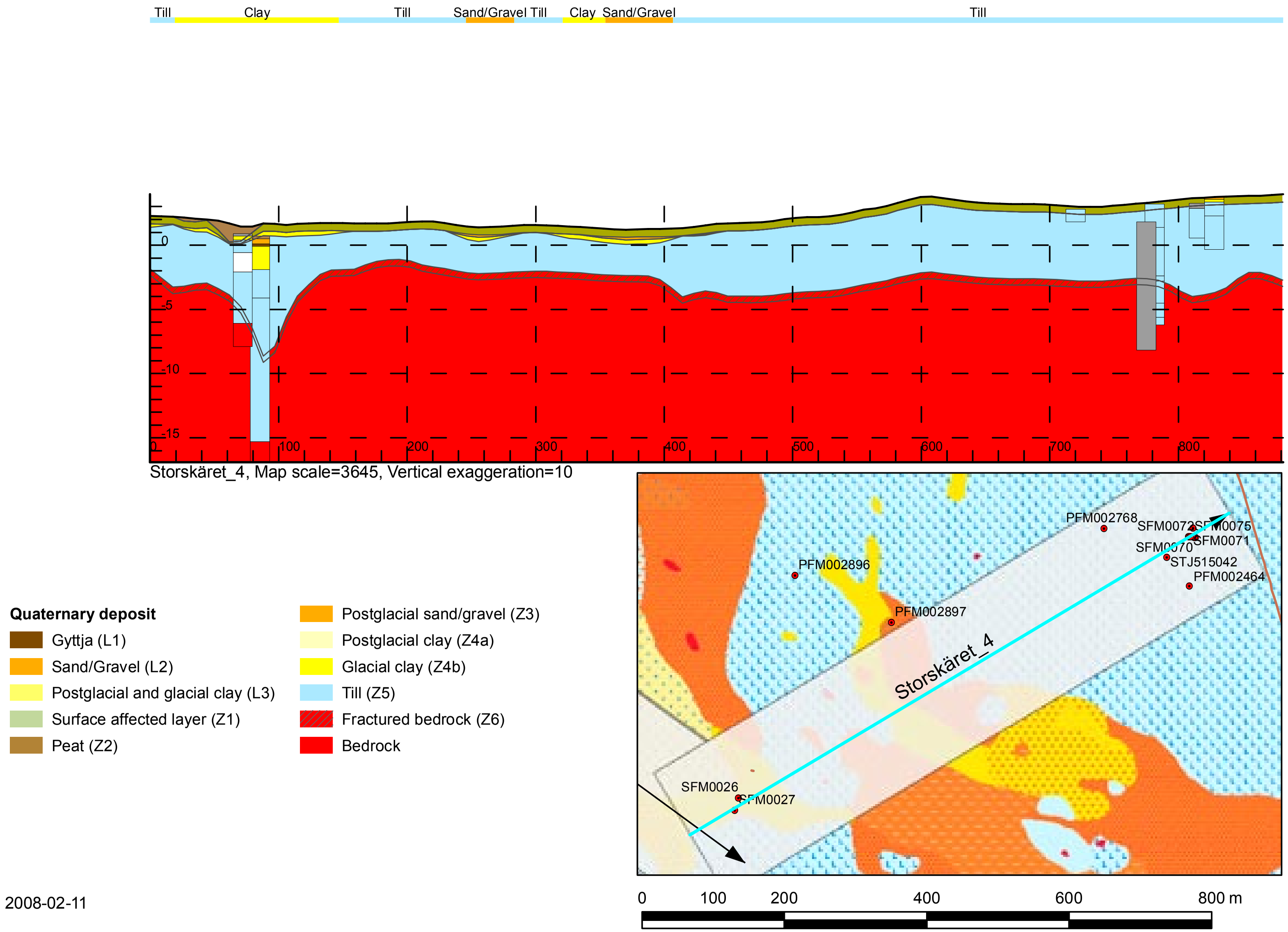


Figure A1-14. *Vertical profile showing stratigraphy and total regolith depth along profile "Storskäret". For location of the profile, see Figure 4-3.*

Appendix 2

The FM RDM 2.2 model

The 2.3 version of the regolith depth model for Forsmark was preceeded by a 1.2 /Vikström 2005/ and a 2.2 version. The 2.2 model was used for hydrological modelling before it was presented and evaluated in any report. When evaluated, the 2.2 model was found not to meet the required quality for further modelling. This Appendix discusses the differences between the 2.2 and 2.3 RDM versions. The reasons for the decision not to use the 2.2 in any future models, of e.g surface hydrology, and to produce a new 2.3 version are also discussed. The data used in the 2.2 version are shown in Table A2-1 and the corresponding data used in the 2.3 version are shown in Table A2-2.

There are three main methodological differences between the two models:

1) In the 2.2 version almost all available regolith depth data was used. In the 2.3 version some data were excluded. The largest data set regarded as uncertain was the data obtained from the helicopter-borne survey. Consequently, the data set used for modelling regolith depth in the terrestrial area is significantly smaller in the 2.3 model compared to the 2.2 model.
2) In both versions the regolith depths were interpolated with the Kriging method. In the 2.3 version domains were defined by using the surface distribution of Quaternary deposits (see Chapter 2). The average regolith depths within the domains 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. In the 2.2 version, average depths were only used in the modelled areas situated outside the Forsmark regional model area.
3) In the 2.2 version the model did not capture some small bedrock outcrops. In the 2.3 model all pixels containing an outcrop were given regolith depth zero.

The 2.2 version of regolith depth in the Forsmark area is shown in Figure A2-1. The difference in absolute depth between the 2.2 and 2.3 versions is shown in Figure A2-2. An evaluation of the 2.2 model showed some uncertainties.

1) There are several areas where regolith depth interpreted from the helicopter-borne data show values larger than the values recorded with any of the other applied methods. This was especially notable in the terrestrial parts of the coastal area. For example at some of the small islands with a high frequency of exposed bedrock, regolith depth exceeding 20 m was presented in the helicopter-borne data. All other available data suggests a thin coverage of regolith in these areas.
2) The helicopter-borne data was compared with data obtained from other surveys e.g. coring and ground geophysical measurements. Data points situated within 10 metres from the closest point from the helicopter-borne survey were included in the comparison. The correlation between the two data sets is not acceptable (Figure A2-3). All data used in the regolith depth model have uncertainties. However, all applied methods, with the exception of the helicopter-borne survey, have been used in other regolith depth surveys.
3) The duplicate points obtained from the helicopter-borne survey show large variations in regolith depths at some points within the data set. Differences of more than 20 m were recorded.
4) Some small areas shown as exposed bedrock on the QD map have regolith depths of several metres.
5) In the marine area and in some of the lakes the modelled regolith depths are almost zero in many areas with a low density of depth data. This accounts for large areas where clay is presented on the QD map. All available data shows that the regolith depth is several metres in clay covered areas.

Due to the above described uncertainties, it was decided that the 2.2 model version was replaced with a 2.3 version. It was decided to omit the helicopter-borne data in the 2.3 model since these data contain too large uncertainties. To avoid too thin regolith depths in areas where large depths can be expected it was decided to use the average regolith depths in areas where no data is available. Finally it was decided to give the bedrock outcrops a higher dignity in the new model. In the 2.3 version all pixels containing an outcrop have therefore regolith depth zero.

The same conceptual model for the stratigraphical distribution of regolith was used in the two models. The same stratigraphical subdivision of the deposits in L- and Z-layers was consequently used in the two models (see Chapter 3). The differences between the 2.2 and 2.3 models are presented in the section below.

The comparison between the two models (Figure A2-2) shows that the regolit depth in the lakes and marine areas is generally larger in the new 2.3 model. In the terrestrial areas the regolith depth is generally thinner in the 2.3 model, especially in the coastal area. Figure A2-4 shows total depth and stratigraphy in a vertical profile through Lake Bolundsfjärden obtained from the 2.2 version of the regolith depth model. Figure 4-4 shows the same profile from the 2.3 version. A comparison between the two profiles clearly shows that the 2.2 version shows a thinner total regolith cover in the lake and a thicker layer in the surrounding terrestrial areas compared to the 2.3 version.

Database used for interpolation of raster surfaces included in the regolith depth model version 2.2

This section gives a description of the data used in the 2.2 version. The lower boundary of Z5 corresponds to the bedrock surface. For both the 2.2 and 2.3 versions a Z5 database was produced and used to model the total depth of the regolith (Tables A2-1 and 3-4). Databases for the thickness of the other Z-layers were also used in the two versions.

In the 2.2 version data obtained from a helicopter-borne geophysic survey /Rönning et al. 2003/ was used. This survey produced a huge set of data from a large part of the terrestrial part of the Forsmark regional model area. The regolith depth have earlier been calculated by inversion of the electromagnetic measurements from the helicopter-borne survey /Thunehed 2005/. These regolith depths were used in the 2.2 version. All observations with a regolith depth larger than 30 m were however removed since these large regolith depths were regarded as unreliable. The regolith depths obtained from areas close to lakes and power transmission line have large uncertainties /Thunehed 2005/. All observations closer than 50 m from lakes and 80 m from power transmission lines respectively were therefore removed. The data set contains several duplicate observation points with a difference in the depth value. Some values have a large difference, other just a small. Only duplicate points with a standard deviation less than ± 0.5 m is used in the model. All measurement points from the inversion of helicopter-borne electromagnetic measurements within 30 m from other observation points were removed.

Areas shown as bedrock outcrops on the QD map have a regolith depth of zero (0.1 m) in both models. In the 2.2 version only points from the 20 m DEM /Strömgren and Brydsten in prep/ situated completely within the bedrock outcrop surfaces shown on the QD map were used in the Z5 database. A number of small outcrops were consequently not captured in the 2.2 database of the bedrock surface. In the 2.3 database all outcrops are included.

In both versions seismic and sediment echo sounding data /Elhammer and Sandkvist 2005/ were included in the Z5 database. During the 2.3 modelling work it was revealed that the data from the detailed marine area has a higher reliability than depth data from the regional area (cf. Chapter 5). Data from the regional mapping that was located within 100 m from data from the detail mapping was therefore excluded in the 2.3 version.

In the 2.2 version all observations points not reaching bedrock surface, within 30 m from observation points reaching bedrock surface were excluded from the Z5 database. A temporary Z5 database was constructed without observation points not reaching the bedrock surface. A raster surface was then interpolated, and all observation points not reaching bedrock with higher elevation levels than the interpolated raster surface were removed. All observation points reaching bedrock were included in the final Z5 database.

Except for the buffering off helicopter-borne data and other data there was no buffering between regolith depth data obtained from different methods in the 2.2 model. In the 2.3 model regolith depth data situated within 30 metres (or 100 m in the marine area) from data with a higher confidence were not used (cf. Table A2-2).

For the 2.2 model, the average regolith depth was calculated from data obtained within the terrestrial part of the model area. That value (4.6 m) was included in the Z5 database and used in areas outside the regional model area that were included in the area modelled for regolith depths. These points are referred to as supporting points in Table A2-1. This was done since these areas have a low density of measured data. The average regolith depth values were, however, not included in the database within 30 m from actual observation points (e.g. helicopter-borne data and bedrock outcrops). No other average QD depth values were included in the 2.2 version of the Z5 database. In the 2.3 version average regolith depths were used in any areas with a low density of data. The number of supporting points used in the 2.3 version is therefore much larger compared to the number used in the 2.2 version (Tables A2-1 and A2-2).

Data included in the databases used for the version 2.2 interpolation of the sand/gravel (Z3), postglacial clay (Z4a), and glacial clay (Z4b) raster layers are shown in Table A2-1.

Data from the marine seismic and sediment sounding survey were included in these databases. However, only data from areas shown as postglacial sand/gravel on the QD map were included in the Z3 database. Data from marine areas mapped as postglacial clay and glacial clay were included in the Z4a and Z4b databases respectively. In order to force the Z3 layer up to the regolith surface, supporting points were placed every 10 metres along the boundary between Z3 and other deposits shown on the QD map. These points are referred to as extension points in Table A2-1. Due to the lower number of data from areas mapped as glacial clay (Z4a), extension points were only placed every 100 metres along the Z4a boundary. It was not necessary to include any extension points in the Z4b database. The extension points were given elevation levels from the 20 m DEM /Strömgren and Brydsten in prep/. Extension points were also used in the 2.3 version (Table A2-2, see Chapter 3.3.1). In contrary to the 2.3 version, no average QD depth values were included in the databases for the Z3, Z4a, and Z4b raster layers.

In the 2.3 model version, some of the measurements from the ground penetrating radar was omitted since an evaluation showed that the data set presented a thinner regolith cover than neighbouring measurements using other methods /Marek 2004b/. Most of the results from other methods are from the seismic survey carried out by /Bergman et al. 2004/. /Marek 2004b/ concluded that the data from the ground penetrating radar gave poor data along some of the investigated profiles. It was decided to omit the ground penetrating radar data when these results were conflicting with other data.

In order to enhance the comparison between the RDM version 2.2 and 2.3, profiles with the same distribution are presented in Chapter 4 and Appendix 1 and below in Figures A2-5 to Figure A2-15. For localisation of the profiles, see Figure 4-3.

Table A2-1. Data used for interpolation of the 2.2 version of the regolith model. The Z5 data was used for interpolation of the bedrock surface. Data for modelling the lower boundaries of glacial clay, postglacial clay and postglacial sand/gravel in the marine areas are referred to as Z4b, Z4a and Z3 respectively.

Datasource (number of points)	**Layer** Z5	Z4b	Z4a	Z3
Seismic and sediment echo sounding data	162,553	108,421	6,935	46,045
Other data reaching bedrock	13,771			
Data not reaching bedrock	80			
Total thickness of individual Z layers		9	–	136
Helicopter-borne electromagnetic measurements	135,247			
Bedrock outcrops	42,811			
Supporting points	24,362			
Extension points		–	10,192	5,454
Total number of points	**378,824**	**108,430**	**17,127**	**51,635**

Table A2-2. Data used for interpolation of the 2.3 version of the regolith model.

Data source (no of points)	**Layer** Z5	Z4b	Z4a	Z3
Seismic and sediment echo sounding data	147,151	101,551	6,894	19,514
Other data reaching bedrock	18,119			
Data not reaching bedrock	3			
Total thickness of individual Z layers		8	1	1
Helicopter-borne electromagnetic measurements	0			
Bedrock outcrops	88,945			
Supporting points	283,529	108,165	38,133	2,646
Extension points		23,675	4,189	3,032
Total no of points	**527,747**	**233,399**	**49,217**	**25,193**

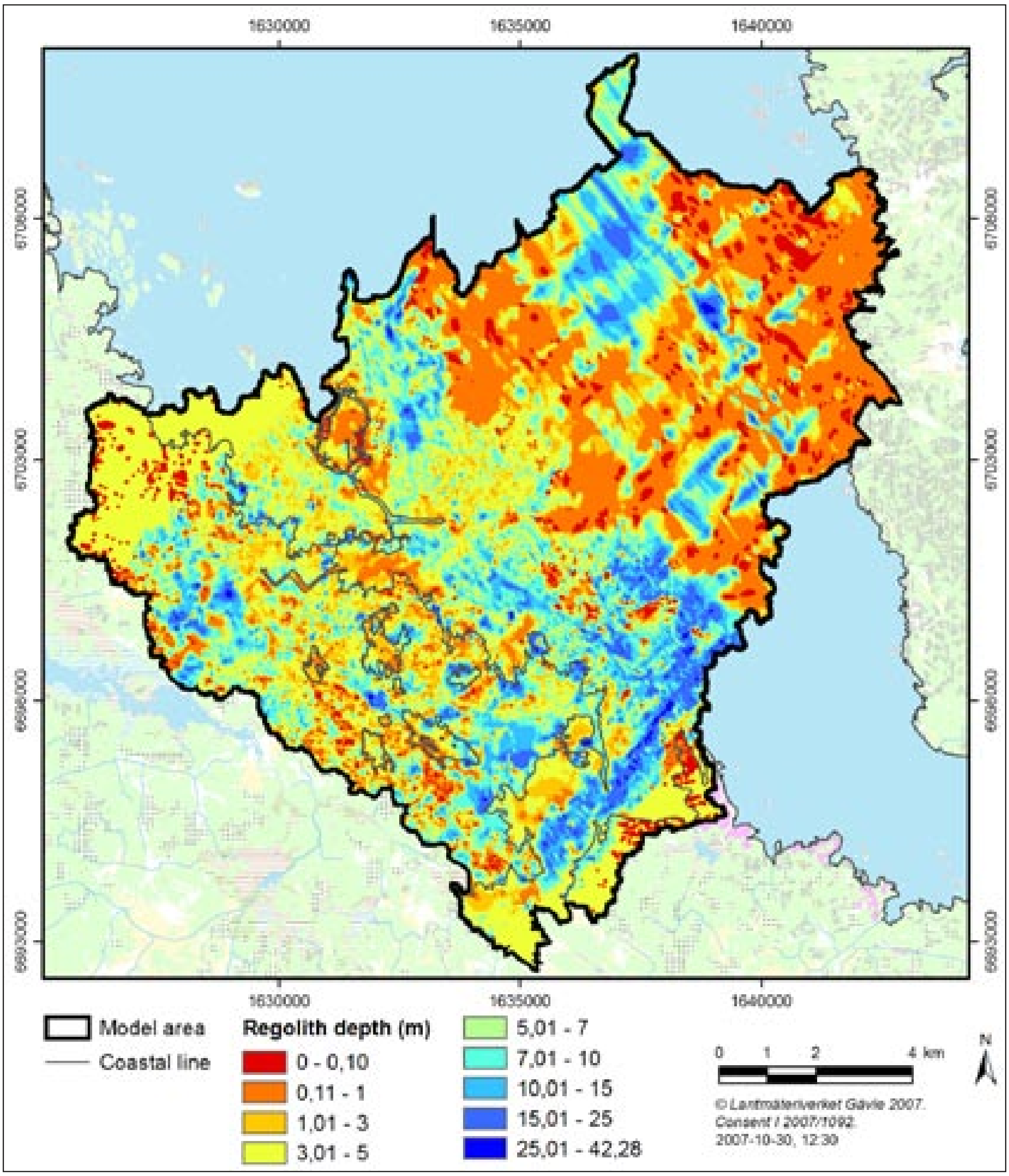


Figure A2-1. *Modelled regolith depths from version 2.2.*

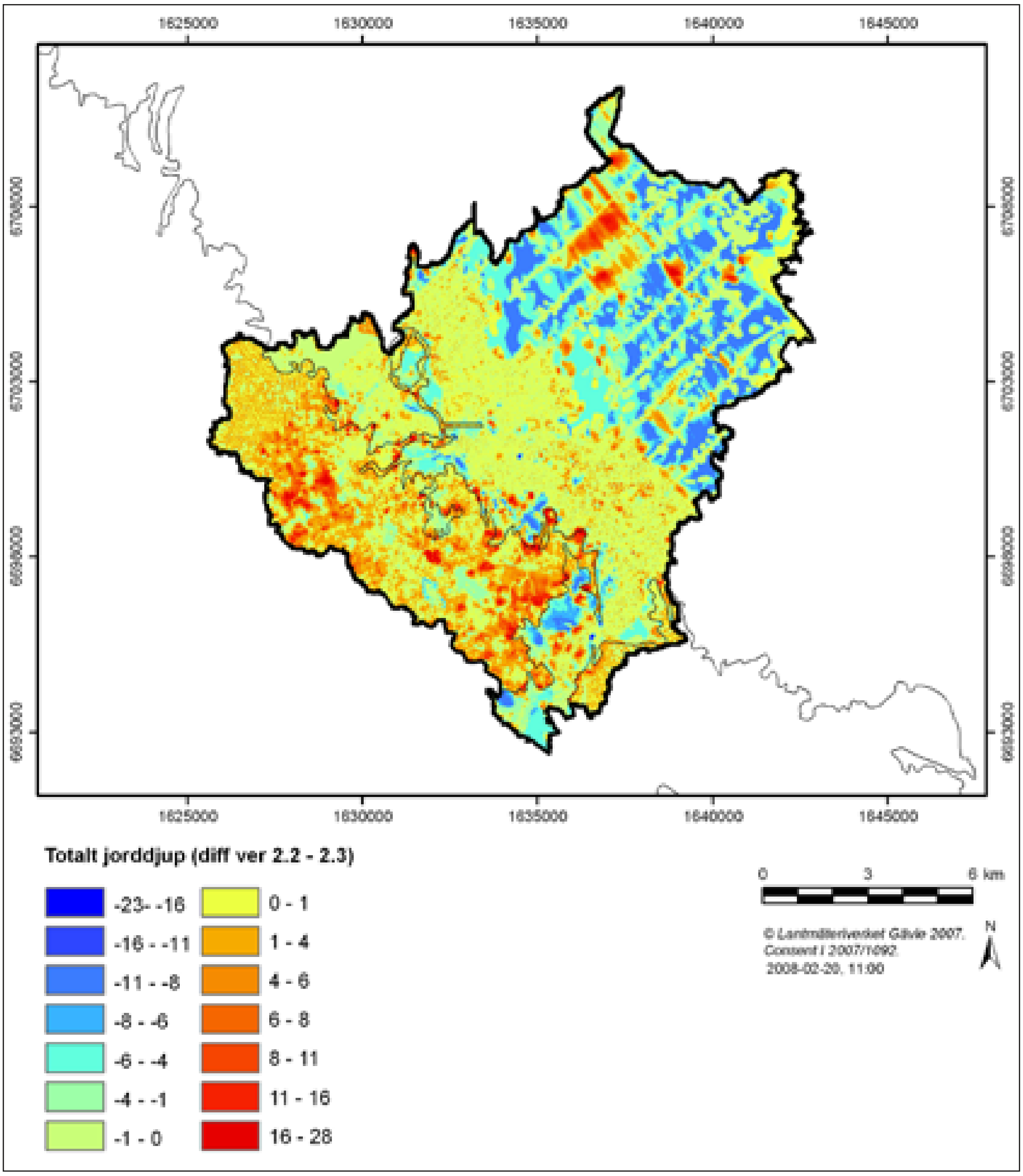


Figure A2-2. *The difference in meter between the 2.2 and 2.3 versions of regolith depth models. The values shown on the map were calculated as regolith depths from the 2.2 version minus regolith depths from the 2.3 version. Orange areas have significantly thinner regolith depths in the 2.2 version, whereas blue areas have a significantly larger regolith depth in the 2.2 version compared to the 2.3 version respectively.*

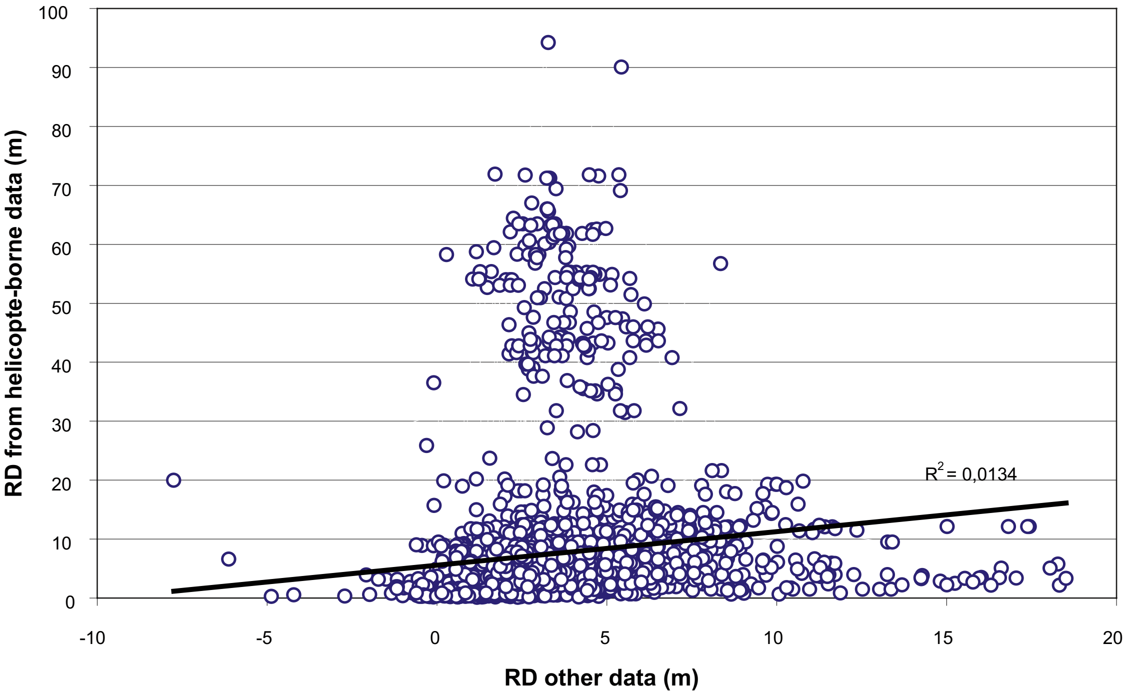


Figure A2-3. The correlation between regolith depths obtained from the helicopter-borne survey and other data used in the 2.2 version of the regolith depth model. There is no correlation between the two sets of data and the helicopter-borne data was therefore not used in the 2.3 version.

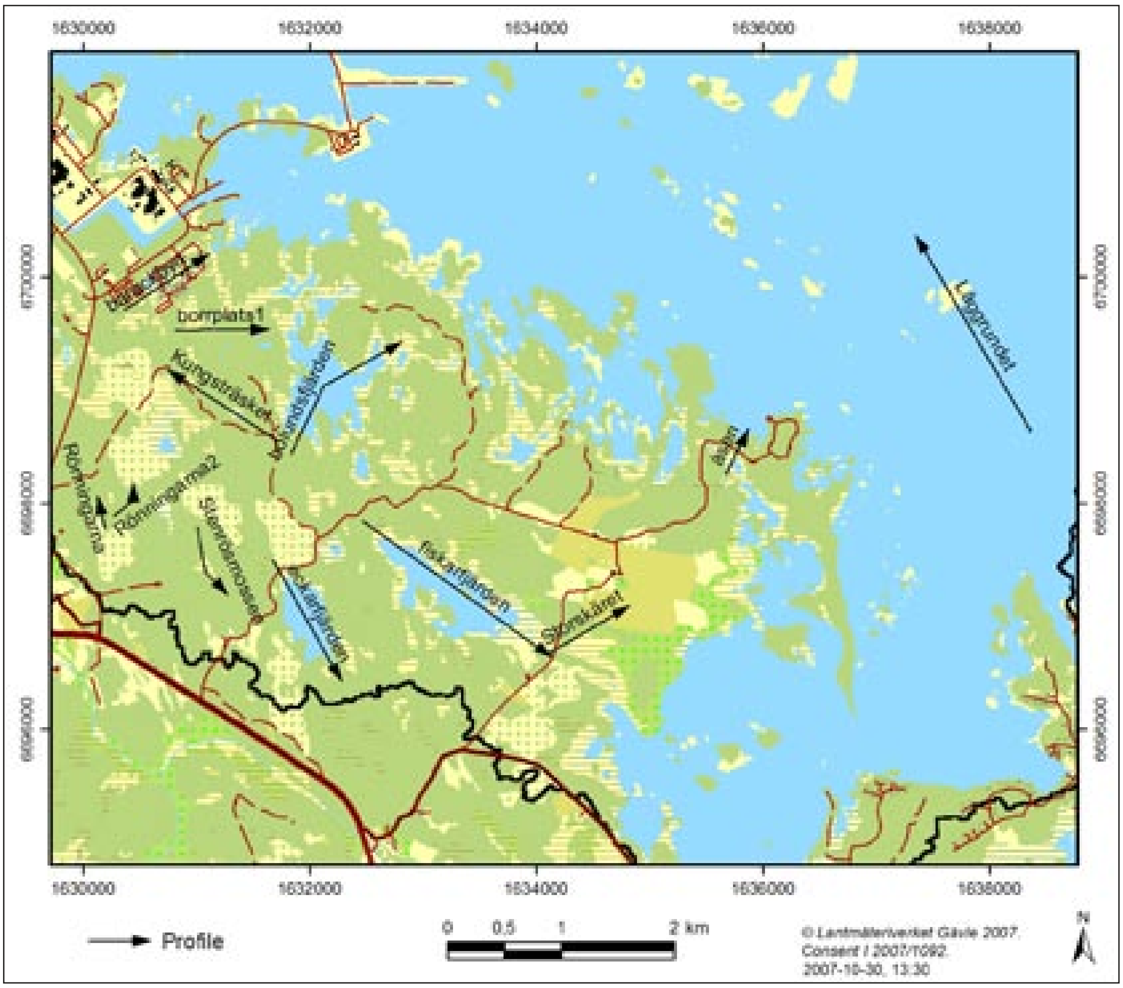


Figure A2-4. The location for the vertical profiles showed in Figures A2-5 to A2-15. The same profiles are presented in the main report, showing the results of the 2.3 model version.

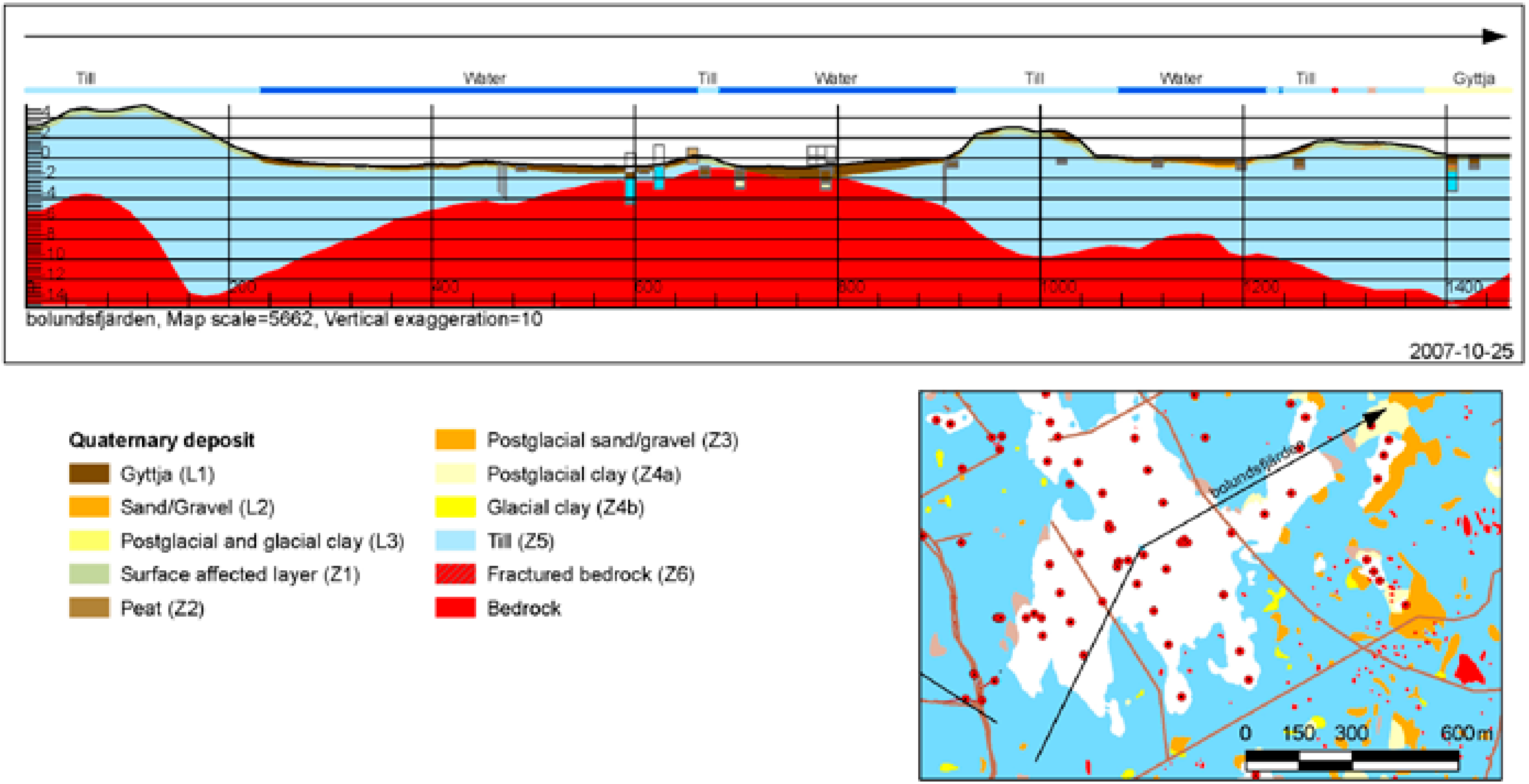


Figure A2-5. *Vertical profile showing the stratigraphy and total regolith depths (version 2.2) along a profile from Lake Bolundsfjärden. Figure 4-4 shows the same profile obtained from the 2.3 version. A comparison between the two profiles clearly shows that the 2.2 version shows a thinner regolith cover in the lake and a thicker layer in the surrounding terrestrial areas compared to the 2.3 version. For location of the profile, see Figure A2-4.*

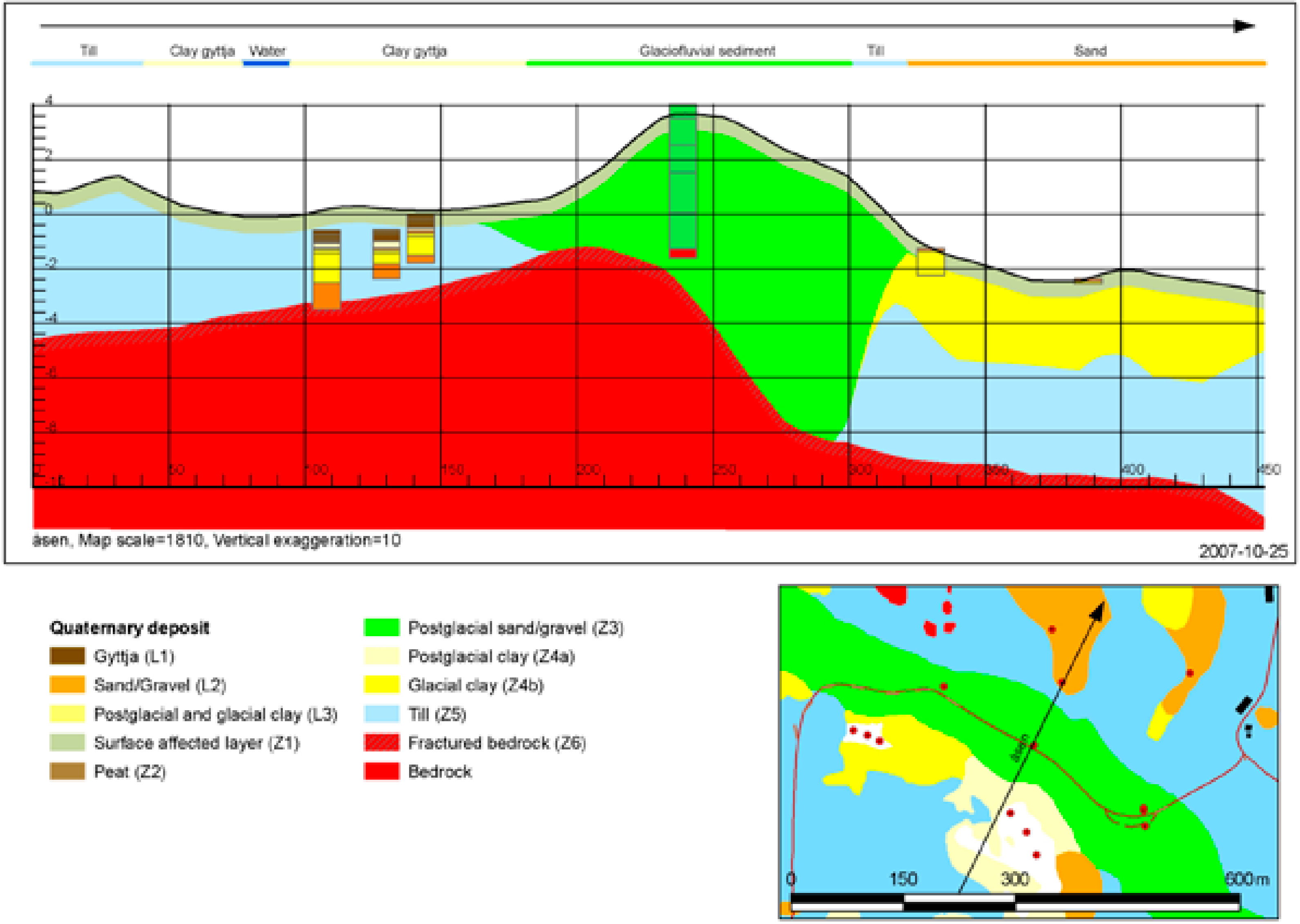


Figure A2-6. Vertical profile (version 2.2) showing stratigraphy and total regolith depth along profile "Åsen". For location of the profile see Figure A2-4.

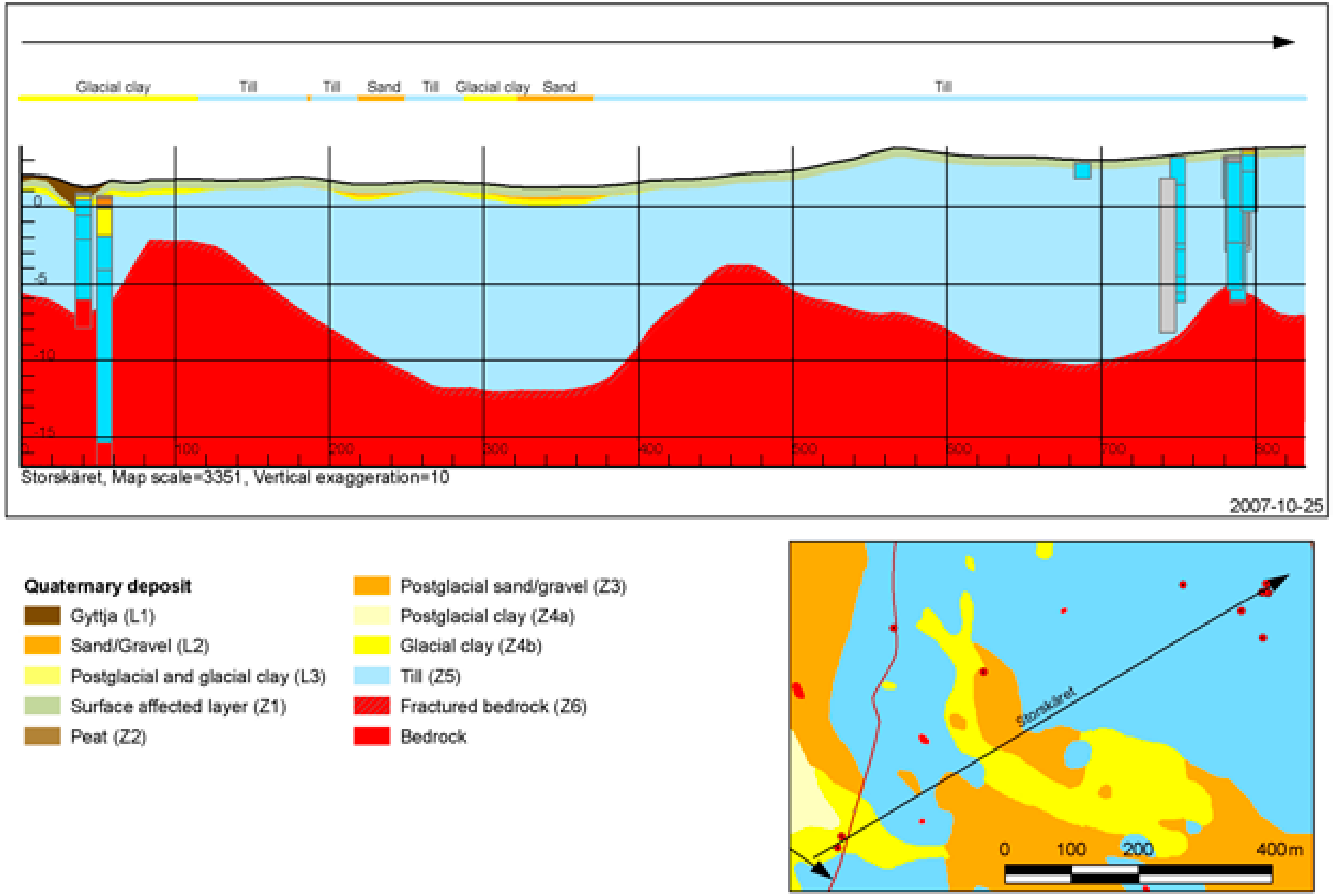


Figure A2-7. *Vertical profile (version 2.2) showing stratigraphy and total regolith depth along profile "Storskäret". For location of the profile, see Figure A2-4.*

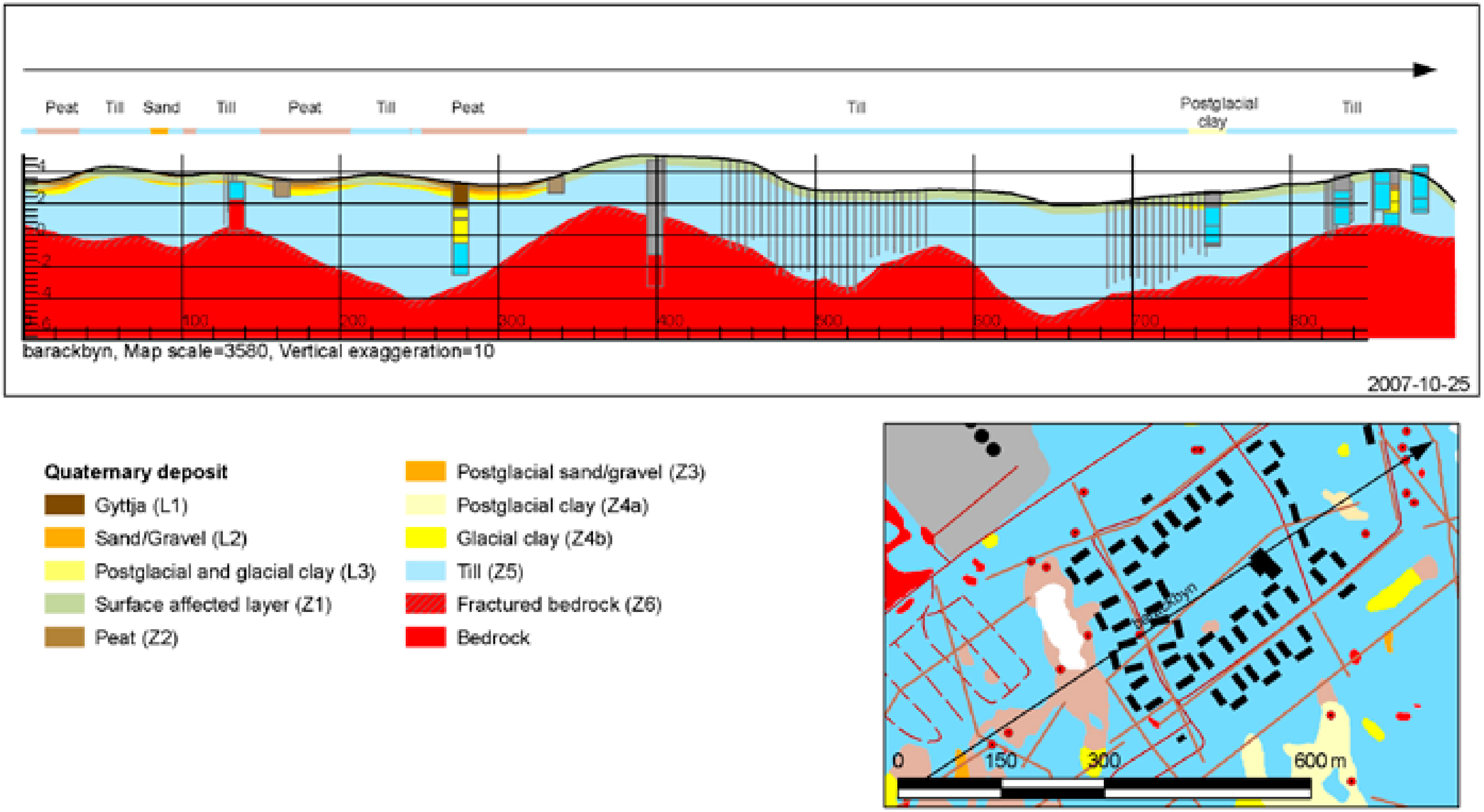


Figure A2-8. *Vertical profile (version 2.2) showing stratigraphy and total regolith depth along profile "Bolundsfjärden". For location of the profile see Figure A2-4.*

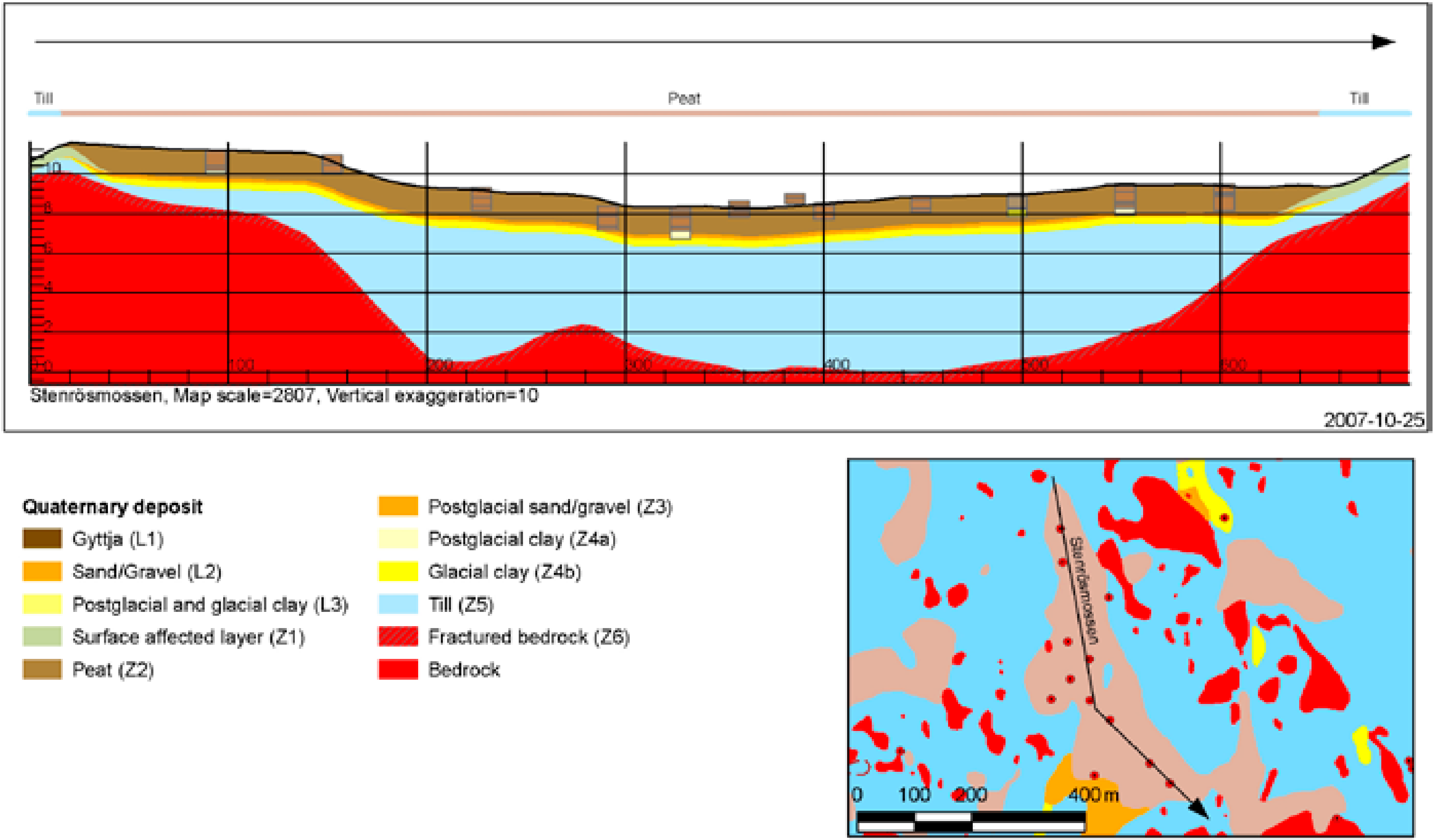


Figure A2-9. *Vertical profile (version 2.2) showing stratigraphy and total regolith depth along profile "Stenrösmossen". For location of the profile see Figure A2-4.*

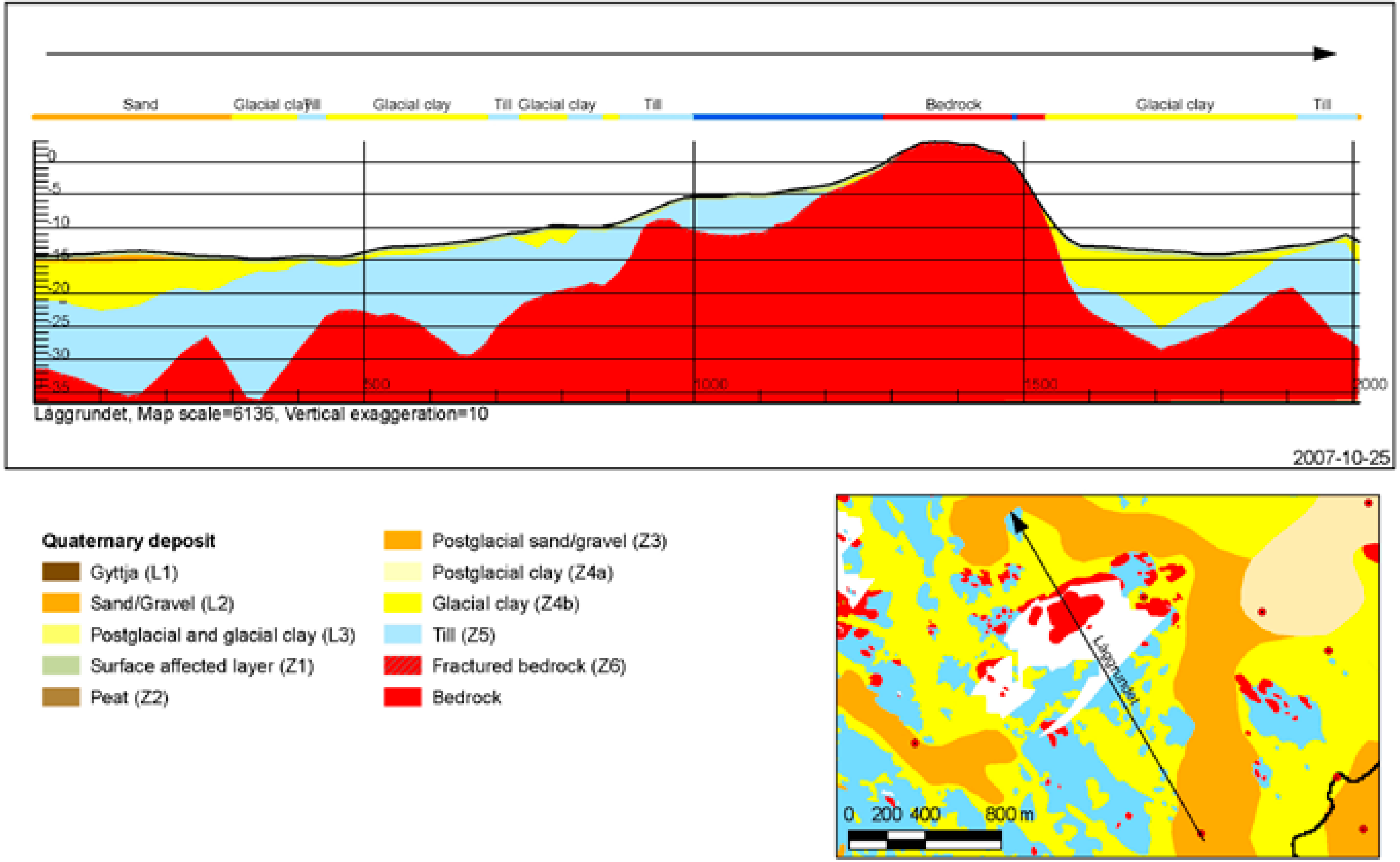


Figure A2-10. *Vertical profile (version 2.2) showing stratigraphy and total regolith depth along profile "Låggrundet". For location of the profile, see Figure A2-4.*

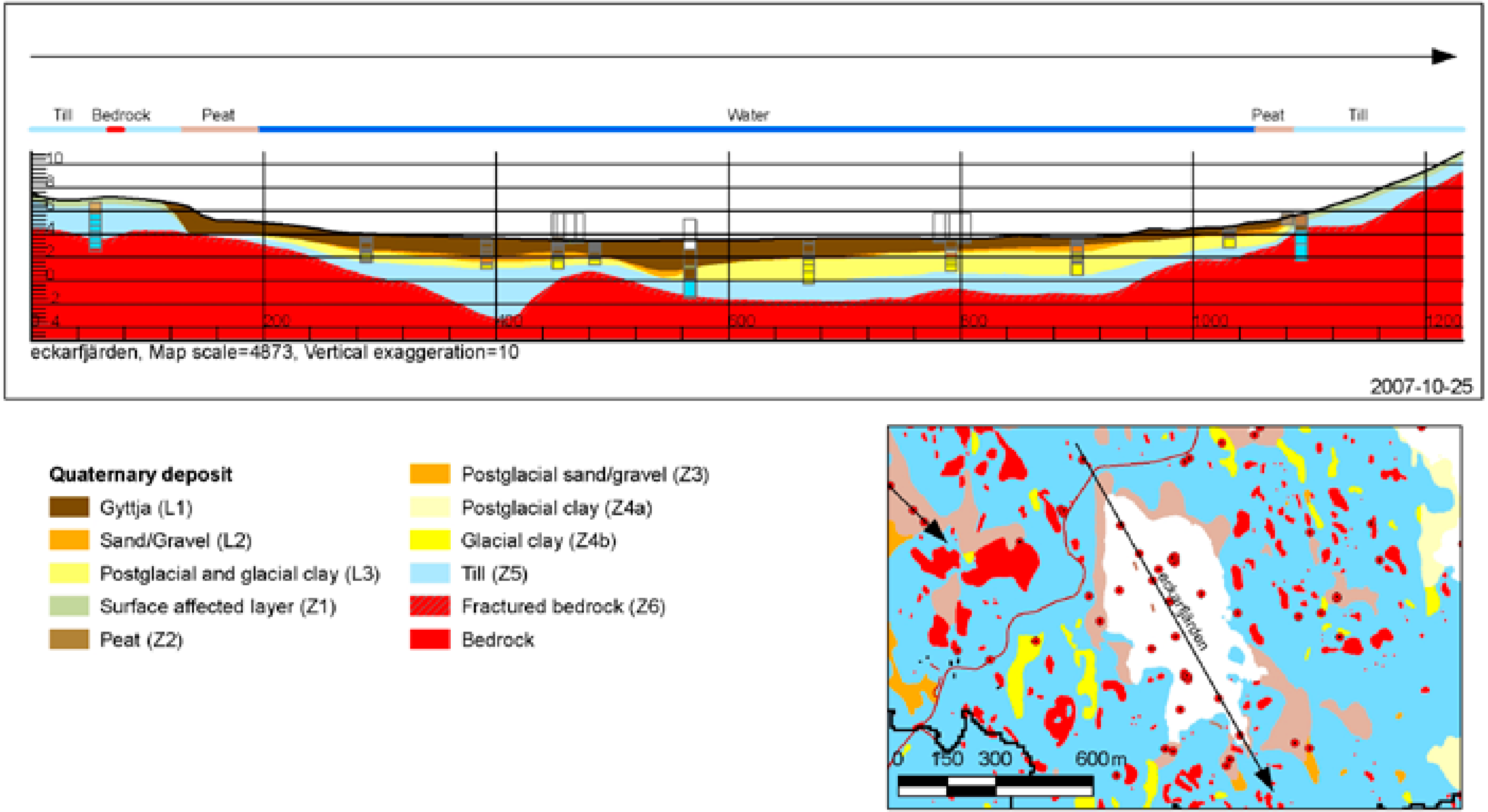


Figure A2-11. *Vertical profile (version 2.2) showing stratigraphy and total regolith depth along profile "Eckarfjärden". For location of the profile, see Figure A2-4.*

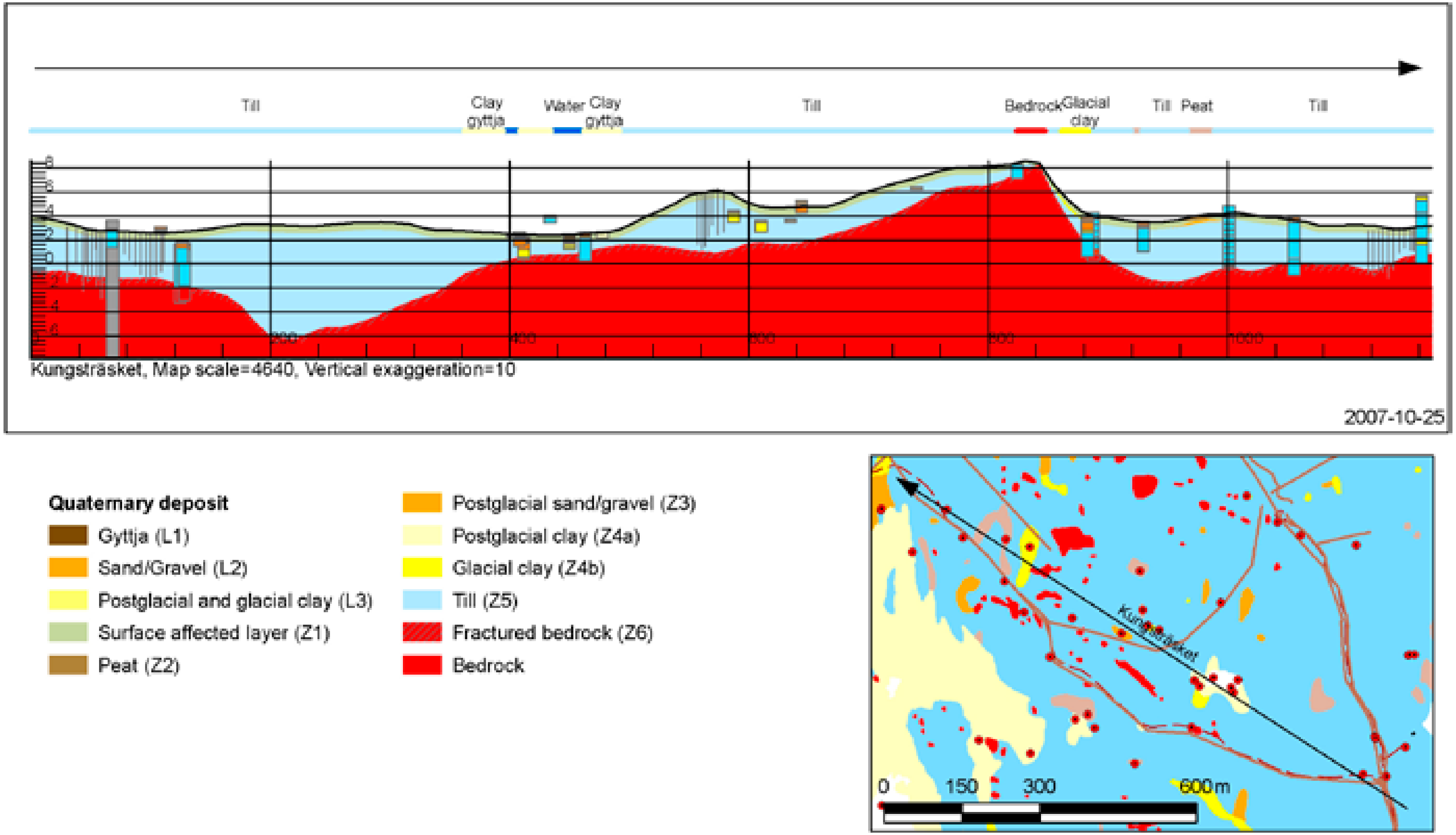


Figure A2-12. *Vertical profile (version 2.2) showing stratigraphy and total regolith depth along profile "Kungsträsket". For location of the profile see Figure A2-4.*

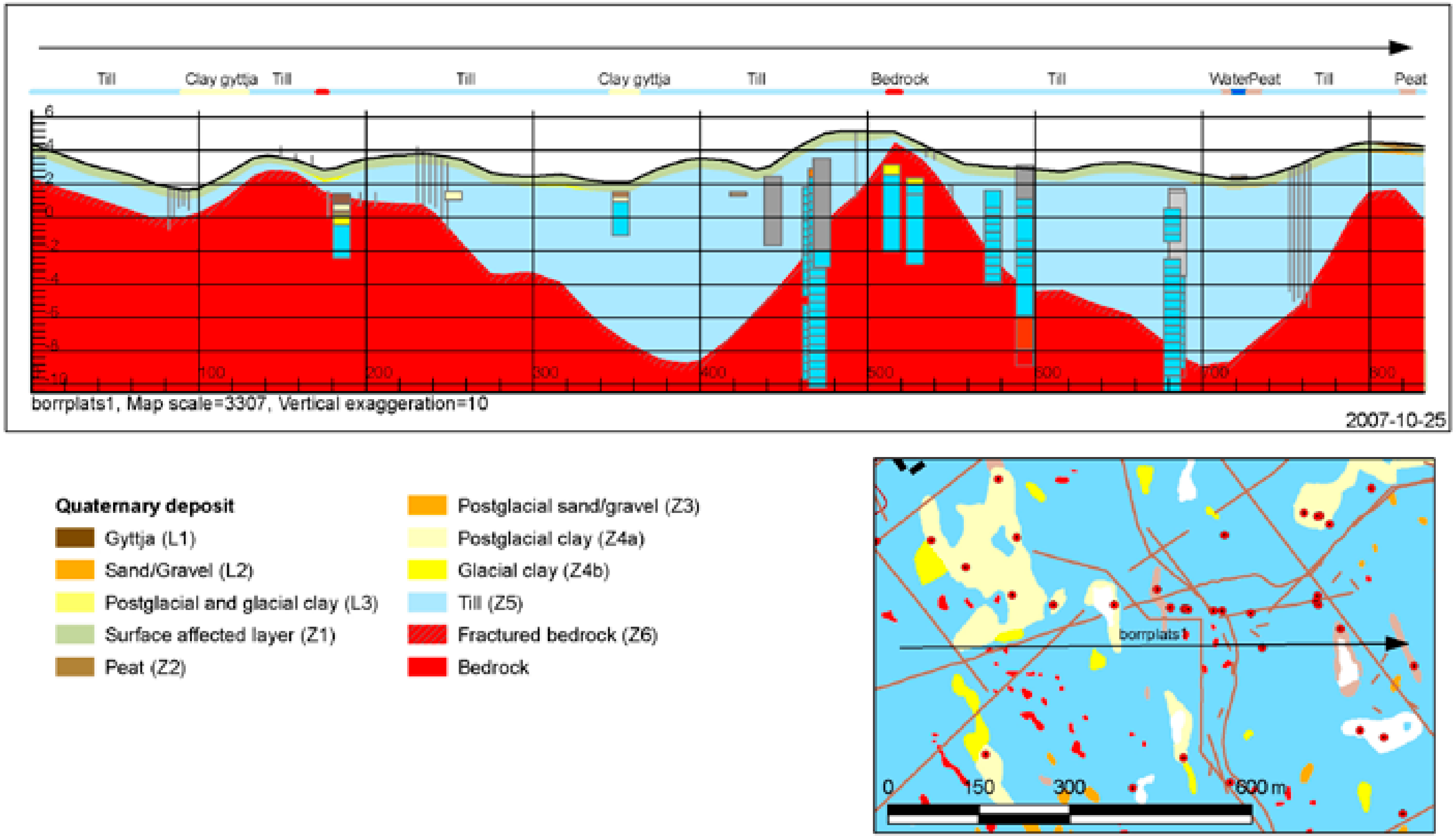


Figure A2-13. *Vertical profile (version 2.2) showing stratigraphy and total regolith depth along profile "Borrplats1". For location of the profile, see Figure A2-4.*

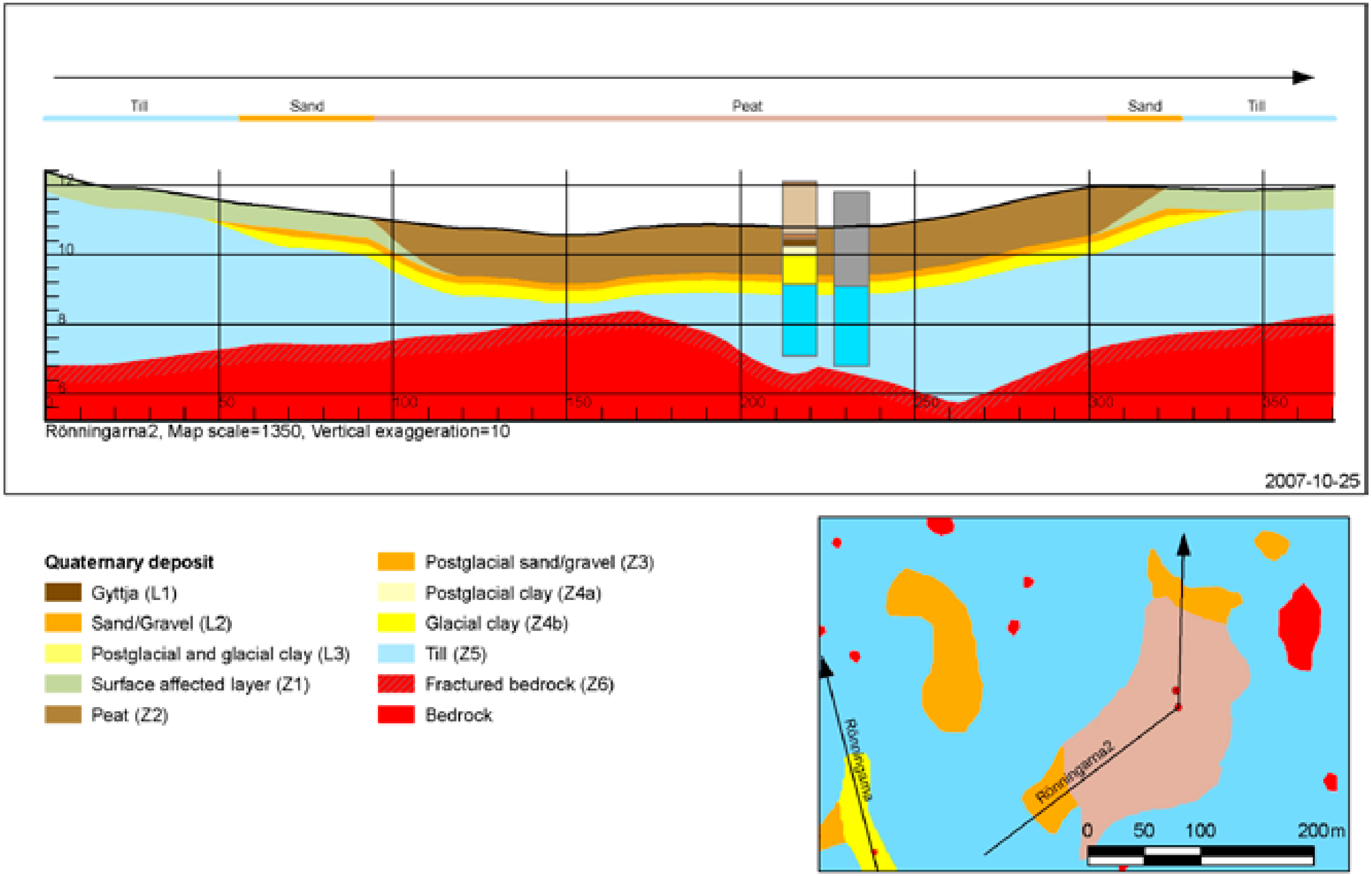


***Figure A2-14.** Vertical profile(version 2.2) showing stratigraphy and total regolith depth along profile "Rönningarna2". For location of the profile, see Figure A2-4.*

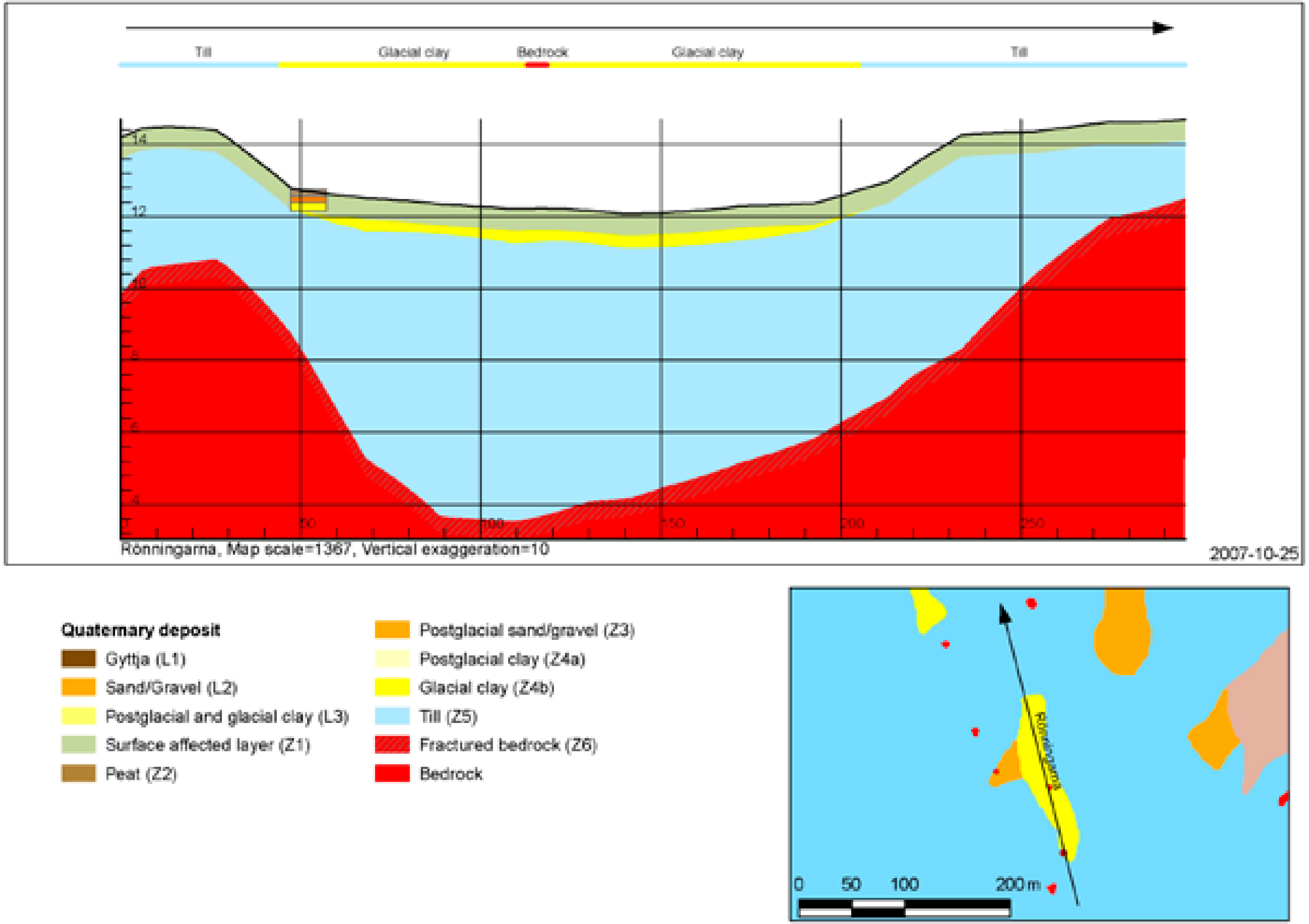


Figure A2-15. *Vertical profile (version 2.2) showing and total regolith depth along profile "Rönningarna". For location of the profile, see Figure A2-4.*

Geostatistical parameters used for interpolation of model 2.2 and 2.3

Cross validation of models

Layer	Lag size	Number of lags	Regression function	Mean	RMS	Average SE	Mean stand	RMS stand	Samples
Z5 (ver 2.2)	30	12	0.995 * x + –0.060	–0.01008	1.161	1.607	–0.002815	0.7195	352,023
Z4a (ver 2.2)	60	12	1.000 * x + –0.011	–0.007267	0.3081	0.7223	–0.005827	0.4063	17,127
Z4b (ver 2.2)	31	12	1.000 * x + 0.001	–0.006266	0.1403	0.4078	–0.006294	0.3046	108,430
Z3 (ver 2.2)	29	12	1.000 * x + –0.001	–0.02756	0.3897	0.2837	–0.03865	1.111	51,635
Z5 (ver 2.3)	30	12	0.999 * x + –0.020	–0.002972	0.5545	1.555	–0.00088	0.3533	527,663
Z4b (ver 2.3)	100	12	1.000 * x + 0.004	–0.008827	0.3186	0.8505	–0.004833	0.4064	49,522
Z4a (ver 2.3)	81	12	0.998 * x + –0.018	–0.03006	0.7612	1.168	–0.01126	0.6104	230,399
Z3 (ver 2.3)	76	12	1.000 * x + 0.001	–0.01249	0.1973	0.1834	–0.02562	0.7011	51,553
Bolundsfjärden L1	13	12	0.862 * x + –0.041	0.0001884	0.2674	0.2767	0.003717	1.028	894
Bolundsfjärden L2	35	12	0.903 * x + –0.004	–0.005577	0.2696	0.2902	–0.001056	0.8796	502
Bolundsfjärden L3	35	12	0.871 * x + 0.022	–0.003841	0.2201	0.2302	–0.002598	673.1	408
Gällsboträsket L1	14	12	0.839 * x + 0.211	–0.000957	0.2239	0.1894	0.00241	1.159	244
Gällsboträsket L2	12	12	0.928 * x + 0.074	–0.03765	0.2444	0.4598	–0.04326	0.5885	61
Gällsboträsket L3	19	12	0.910 * x + 0.057	–0.05565	0.6665	0.8318	–0.03642	1.008	60
Fiskarfjärden L1	37	12	0.925 * x + –0.006	0.0003887	0.2027	0.1901	–0.0003789	1.299	779
Fiskarfjärden L2	33	12	0.945 * x + –0.014	–0.01535	0.2343	0.4024	–0.007682	0.5223	260
Fiskarfjärden L3	52	12	0.961 * x + –0.019	–0.01056	0.346	0.7702	–0.001236	0.4235	250
Eckarfjärden L1	25	12	0.607 * x + 1.415	–0.007606	0.6798	0.6928	–0.002586	0.9653	313
Eckarfjärden L2	34	12	0.937 * x + 0.214	–0.03519	0.4735	0.6926	–0.01608	1.108	133
Eckarfjärden L3	49	12	0.946 * x + 0.183	–0.03308	0.5697	0.8827	–0.005912	0.5782	128
Lillfjärden L1	47	12	0.782 * x + –0.120	–0.002822	0.2886	0.3129	–0.005469	0.9872	166
Lillfjärden L2	58	12	0.880 * x + –0.076	–0.005619	0.26	0.3274	–0.002533	1.081	121
Lillfjärden L3	67	12	0.916 * x + –0.081	–0.02722	0.4361	0.5986	–0.01881	1.101	109
Puttan L1	21	12	0.774 * x + –0.078	–0.01712	0.3813	0.4146	–0.01503	1.005	124
Puttan L2	27	12	0.722 * x + –0.093	–0.04018	0.5054	0.5625	–0.02912	0.8966	98
Puttan L3	13	12	0.557 * x + 0.011	–0.04121	0.4857	0.5749	–0.04558	0.8829	74
Vambörsfjärden L1	11	12	0.680 * x + 0.075	–0.007532	0.3561	0.3606	–0.01006	0.9995	80
Vambörsfjärden L2	27	12	0.816 * x + 0.018	–0.02635	0.3694	0.4715	–0.02704	0.7617	52
Vambörsfjärden L3	28	12	0.834 * x + 0.016	–0.04305	0.4394	0.5738	–0.03793	0.7294	42
Stocksjön L1	28	12	0.798 * x + 0.451	–0.006155	0.2704	0.2389	–0.002975	1.031	53
Stocksjön L2	27	12	0.849 * x + 0.302	–0.02714	0.3074	0.3291	–0.0142	0.7583	40
Stocksjön L3	27	12	0.848 * x + 0.363	–0.04503	0.4389	0.6783	–0.03888	0.7102	21

Validation of models

Layer	Lag size	Number of lags	Regression function	Mean	RMS	Average SE	Mean stand	RMS stand	Samples
Z5 (ver 2.2)	30	12	0.993 * x + –0.081	–0.01499	1.283	1.699	–	–	176,012
Z4a (ver 2.2)	60	12	0.999 * x + –0.019	–0.02175	0.3527	0.9262	–0.01341	0.3878	1,102,981
Z4b (ver 2.2)	31	12	0.999 * x + –0.015	–0.01037	0.2856	0.532	–0.005901	0.4499	8,564
Z3 (ver 2.2)	29	12	1.000 * x + –0.002	–0.04137	0.4597	0.3368	–0.05125	0.6916	54,215
Z5 (ver 2.3)	30	12	0.998 * x + –0.032	–0.00394	0.7551	1.706	–0.0003699	0.4471	263,831
Z4b (ver 2.3)	81	12	0.996 * x + –0.041	–0.05283	0.8388	1.267	–0.02236	0.6146	115,200
Z4a (ver 2.3)	100	12	0.999 * x + 0.001	–0.0142	0.3482	0.9714	–0.005262	0.3696	24,761
Z3 (ver 2.3)	76	12	1.000 * x + 0.000	–0.01996	0.2711	0.2264	–0.03158	0.7539	25,777
Bolundsfjärden L1	13	12	0.815 * x + –0.104	–0.07646	0.3327	0.3312	–0.2258	1.055	447
Bolundsfjärden L2	35	12	0.828 * x + –0.024	–0.01207	0.2919	0.3424	–0.03673	0.8145	251
Bolundsfjärden L3	35	12	0.803 * x + 0.028	–0.02126	0.2929	0.2737	–0.04361	0.9659	204
Gällsboträsket L1	14	12	0.724 * x + 0.355	–0.01113	0.2577	0.211	–0.06907	1.196	122
Gällsboträsket L2	12	12	0.908 * x + 0.073	–0.09331	0.3327	0.5385	–0.1086	0.5078	30
Gällsboträsket L3	19	12	0.984 * x + –0.196	–0.1655	0.7575	0.9308	–0.1035	1.046	389
Fiskarfjärden L1	37	12	0.871 * x + –0.023	–0.00555	0.2538	0.2222	–0.01186	1.149	389
Fiskarfjärden L2	33	12	0.865 *x + –0.029	–0.01288	0.4109	0.4772	0.01842	0.792	130
Fiskarfjärden L3	52	12	0.907 * x + –0.044	–0.05108	0.5092	0.9072	–0.02231	0.4931	125
Eckarfjärden L1	25	12	0.510 * x + 1.785	0.0946	0.7468	0.736	0.1295	0.9993	157
Eckarfjärden L2	34	12	0.869 * x + 0.493	–0.01007	0.5445	0.7936	0.03645	0.7278	67
Eckarfjärden L3	49	12	0.870 * x + 0.389	0.01557	0.7137	1.032	0.08276	0.6478	64
Lillfjärden L1	47	12	0.702 * x + –0.241	–0.1024	0.3623	0.3871	–0.178	0.9213	83
Lillfjärden L2	58	12	0.882 * x + –0.138	–0.08801	0.3312	0.3915	–0.155	1.002	61
Lillfjärden L3	67	12	0.883 * x + –0.076	0.04466	0.4611	0.6794	–0.03517	0.9765	55
Puttan L1	21	12	0.723 * x + –0.119	–0.00886	0.4226	0.465	–	–	62
Puttan L2	27	12	0.670 * x + 0.001	0.06343	0.5532	0.6352	–	–	49
Puttan L3	13	12	0.518 * x + –0.013	0.01525	0.4358	0.6165	0.04487	0.7298	37
Vambörsfjärden L1	11	12	0.303 * x + 0.305	0.02709	0.4402	0.439	0.01106	1.017	40
Vambörsfjärden L2	27	12	0.689 * x + 0.099	–0.04889	0.3484	0.6002	–0.07196	0.6994	26
Vambörsfjärden L3	28	12	0.802 * x + 0.159	–0.03573	0.4939	0.7165	0.04074	0.7236	21
Stocksjön L1	28	12	0.663 * x + 0.714	–0.06922	0.3081	0.2841	–0.1716	0.9738	27
Stocksjön L2	27	12	0.726 * x + 0.534	–0.01464	0.2972	0.3703	0.03759	0.7011	20
Stocksjön L3	27	12	0.589 * x + 0.993	–0.03865	0.4086	0.505	0.1169	1.003	11

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)]
Z5 (ver 2.2)	352,023	33.009*Spherical(344.4,313.53,8.1)+1.2252*Nugget	1.2252 (100%)	0 (0%)	5/2	4
Z4a (ver 2.2)	17,127	35.22*Spherical(711.2,711.2,24.5)+0*Nugget	0 (100%)	0 (0%)	5/2	4
Z4b (ver 2.2)	108,430	12.423*Spherical(367.45,283.13,327.1)+0*Nugget	0 (100%)	0 (0%)	5/2	4
Z3 (ver 2.2)	51,635	1.9572*Spherical(343.74,343.74,16.9)+0*Nugget	0 (100%)	0 (0%)	5/2	4
Z5 (ver 2.3)	527,663	27.831*Spherical(355.6,307.08,335.9)+0.68838*Nugget	1.2252 (100%)	0 (0%)	5/2	4
Z4b (ver 2.3)	230,399	35.053*Spherical(960.11,769.54,359.4)+0.59368*Nugget	0.16266 (100%)	0 (0%)	5/2	4
Z4a (ver 2.3)	49,522	35.032*Spherical(1185.3,829.99,34.0)+0*Nugget	0.041924 (100%)	0 (0%)	5/2	4
Z3 (ver 2.3)	51,553	4.3769*Spherical(900.85,798.8,1.5)+0*Nugget	0 (100%)	0 (0%)	5/2	
Bolundsfjärden L1	894	0.38167*Spherical(154.09,109.37,358.0)+0*Nugget	0 (100%)	0 (0%)	5/2	4
Bolundsfjärden L2	502	0.94278*Spherical(414.86,286.2,20.1)+0*Nugget	0 (100%)	0 (0%)	5/2	4
Bolundsfjärden L3	408	0.56733*Spherical(414.86,293.55,20.8)+0*Nugget	0 (100%)	0 (0%)	5/2	4
Gällsboträsket L1	244	0.10025*Spherical(165.95,137.06,336.4)+0.013869*Nugget	0.013869 (100%)	0 (0%)	5/2	4
Gällsboträsket L2	61	0.50537*Spherical(142.24,113.99,325.2)+0*Nugget	0 (100%)	0 (0%)	5/2	4
Gällsboträsket L3	60	1.4361*Spherical(225.21,134.01,358.2)+0.17803*Nugget	0.17803 (100%)	0 (0%)	5/2	4
Fiskarfjärden L1	779	0.46913*Spherical(438.57,284.99,307.8)+0*Nugget	0.22402 (100%)	0 (0%)	5/2	4
Fiskarfjärden L2	260	1.2157*Spherical(391.16,276.17,274.8)+0*Nugget	0 (100%)	0 (0%)	4/2	4
Fiskarfjärden L3	250	5.2753*Spherical(379.3,287.92,294.0)+0*Nugget	0 (100%)	0 (0%)	5/2	4
Eckarfjärden L1	313	1.1645*Spherical(296.33,227.03,330.0)+0.29119*Nugget	0.29119 (100%)	0 (0%)	5/2	4
Eckarfjärden L2	133	3.4052*Spherical(403.01,227.29,342.2)+0*Nugget	0 (100%)	0 (0%)	5/2	4
Eckarfjärden L3	128	5.9383*Spherical(580.81,195.72,340.0)+0*Nugget	0 (100%)	0 (0%)	5/2	4
Lillfjärden L1	166	0.33754*Spherical(289,126.55,69.6)+0.034925*Nugget	0.034925 (100%)	0 (0%)	5/2	4
Lillfjärden L2	121	0.69265*Spherical(423.29,170.86,66.8)+0.015902*Nugget	0.015902 (100%)	0 (0%)	5/2	4
Lillfjärden L3	109	2.0433*Spherical(414.64,129.14,58.0)+0.038895*Nugget	0.038895 (100%)	0 (0%)	5/2	4
Puttan L1	124	0.61301*Spherical(162.26,99.19,39.8)+0.022777*Nugget	0.022777 (100%)	0 (0%)	5/2	4
Puttan L2	98	0.82961*Spherical(320.04,96.101,49.7)+0.12245*Nugget	0.12245 (100%)	0 (0%)	5/2	4
Puttan L3	74	0.29876*Spherical(154.09,44.7,354.5)+0.15175*Nugget	0.15175 (100%)	0 (0%)	5/2	4
Vambörsfjärden L1	80	0.42723*Spherical(130.39,59.718,353.1)+0*Nugget	0 (100%)	0 (0%)	5/2	4
Vambörsfjärden L2	52	0.76657*Spherical(320.04,49.187,351.5)+0*Nugget	0 (100%)	0 (0%)	5/2	4
Vambörsfjärden L3	42	1.016*Spherical(331.89,51.008,351.2)+0.010196*Nugget	0.010196 (100%)	0 (0%)	5/2	4
Stocksjön L1	53	0.32561*Spherical(219.95,112.12,4.7)+0*Nugget	0 (100%)	0 (0%)	5/2	4
Stocksjön L2	40	0.63493*Spherical(267.97,142.19,4.3)+0*Nugget	0 (100%)	0 (0%)	5/2	4
Stocksjön L3	21	0.70898*Spherical(267.97,51.085,60.0)+0.060613*Nugget	0.060613 (100%)	0 (0%)	5/2	4

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