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SR-PSU Biosphere

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December 2013

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This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the authors. SKB may draw modified conclusions, based on additional literature sources and/or expert opinions.

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Summary

A Regolith Depth Model (RDM) has been produced, which shows the total depth and stratigraphical distribution of the most commonly occurring regolith types in the Forsmark area. Regolith refers to the unconsolidated deposits overlying the bedrock. The modelled area extends over almost 300 km^2 and includes terrestrial areas as well as regolith underlying lakes and the Baltic Sea. The model is used for hydrological and transport modelling in SKBs safety assessment for the extension of SFR.

The data used for the RDM includes a digital elevation model (DEM), maps of regolith, as well as data from drillings and geophysical surveys. For the terrestrial areas and for areas with lakes and shallow marine water, results from refraction seismics and resistivity measurements give information about the total regolith depths, whereas data from corings also give information about the stratigraphy of the regolith. For the marine areas, results from seismic and sediment echo soundings were used to model both the total depth and stratigraphy. Data from almost 400,000 observations were used to model the total regolith depths. A vast majority of these data emanates from marine geological surveys. Data used in an earlier version of the RDM was re-evaluated and to a large extent used in the RDM presented in this report. Additional data from a new Digital Elevation Model (DEM) and stratigraphical data from a detailed marine geological survey around SFR was used as further input.

First a general stratigraphy was constructed, representing the regolith layers and the uppermost bedrock. The area was then divided into fourteen domains, each with a specific stratigraphical representation of regolith. In the marine area there is a relatively high density of data, which made it possible to model the thickness of the regolith layers by the use of a Kriging interpolation. In the terrestrial areas, including areas covered by lakes, the density of data is lower and in areas lacking data the average thickness of the individual regolith layers was used for interpolating the thickness of the layers. The raster representing the upper elevation and thickness of each regolith layer was made using the software ArcGIS 9.3.1. All raster data were exported to another software, GeoScene3D, which was used to visualise the RDM. This program produces profiles showing the stratigraphical distribution of the regolith layers and the input data that was used along the profile.

Two RDM variants were produced. One of these includes an uppermost surface layer, representing the regolith affected by soil forming processes and other currently occurring surface processes. The maximum depth of regolith in the model area is about 47 m, and the average depth in the area is 6.7 m with bedrock outcrops included and 7.5 m with outcrops excluded. There is a general difference between the regolith depths in the terrestrial and marine areas, which are 4.0 m and 8.3 m, respectively. The regolith thickness and the distribution of the regolith types are largely determined by the bedrock morphology. The most low laying bedrock areas, with some major lineaments, are situated in the marine areas and are characterised by thick regolith layers, dominated by clay and till. The higher laying terrestrial areas have a higher frequency of outcrops and are characterised by thinner regolith layers, mainly till.

The present RDM demonstrates some features that were not represented in earlier RDMs. The present model includes a larger area and comprises parts of Island Gräsö and a larger marine area. The most prominent new feature of the model is a large glaciofluvial deposit underlying the clay in the marine area. Furthermore, an extension of a glaciofluvial esker "Börstilsåsen"), earlier recorded on land, was recorded also on the sea floor.

Sammanfattning

En jorddjupsmodell (RDM) har tagits fram, som visar som visar tjocklek och stratigrafisk fördelning för de i Forsmarksområdet vanligast förekommande jordarterna. Med jordarter avses de löst konsoliderade avlagringar vilka överlagrar berggrunden. Modellområdet är närmare 300 km^2 och innefattar dels landområden och dels områden där jordarterna ligger under sjöar eller marint vatten. Modellen används för modellering av hydrologi och transportmodellering inom SKB:s säkerhetsanalys inför utbyggnaden av SFR.

De data som använts för att producera denna RDM innefattar data från en höjdmodell, jordartskartor samt data från borrningar och geofysiska undersökningar. I landområden, sjöar och grunda havsområden ger data från refraktionsseismik och resistivitetsundersökningar information om jordtäckets totala mäktighet, medan data från borrningar ger information om jordarternas stratigrafiska fördelning. För de marina områdena användes resultat från seismisk och sedimentekolod för att modellera både jordarternas totala mäktighet och stratigrafi. Totalt användes data från närmare 400 000 observationer för att modellera jordarternas totala mäktighet. Dessa data kommer till övervägande delen från de maringeologiska undersökningarna. Data som använts vid tidigare jorddjupsmodelleringar utvärderades och användes i stor utsträckning för att ta fram den RDM som presenteras i denna rapport. Dessutom användes data från en ny höjdmodell och data från en mycket detaljerad maringeologisk undersökning kring SFR.

Först togs en generell stratigrafi fram som representerar de olika jordarterna samt den överst liggande berggrunden. Området delades därefter in i fjorton domäner, vilka alla karaktäriserades av en specifik stratigrafisk fördelning av jordlagren. I de marina områdena finns en relativt hög täthet av data och det var möjligt att använda dessa data för att direkt modellera jordlagrens mäktighet med Kriging-interpolering. I landområdena, inklusive områden som täcks av sjöar, är datatätheten låg och i områden som saknar data användes därför de olika jordlagrens genomsnittliga mäktigheter för att interpolera jordlagrens mäktighet. Rasterskikt som representerar nivån för varje jordlagers övre begränsning och tjocklek togs fram i ArcGIS 9.3.1. Dessa raster exporterades till ett annat program, GeoScene3D, som användes för att visualisera RDM. Det programmet användes för att ta fram profiler som visar jordarternas stratigrafiska fördelning samt de data i profilens närhet som använts vid modelleringen.

Två varianter av RDM har tagits fram. En av dessa inkluderar ett övre ytlager som representerar de jordarter som påverkats av jordmånsprocesser och andra idag pågående processer nära markytan. Det största modellerade jorddjupet inom modellområdet är 47 meter, och det genomsnittliga jorddjupet i detta område är 6,7 meter då hällar inkluderas och 7,5 meter då hällar exkluderas. Jorddjupen i landområdena och de marina områdena är 4,0 respektive 8,3 meter. Jordarternas mäktighet och geografiska fördelning bestäms främst av berggrundens morfologi. I de marina områdena finns markanta lineament och den topografiskt lägst liggande berggrunden. Dessa områden kännetecknas av tjocka jordlager vilka domineras av lera och morän. De högre belägna landområdena kännetecknas av en högre frekvens hällar och tunnare jordlager som främst utgörs av morän.

Denna nya RDM innehåller flera företeelser som inte fanns representerade i tidigare RDM-versioner. Den här presenterade modellen inkluderar ett större område och omfattar ön Gräsö och större marina områden. Den mest framstående företeelse som inte visas i tidigare RDM är en stor glaciofluvial avlagring som är belägen under leran i det marina området. Dessutom illustreras fortsättningen på en glaciofluvial ås (Börstilsåsen), som tidigare bara noterats på land, nu även på havsbotten.

Contents

1 Introduction

The final repository for short-lived low- and intermediate-level radioactive waste, SFR, is located at the coast of the Baltic Sea in the vicinity of the Forsmark nuclear power plants. The SFR repository consists of a set of disposal chambers situated in rock at ca 60 m depth beneath the sea floor, and is built to receive and after closure serve as a passive repository for the radioactive waste. The radioactive waste stored in SFR includes operational waste from Swedish nuclear power plants and from the interim storage facility for spent nuclear fuel, Clab, as well as radioactive waste from other industries, research institutions and medical care. In order to be able to also store decommissioning waste from the Swedish nuclear power plants in SFR, an extension of the repository, referred to as SFR 3, is planned. As a part of the license application for the extension of SFR, the Swedish Nuclear Fuel and Waste Management Company (SKB) has performed the SR-PSU project. The objective of SR-PSU is to assess the long-term radiological safety of the entire future SFR repository, i.e. both the existing SFR 1 and the planned SFR 3. SR-PSU is reported in a series of SKB reports. This report is a background report to the Biosphere part of the SR-PSU assessment.

In order to support SR-PSU, numerical and descriptive modelling is performed both for the bedrock and for the surface systems. The surface geology and regolith depth are important parameters for understanding hydrological and geochemical processes in the area. Regolith refers to all unconsolidated deposits overlying the bedrock. The Regolith Depth Model (RDM) presented in this report visualises the present spatial distribution of the regolith as well as the upper surface of the bedrock. The model area (Figure 1-1) extends over almost 300 km^2 and includes marine areas, terrestrial areas and lakes.

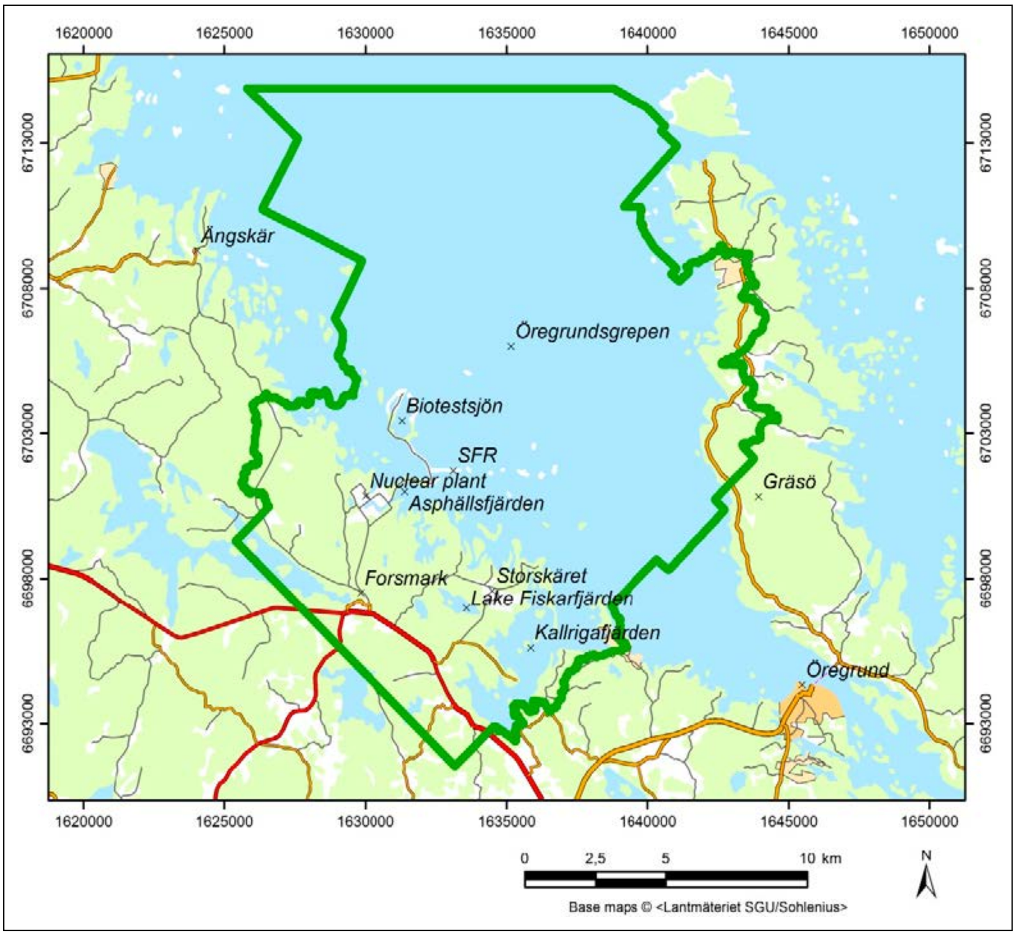

Figure 1-1. *The area represented in the Regolith Depth Model (RDM) is delineated by a green line. The area comprises almost 300 km^2 and includes terrestrial areas, lakes and marine areas. The latter belong to the Baltic Sea.*

The model area was partly delineated based on distribution of available data and partly on the location of present and future water divider. The RDM is used in hydrological and contaminant transport modelling, but also as an input to a dynamic regolith depth model that describes the distribution of regolith through time from the latest deglaciation to 40,000 AD (Brydsten and Strömgren 2013). The dynamic regolith depth model is used for modelling hydrological and contaminant transport of the future. By compiling all available information regarding depth of regolith and location of bedrock surface, the model also identifies areas with a low density of data.

The use of the term regolith is based on the need of a concept where all unconsolidated deposits overlying the bedrock are included, regardless of their origin. This means that both Quaternary deposits (QD) of all kinds, such as till, clay and peat, together with artificial filling material and granular weathered bedrock are included in the regolith. All known naturally occurring regolith in the Forsmark regional model area was formed during the Quaternary period (Hedenström and Sohlenius 2008). The term Quaternary deposits (QD) is therefore often used for the regolith in the Forsmark area. The regolith also includes the uppermost deposits, which are affected by surface processes, i.e. bioturbation, weathering and other currently active processes. In terrestrial areas these processes form soils. Different types of soils are characterised by horizons with special chemical and physical properties.

The RDM is a geometric model that describes the total regolith depth, subdivided into nine layers, which from the top are denoted Z1, Z2, Z3a, Z3c, Z4a, Z4b, Z3b and Z5, additionally Z6 describes the uppermost bedrock. The layers in the model are purely geometrical, and represent the conceptual and stratigraphical understanding of the site. The properties of the layers could be ascribed by the user. Z2 through Z5 represent different regolith types with specific properties. The upper layer Z1 can be given different properties in different areas through connection to the e.g. maps of QD or soil types. In areas with a high data density the thicknesses of the layers were estimated by interpolating the data with Kriging interpolation. In areas with low data density the average thicknesses of the layers were calculated and thereafter distributed geographically even and interpolated with Kriging together with data from the observation points.

Two earlier RDM-versions were produced in connection with the site investigations for localisation of a deep repository for high level radioactive waste in Forsmark; they were reported in Vikström (2005) and Hedenström et al. (2008). The model presented here represents a larger geographical area and was produced by the use of a partly different methodology. Furthermore, additional data from the marine area around SFR was included in the present model.

2 Input data

Data from a large number of sources were used for the RDM (Table 2-1 and Table 2-2). A large proportion of the data was obtained from studies of regolith carried out during the site investigation for the repository for spent nuclear fuel (Hedenström and Sohlenius 2008) and have been used in an earlier RDM (Hedenström et al. 2008). Additional data from the sea floor above SFR is included in the present RDM (Nyberg et al. 2011). Figure 2-1 shows the digital elevation model (DEM), which constitutes the ground surface and the uppermost level of the RDM. Figure 2-2, Figure 2-3 and Figure 2-4 show the location of regolith depth data used for the model. Some of the data gives information regarding the thickness of the individual regolith layers whereas other data only gives information regarding the total depth of regolith.

Some observations do not reach down to the bedrock surface and could consequently not be used for modelling the bedrock surface. Many of these observations were, however, used for modelling the thickness of the uppermost regolith layers and for modelling the minimum total thickness of the regolith. In addition, the distribution of outcrops from regolith maps was used to delineate areas not covered by regolith. The regolith maps were also used to delineate areas with different stratigraphical representation of regolith. Figure 2-5 shows the distribution of the regolith maps used in the model. The different observation types used in the RDM have different accuracy. If overlap occurs, data with lower accuracy was excluded. The data sets used were classified and ranked according to accuracy in their estimation of regolith depth (see Section 2.5).

2.1 Digital elevation model

The DEM used for this RDM has a resolution of 20×20 m^2 (Strömgren and Brydsten 2013) and displays the elevation of the ground surface (Figure 2-1). This DEM is mostly based on a DEM from the Swedish national land survey (LMV) with a 50×50 m^2 resolution, the SKB DEM with 10×10 m^2 resolution (Brydsten and Strömgren 2004), data from airborne laser scanning (Strömgren and Brydsten 2013), and in the marine area data from nautical charts and depth soundings. The reason for producing the model in 20×20 m^2 resolution is that for the marine areas it is not allowed for security reason to publish a DEM with higher resolution. It was consequently not possible to use the DEM with the 10×10 m^2 resolution for the RDM. 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.

2.2 Maps of regolith

The map of regolith is a compilation of eight maps, originally produced with different methods (Figure 2-5) and adjusted for presentation at different scales. The ranges relevant for the derivation of the RDM covered by each of these eight maps are denoted from “Area 1” to “Area 8”. The regolith map covers the whole modelled area and can be used to ascribe properties to the surface layer. The maps show the distribution of regolith at a depth of 0.5 metres. This depth is used to characterise deposits that are more or less unaffected by surface processes (e.g. weathering and bioturbation). Thinner layers of regolith covering large areas are, however, also shown on the maps, e.g. thin layers of sand commonly occurring at the sea floor. The regolith map also shows the distribution of outcrops and artificial fill. During the modelling of regolith depths the regolith maps were used to delineate areas with specific stratigraphical distributions of regolith. The map of regolith is often referred to as the map of Quaternary deposits (QD)

The most detailed map (Sohlenius et al. 2004) covers the terrestrial area in the central part of the model area (Area 1 in Figure 2-5). It includes all observed bedrock exposures and regolith with areas larger than 10×10 m^2. The detailed geological map was initially presented at the scale 1:10 000.

Area 2 is represented by data from the Geological survey of Sweden (SGU) database for regolith in terrestrial areas and is adapted for presentation at the scale 1:50 000. The maps cover also areas beyond the range of the RDM and were originally published by Persson (1985, 1986). This map was used to model was used to model (the) distal parts of the model area the distal terrestrial parts of the model area.

In the shallow coastal bays, Area 3, the survey vessel used for the regular mapping could not enter. Therefore, the distribution of regolith was investigated in a large number of point observations from the sea ice or using a small boat (Ising 2006). Many of the studied points include determinations of the thickness of regolith layers (Figure 2-4). It was, however, not possible to determine the total thickness of regolith. The investigations were performed along lines, approximately 200 metres apart. This method makes the precision of the map adapted to the presentation scale 1:50 000 and no regolith areas smaller than 50×50 m^2 are displayed.

Area 4, Area 5 and Area 6 are modelled using data from the marine area, which were collected to determine the geographical distribution of regolith as well as the thickness of the regolith layers. Area 4 contains geological data collected along lines with a distance of 100 m (Elhammer and Sandkvist 2005). Area 5 contains data collected along lines with a spacing of 1 000 m (Elhammer and Sandkvist 2005). Area 5 also contains additional data collected during 2008 within SGUs mapping program. All data from Area 5 presented by Elhammer and Sandkvist (2005) was reinterpreted by Nyberg et al. (2011) to fit with the data obtained by SGU 2008. Data from both Area 4 and 5 was originally presented by Elhammer and Sandkvist (2005) at the scale 1:100,000.

Area 6 represents the area above the present SFR and comprises data obtained from network of lines with a spacing of 100 m, which was interpreted (Nyberg et al. 2011). Data from some of these lines were collected and originally interpreted by Elhammer and Sandkvist (2005) and additional data was obtained during 2010 (Nyberg et al. 2011). Area 7 is represented by data collected within the SGU mapping program and was interpreted by Nyberg et al. (2011). Regolith data from Area 7 has not yet been delivered to the SGU database, but will be included in a larger marine geological map produced by SGU.

In order to obtain a complete map showing the distribution of regolith, the remaining areas located under shallow water in the marine area and under the lakes and streams were interpreted as well. The resulting map (Area 8) is based on interpretations from the general knowledge of sediments in the lakes of the area (Hedenström 2003), bathymetry from the DEM and interpolation from the surrounding regolith. The regolith map in Area 8 has consequently larger uncertainties than the maps from remaining areas. Some of the lakes and ponds in Area 8 have, however, been thoroughly investigated (Hedenström 2003, 2004a, b, Sohlenius and Hedenström 2009). The sites cored during these studies are shown in Figure 2-4.

2.3 Stratigraphy and total depth of the regolith

A large number of methods have been used to obtain data representing depth and stratigraphy of regolith. The data includes both direct observations from e.g. corings and interpretations from different types of geophysical measurements. Bedrock exposures are shown on the regolith maps representing areas lacking a regolith layer and were used for the RDM as areas with zero regolith depth values. These observations generally have a high reliability, even though the accuracy of the regolith map varies within the modelled area (see Section 2.2 above).

In the marine area, sediment echo sounding and seismic data give information of the total thickness of all the regolith layers overlying the bedrock surface (Elhammer and Sandkvist 2005, Nyberg et al. 2011). The data was obtained after interpretations of seismic and echo sounding profiles. The distance between the investigated lines varies between the mapped areas (Figure 2-2). The reliability of these interpretations varies with the quality of the profiles. In certain areas, gas in the postglacial sediments obstructed the interpretations of underlying deposits. The interpreted thicknesses of water laid sediments generally have a higher reliability compared to the interpreted thickness of till. Furthermore, the interpretations from the shallow areas (Area 4) obtained by Elhammer and Sandkvist (2005) have lower reliability than interpretations from deeper marine areas. That is due by problems with double echoes that is common when using seismic and sediment echo sounding in shallow areas

In lakes, wetlands and shallow bays the stratigraphy of clay and gyttja was determined by characterisation of cores obtained by hand coring (Ising 2006, Fredriksson 2004, Hedenström 2003, 2004a, b, Sohlenius and Hedenström 2009). Additional stratigraphical information was obtained from the mapping of regolith in the terrestrial areas (Sohlenius et al. 2004) and by stratigraphical studies in machine dug trenches (Albrecht 2005, Sundh et al. 2004). All data obtained from characterisation of regolith in the field and generally has a higher reliability than interpretations done from geophysical measurements. Most of these observations did, however, not reach the bedrock surface.

Data from the SGU archive of wells (SGU 2011) gives information about the total depth of regolith (Figure 2-2 and Figure 2-3). However, some of these observations have a low reliability concerning the coordinates of the observation points. Data from drillings provides information on stratigraphy and total depths of regolith in the terrestrial areas (Figure 2-3) and also in certain lakes (Johansson 2003, Hedenström et al. 2004, Werner and Johansson 2003, Albrecht 2007). These data have high reliability compared to most other data used for the RDM.

Refraction seismics and continuous vertical electrical sounding (CVES) measurements (Figure 2-3) give information concerning the total regolith depth along lines (Keisu and Isaksson 2004, Toresson 2005, 2006, Bergman et al. 2004, Bergman 2004, Nissen 2003, 2004). Unfortunately, data showing the total depth of regolith from 30 electrical soundings from Thunehed and Pitkänen (2003) were omitted by mistake when the database for the present RDM was constructed. These data are available in SKBs database and will be used for future possible updates of the RDM. The seismic data from Bergman et al. (2004) and Bergman (2004) were initially not collected for regolith depth interpretations, and are regarded as less reliable than remaining interpretations of refraction seismics data. CVES has the highest reliability of the ground geophysical data.

In the land area there are large parts that lack information concerning both depth and stratigraphy of regolith (see Figure 2-2). These areas are modelled by the use of data from the areas where regolith depth data are at hand, which is further discussed in the description of methods below (Chapter 4).

2.4 Data excluded from the modelling

Results from drillings and observations of bedrock exposures are regarded as having a high reliability. After comparing all other datasets with results from drillings and bedrock observations, some data was excluded from the modelling of regolith depths.

An early RDM version in Hedenström et al. (2008) used more than 130,000 points with total regolith depths (Thunehed 2005), calculated from measurements from helicopter (Rönning et al. 2003) in the terrestrial area. The helicopter data reflects the electric resistivity of the ground. This resistivity dataset was used by Thunehed (2005) to calculate the regolith depth. However, in an updated RDM Hedenström et al. (2008) used several testes that showed that the helicopter data had a too low confidence for the modelling of regolith depths. The reasons for this are listed below.

1) There are several areas where regolith depth interpreted from the helicopter 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 much thinner coverage of regolith in these areas.
2) The helicopter data was compared with data obtained from other surveys, e.g. corings and ground geophysical measurements. Data points situated within 10 metres from the closest point in the helicopter-borne survey were included in the comparison. The correlation between the two data sets was found not acceptable (Hedenström et al. 2008, Figure A2-3).
3) Some data from the helicopter survey are duplicates, but show large regolith depth variations at some positions. Differences of more than 20 m were recorded.
4) The results from the helicopter survey indicate regolith depths of several metres in some small areas that in fact were recognised as bedrock outcrops during the mapping of regolith.

Data from measurements with ground penetrating radar (Marek 2004a, b) was used as input to the earlier RDM presented in Hedenström et al. (2008). This dataset was collected along lines which in several places coincide with the locations of other data, mainly refraction seismic measurements. Hedenström et al. (2008) compared the datasets and concluded that the seismic data has a higher reliability than the data obtained with ground penetrating radar. The evaluation showed that the data from ground penetrating radar presented a thinner regolith cover than neighbouring measurements using other methods. Hedenström et al. (2008) therefore decided to omit the ground penetrating radar data when these results were conflicting with other data. For the model presented here further comparisons with neighbouring data, mainly from refraction seismics, were carried out and it was concluded that some of the ground penetrating data used by Hedenström et al. (2008) was conflicting with other data. It was therefore decided to omit all ground penetrating radar data in the present model.

The refraction seismics data from the marine area (Keisu and Isaksson 2004) includes data that conflict with data from Area 6 (Nyberg et al. 2011). Compared to the refraction seismics, the data from Nyberg et al. (2011) has a higher quality for evaluating regolith deep and stratigraphy, and some of the refraction seismics data was therefore omitted.

2.5 Ranking of data used in the RDM

The different observation types used in the regolith depth model have different accuracy. In certain cases, overlaps occur and data with lower accuracy were then excluded. The datasets used were classified and ranked according to their accuracy in the estimation of the total regolith depth as listed below in order of decreasing accuracy.

1. Direct observations of bedrock outcrops and corings and probings that reach the bedrock and have GPS-measured coordinates.
2. Data from marine geological measurements in Area 6 in Figure 2-5.
3. Data from the marine geological measurements in Area 4 in Figure 2-5.
4. Data from the SGU archive of wells and data from marine geological measurements in Areas 5 and 7 in Figure 2-5. Data from the well archive often have a low accuracy of positioning.
5. Stratigraphical observations from the investigations that did not reach the bedrock surface. These observations have, however, the highest ranking for estimating the thickness of individual regolith layers.
6. Ground geophysical measurements (refraction seismics and electrical soundings) in terrestrial areas performed with purpose to investigate regolith thickness.
7. Data from refraction seismic sounding that was carried out with other purposes than determining regolith depth.

The order of the ranking is based on information from the reports describing the data, as well as discussions with some of the persons involved in the measurements (Björn Bergman SGU, Johan Nyberg SGU). In addition, there is a general assumption that the direct observations from the field are more reliable than the interpretations from geophysical data.

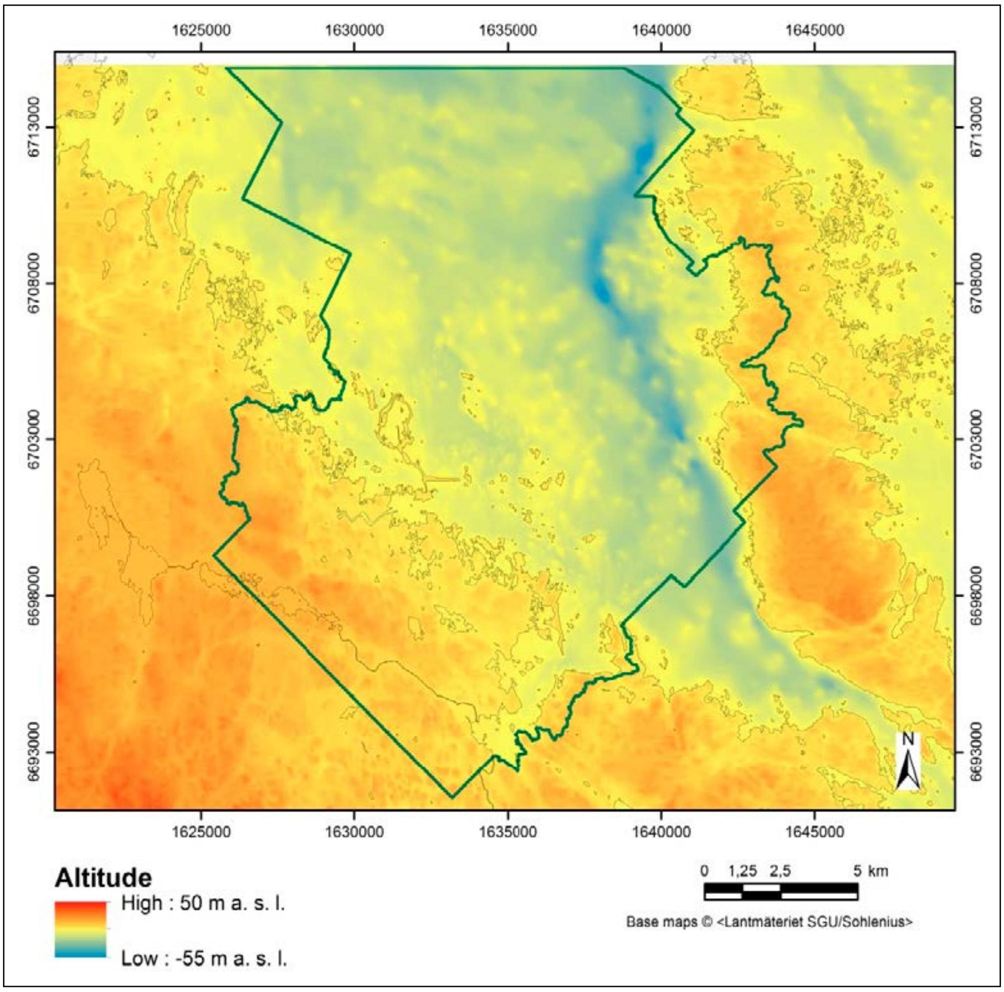

Figure 2-1. *The Digital Elevation Model (DEM) showing the elevation of the ground surface in a 20×20 m^2 resolution (Strömgren and Brydsten 2013).*

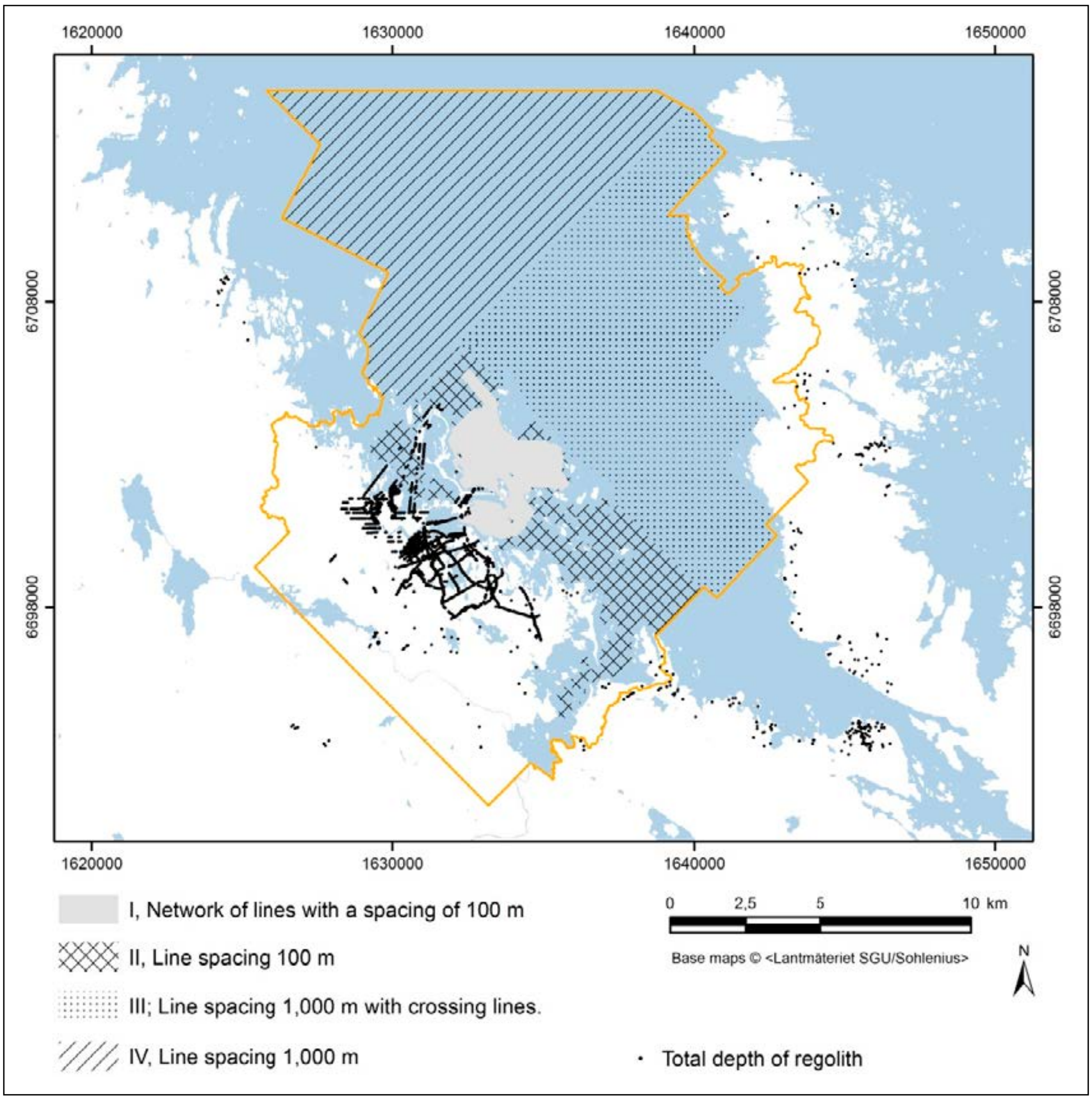

Figure 2-2. *Distribution of observation points and data sources that were used for modelling the total regolith depth and the thickness of the different regolith layers. Data used to model the depth of the regolith layers in lakes, terrestrial areas and shallow marine areas are shown in Figure 2-4. The orange line represents the border of the model area. The black points represent sites in the terrestrial areas which were used to model the total depth of regolith, and are further explained in Figure 2-3. Most of the points situated outside the model area are data from wells obtained from the SGU well archive. In the marine area echo and seismic soundings were collected along lines. I = depth and stratigraphy of regolith obtained along a network of lines with a spacing of 100 m (Nyberg et al. 2011). II = depth and stratigraphy of regolith obtained along lines with a spacing of 100 m (Elhammer and Sandkvist 2005). III = depth and stratigraphy of regolith obtained along lines with a spacing of 1,000 m with data from some additional crossing lines (Elhammer and Sandkvist 2005, Nyberg et al. 2011). IV = depth and stratigraphy of regolith that were collected within SGUs mapping program; data was obtained along lines with a spacing of 1,000 m.*

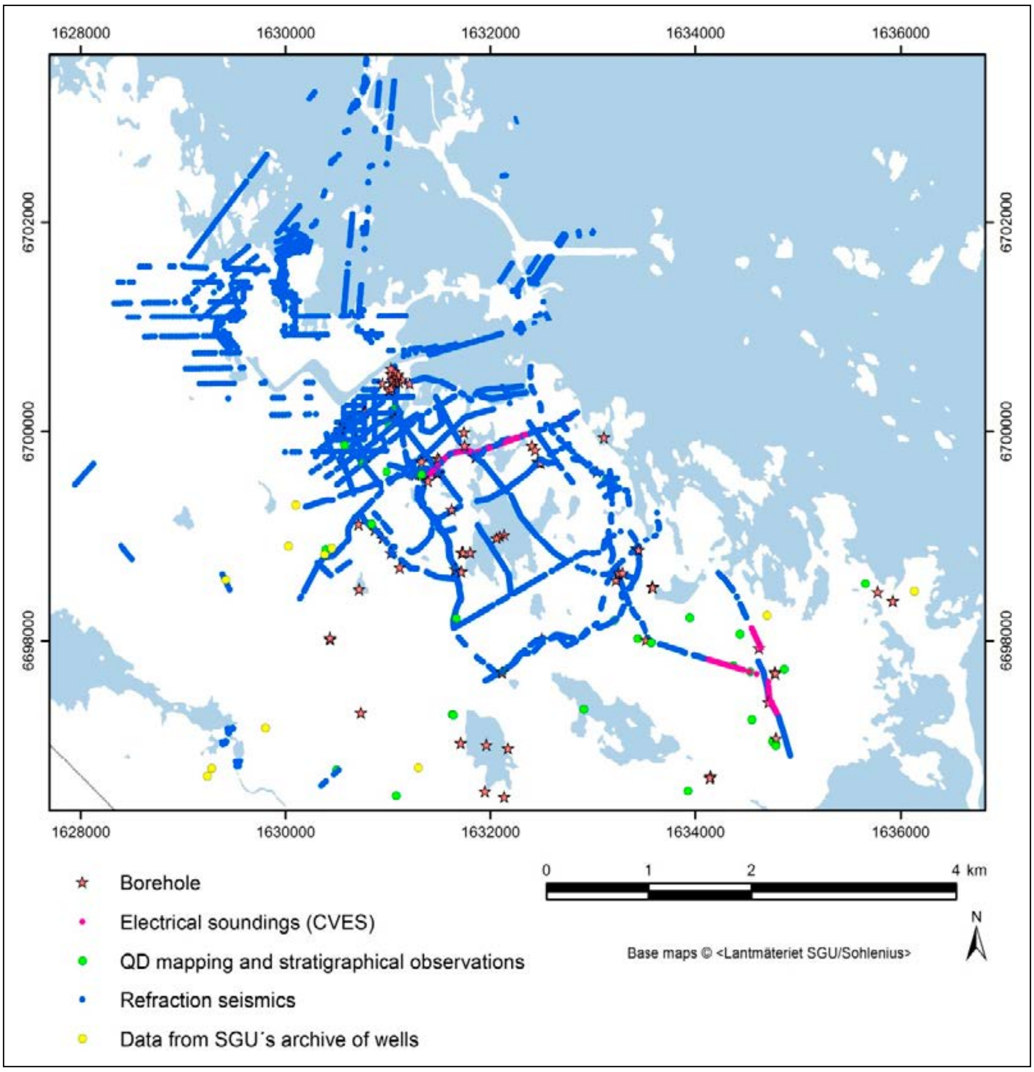

Figure 2-3. *Distribution of observation points from different types of studies that were used for modelling the total regolith depth in terrestrial areas, lakes and shallow marine areas. The number of data from different investigations is shown in Table 2-2. Most of the observation points from SGU´s archive of wells are not shown within the range of this map but can be seen in Figure 2-2.*

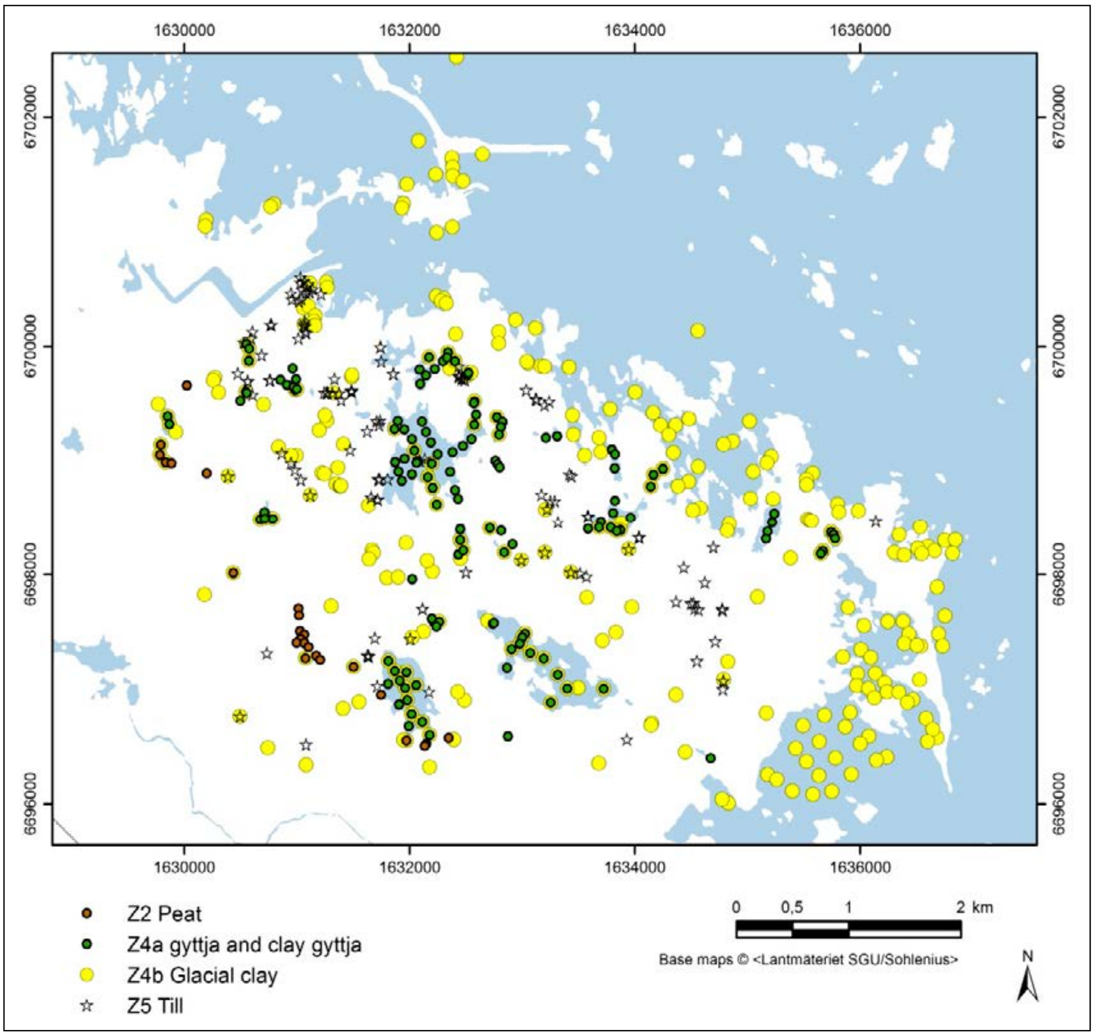

Figure 2-4. *The distribution of observations showing the thicknesses of different regolith layers (peat, till etc). The data were used to model the thickness of the regolith layers in lakes, terrestrial areas and shallow marine areas. Most of these observations were obtained from hand-driven coring and did not reach the bedrock surface (e.g. Ising 2006, Hedenström 2004a, b).*

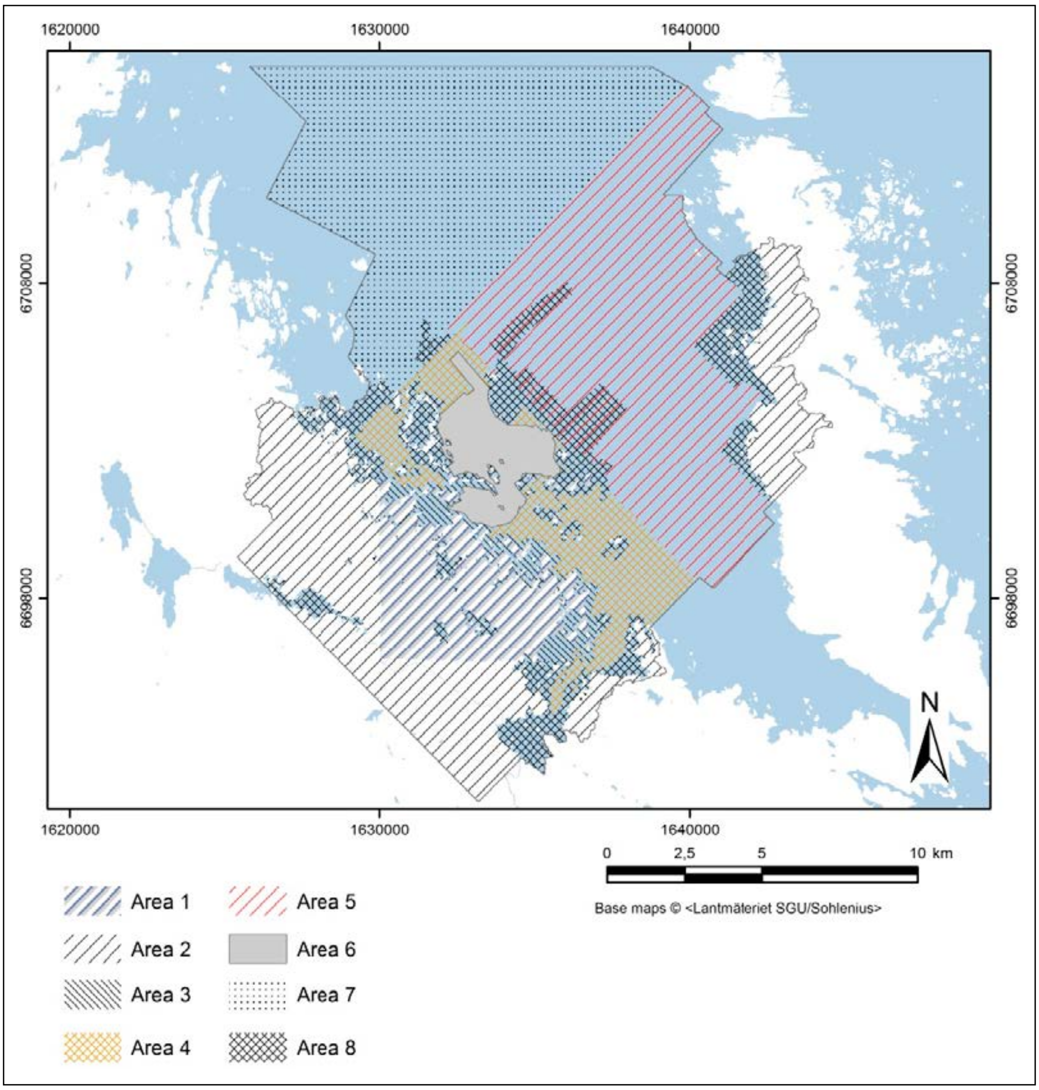

Figure 2-5. *The distribution of the areas represented on the eight different maps of regolith that were used to compile the resulting regolith map used as input to the Regolith Depth Model (RDM). The methods used for mapping the areas are briefly described in Table 2-1 and in the text; Hedenström and Sohlenius (2008) and Nyberg et al. (2011) give thorough descriptions of the mapping.*

Table 2-1. Short description and references to the methods used to produce the regolith map. The geographical distribution of the different areas is shown in Figure 2-5. T = Terrestrial area, M = Marine area, L = Lakes.

Area	Type of data	Reference
1 (Terrestrial)	Detailed regolith map for presentation in 1:10 000	Sohlenius et al. (2004)
2 (Terrestrial)	SGU map of regolith for presentation in 1:50 000	Persson (1985, 1986)
3 (Marine)	Distribution of regolith in shallow coastal areas	Ising (2006)
4 (Marine)	Detailed distribution of regolith in coastal areas with water depths between 3 and 6 m	Elhammer and Sandkvist (2005)
5 (Marine)	Distribution of regolith at the sea floor in areas with water depths > 6 m	Elhammer and Sandkvist (2005), reinterpreted by Nyberg et al. (2011)
6 (Marine)	Detailed distribution of regolith in coastal areas with water depths between 3 and 6 m	Nyberg et al. (2011)
7 (Marine)	SGU mapping of regolith at the sea floor	Data is not included in the SGU database, but will be included after a review at SGU
8 (Lakes and shallow marine areas)	Interpretation from corings in lakes, DEM, and studies of surrounding regolith	Hedenström (2003, 2004a, b), Sohlenius and Hedenström (2009)

Table 2-2. Data sets used in the modelling of the total regolith depth and the thicknesses of Z-layers included in the RDM.

Data	Description	Data quantity	Ref
DEM	The DEM has a resolution of 20×20 m^2 and describes the land surface, and the bathymetry of lakes and sea.		Strömgren and Brydsten (2013)
Geological maps			
Maps of Quaternary deposits	The map of regolith and bedrock outcrops covering the entire model area. The resulting map is a compilation of eight data sets based on different methods and scale.	Eight different data sets maps integrated into one map	Elhammer and Sandkvist (2005), Sohlenius et al. (2004), Persson (1985, 1986), Ising (2006), Hedenström and Sohlenius (2008), Nyberg et al. (2011)
Corings and excavations			
Bedrock and regolith boreholes	Boreholes with an estimated bedrock elevation, i.e. cored, percussion and probing boreholes.	99 boreholes	Johansson (2003), Hedenström et al. (2004), Werner and Johansson (2003), Werner et al. (2006), Albrecht (2007), Hansson et al. (2008), Werner et al. (2004)
Regolith mapping and other stratigraphical studies	Mostly shallow observation points from hand driven corers and excavations with detailed stratigraphy. Stratigraphical investigations in machine cut trenches are also included in this group of data.	37 stratigraphical observations	Lokrantz and Hedenström (2006), Sohlenius et al. (2004), Sundh et al. (2004)
Organic and inorganic sediment mapping, peat land mapping	Stratigraphical information from shallow marine areas, lakes and mires. The corings were performed using hand driven corer, hence data contains information of fine grained sediments and peat.	c. 300 stratigraphical observations	Fredriksson (2004), Hedenström (2003, 2004a, b), Ising (2006), Sohlenius and Hedenström (2009)
The SGU archive of wells	Total depth to bedrock as recorded at the installation of private groundwater wells. The information is extracted from SGU database.	333	SGU (2011)
Geophysical data			
Seismic and sediment echo sounding	Estimated depth to bedrock and stratigraphy in the regional marine area (Area 5 in Figure 2-5).	5 671	Nyberg et al. (2011) interpreted from data collected by Elhammer and Sandkvist (2005)
Seismic and sediment echo sounding	Estimated depth to bedrock and stratigraphy in the regional marine area (re-interpreted data from Area 6 in Figure 2-5).	342 841	Nyberg et al. (2011) interpreted from data collected by Elhammer and Sandkvist (2005)
Seismic and sediment echo sounding	Estimated depth to bedrock and stratigraphy in the area above SFR-Area 6 in Figure 2-5.	206 233	Nyberg et al. (2011)
Seismic and sediment echo sounding	Estimated depth to bedrock and stratigraphy in the detailed marine area (Area 4 in Figure 2-5).	83 378	Elhammer and Sandkvist (2005)
Refraction seismics	Each observed point along the profiles has a surface elevation and an estimated smoothed bedrock elevation.	7 350	Keisu and Isaksson (2004),Toresson (2005, 2006), Bergman et al. (2004), Bergman (2004)
Continuous vertical electrical soundings (CVES)	Observation points from CVES where estimated depth to bedrock is used.	Four profiles including 289 observation points	Nissen (2003, 2004)

3 Description of the model area

SFR is situated close to the coast below the floor of the Baltic Sea (Figure 1-1).The model area has a flat topography with a declining slope towards the east (see Figure 2-1). The most elevated area is the south western part, reaching c. 25 metres above sea level (m.a.s.l). The largest water depths are located in the northern part of the model area, west of Island Gräsö, where the water depth is c. 40 m (Figure 2-1). The distribution of regolith materials in the model area is shown in Figure 3-1.

All known unconsolidated naturally occurring deposits in the Forsmark area were formed during the Quaternary period and is therefore often referred to as Quaternary deposits (QD). The term regolith includes all Quaternary deposits as well as artificial fill. Furthermore, regolith also includes the uppermost regolith that has been affected by surface processes such as bioturbation and weathering. For a detailed description of the properties and distribution of the regolith in Forsmark the reader is referred to Hedenström and Sohlenius (2008), whereas the geological development of the site is summarised in Söderbäck (2008). Regolith covers c. 90% of the ground surface within the model domain. 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 the present RDM, a layer representing fractured bedrock is represented by the layer Z6, which is present in the whole model area. The properties of the uppermost bedrock varies within the model area and must consequently be defined by the users of the RDM.

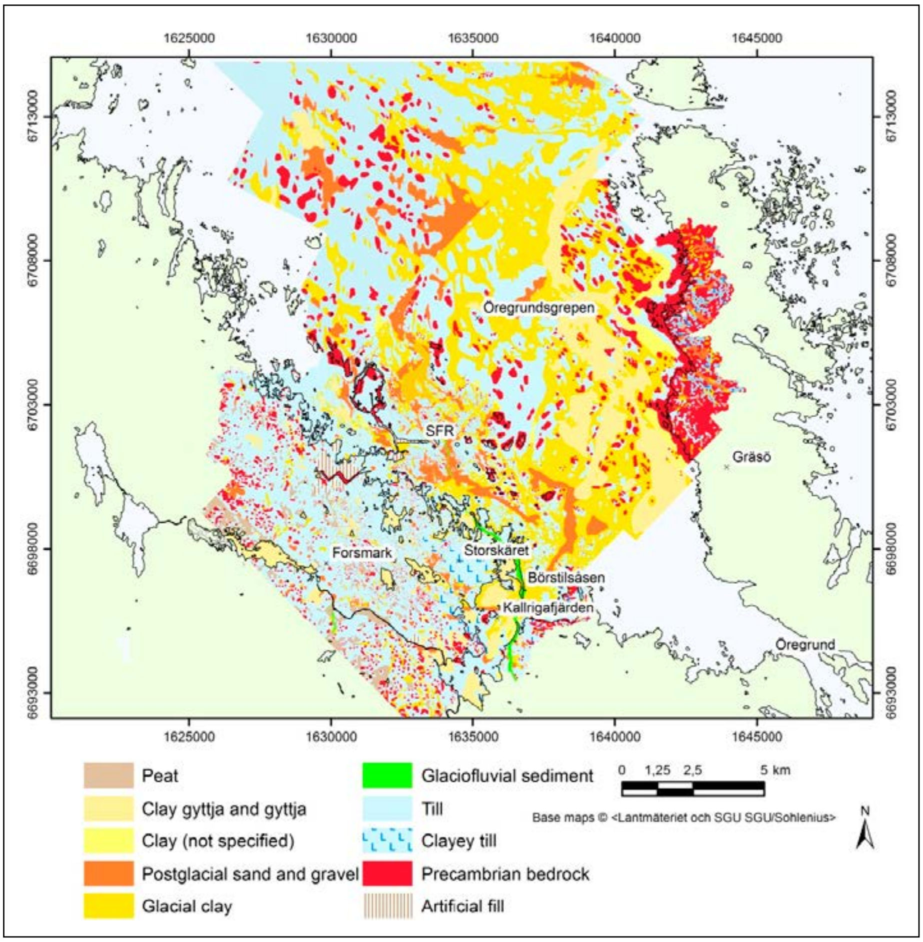

Figure 3-1. *The distribution of the regolith in the Forsmark area 0.5 m below the ground surface. It should be noted that the areas presently covered with water (lakes, streams and sea) are presented without the covering water on the map. The map is a compilation of eight maps, originally presented in different scales (se Figure 2-5 and Table 2-1).*

The QD are grouped, according to the environmental conditions in which they were formed, into two main categories: *glacial* and *postglacial* deposits. The deposits were formed in extremely varying environments giving rise to varying chemical and physical properties characterising the different deposits.

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

Till consists of bedrock fragments and older regolith incorporated and transported by the ice sheet and later deposited. Generally, till is characterised by poor sorting, resulting in grain size composition including all 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 QD. The till in the Forsmark area is generally dominated by sand and silt, which in parts of the area is characterised by a high surface frequency of boulders. In the area, around Storskäret, clayey till, i.e. till with a clay content > 5% of the matrix, with a low frequency of boulders dominates (Figure 3-1). The clayey till is partly used for cultivation, whereas the till in general is covered by forest. The till in the Forsmark area is characterised by a high content of $CaCO_3$ emanating from a limestone area situated north of the model area, at the floor of the Bothnian Bay.

During the latest deglaciation, a large quantity of melt water was produced. The melt water was concentrated to tunnels under the ice and to fractures on the surface of the ice, 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 the terrestrial part of the model area, an esker ("Börstilsåsen", Figure 3-1) situated along the coast, is the most prominent glaciofluvial deposit. There is also a larger, partly clay covered, glaciofluvial deposit situated at the floor of the Baltic Sea between the mainland and Island Gräsö. Since it is situated below clay, this deposit is not shown on the map of QD.

After deglaciation the whole area was covered by the Baltic Sea. The finest particles transported by the melt water, clay and silt, were deposited further from the ice margin in deep and stagnant water. *Glacial clay* is often characterised by varves, i.e. layers of sediment representing summer and winter accumulation. In the terrestrial area the proportion of glacial clay is small and concentrated to local depressions. In these areas the glacial clay is often only a few decimetres thick and probably consists of remnants from erosion on the bottom of the sea. In areas covered by water the glacial clay is often several metres thick and is more frequently occurring. In the marine areas with a water depth of more than 6 metres, the extensional coverage of glacial clay is particularly large (cf. Elhammer and Sandkvist 2005, Nyberg et al. 2011). The glacial clay is rich in $CaCO_3$ emanating from the limestone area at the floor of the Bothnian Bay.

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 shortly after the deglaciation the sea level in the model area was c.150 m above the present level. The entire model area was situated below the Baltic until a few thousand years ago. Thus, the formation of postglacial deposits has mainly been taking place at the floor of the Baltic Sea. In general, postglacial deposits overly till and glacial clay, but they may also rest directly on the bedrock.

In Forsmark, the postglacial deposits are dominated by sand and gravel, clay, gyttja and peat. The *postglacial gravel and sand* deposits often cut discordantly and superimpose glacial clay and are interpreted to mainly represent deposition after erosion and transport by currents on the sea floor. Sand is often the dominant grain size in these deposits. Both in the terrestrial area and offshore, a layer of postglacial sand and/or gravel often covers the glacial clay.

Most of the *postglacial clay* in the model area contains organic material and is denoted *clay gyttja.* This deposit was and still is accumulating after erosion and re-deposition of some of the previously deposited sediments, such as glacial clay. Clay gyttja is predominantly accumulating at the deeper parts of the sea floor and in bays along the coast. The ongoing isostatic uplift results in the emergence of new land areas, which transfers sedimentary basins to a sheltered position, favouring the accumulation of clay gyttja. *Gyttja* is currently deposited in lakes and contains a high proportion of organic material, mainly of remnants from plants that had grown in the lake. In the Forsmark area, as well as in other areas with calcareous soils, calcareous gyttja is deposited in some of the lakes. Many of the ponds and lakes in Forsmark are very shallow, often with less than one metre water depth, and will have only a short duration before the basins are filled with sediment and peat and develop into wetlands.

Peat consists of remnants of dead plants, which are preserved in areas where the prevailing wet conditions prevent the breakdown of the organic material. Peat is most frequently found in the south western part of the model area, i.e. the most elevated areas that have been above the sea level long enough for infilling of basins and peat formation to occur.

Artificial fill is material that has been deposited by man, and is mostly present around the nuclear power plant, along the road towards SFR, and in the SFR and Forsmark harbour area. There is also a pier made up of artificial material, which is situated above the present SFR (Figure 3-1). This regolith type is supposed to rest directly upon the bedrock surface. There are, however, few observations confirming this interpretation. The properties of the material making up the artificial fill have not been studied. Direct observations suggest that the material mostly consists of gravel, stones and boulders.

In the terrestrial areas the uppermost regolith has been affected by soil forming processes such as chemical weathering. In Forsmark, soil processes have been active for a relative short period of time since the area has been uplifted recently (Lundin et al. 2004). In areas with till and glacial clay the soils are consequently often rich in $CaCO_3$.

In summary, the terrestrial part of the model area is dominated by calcareous till and a high frequency of exposed bedrock. Low laying terrestrial areas are covered by thin layers of clay and sand. The region has only been uplifted for a short period and prominent peat layers have only formed wetlands situated at comparatively high altitude. The floor of the Baltic Sea is characterised by a high proportion of sand and clay. Clay gyttja and gyttja are deposited in shallow bays of the Baltic Sea and in lakes. The land areas have been subjected to soil forming processes only for a short period and the soils are rich in calcareous material.

The stratigraphy of QD in the model area is summarised in Table 3-1. The stratigraphy demonstrates how younger deposits successively, from the latest ice age until present, have been superimposed upon older deposits. The different types of regolith (QD) in Table 3-1 are labelled from Z1 to Z5 in the RDM. Note that the Z1 layer can be associated with any QD. In the RDM Z6 belongs to the bedrock and is consequently not regolith. Artificial fill (Z3c) is always resting directly upon the bedrock surface and is never overlaid by other Z-layer, As can be understood from Table 3-1, an area with peat can be expected to be underlain by several types of regolith, whereas an area with till is characterised by till resting directly on the bedrock surface. All areas with peat are, however, not necessarily underlain by all the deposits shown in Table 3-1.

Table 3-1. General stratigraphical distribution of Quaternary deposits (i.e. the regolith) in the Forsmark area. The Z-layers associated with the different deposits are shown in the final RDM. Note that all these layers are not present at the same site. Artificial fill (Z3c) is not shown in the table.

Regolith type	Relative age	Layer in the RDM
Any QD		Z1
Bog peat	Youngest	Z2
Fen peat		Z2
Gyttja	↓	Z4a
Clay gyttja		Z4a
Postglacial sand and gravel		Z3a
Glacial clay	↓	Z4b
Glaciofluvial sediments		Z3b
Till	Oldest	Z5
Uppermost bedrock		Z6

4 Methodology

The following steps were performed during the modelling of the RDM:

- A conceptual model was constructed showing the stratigraphical and geographical distribution of the regolith layers, including the uppermost bedrock.
- The regolith layers were sub-divided into 14 domains. The surface distribution of each domain shows a specific stratigraphical distribution of regolith. The distribution of domains was used to secure that all regolith layers are included in the final model.
- The average thicknesses of regolith layers were calculated for terrestrial areas, lakes and some shallow marine areas. These values were later used for modelling the regolith thicknesses in areas with low density of data.
- Databases were constructed including all data used for producing the RDM. Databases for modelling the bedrock surface and the thicknesses of the regolith layers were constructed separately.
- Areas without regolith (i. e. outcrops) were modelled by using the regolith maps.
- The upper and lower elevation of the regolith layers were interpolated, starting with the elevation of the bedrock surface.
- The elevations of the layers were adjusted in accordance with the stratigraphical distribution of regolith (distribution of domains).
- The thicknesses of the regolith layers were calculated by using the lower and upper elevations of the different layers.

The methodology is described in detail below.

4.1 Conceptual model

The Regolith Depth Model (RDM) is geometrical and presents the total regolith depth, the thickness of individual regolith layers and the bedrock topography. The conceptual model for the construction of the different layers (Figure 4-1) is mainly based on knowledge from the site obtained from studies conducted for the repository for spent nuclear fuel (Hedenström and Sohlenius 2008). Additional data from Nyberg et al. (2011) gave further information regarding the stratigraphical distribution of glaciofluvial sediments.

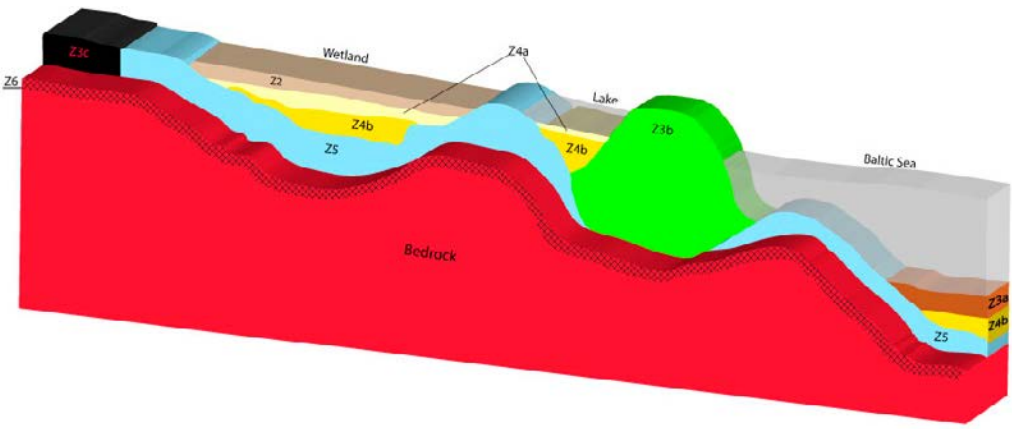

Figure 4-1. *The general distribution of the regolith layers (Z-layers) used in the RDM. The stratigraphy is further explained in Table 3-1 and Table 4-1. The uppermost layer, Z1, which represents the uppermost layer of regolith and outcrops, is not shown in the figure.*

The principle for the definition of the layers is illustrated in Figure 4-1. Note that the layer thicknesses are shown in a schematic way in the figure. The Z-layers and the stratigraphical distribution of these layers are explained in Table 4-1 and Table 4-2. Two RDM variants were produced (Variants 1 and 2). Variant 2 includes an uppermost surface layer (Z1), representing the regolith affected by soil forming processes and other currently occurring surface processes.

The model is subdivided into nine layers which distribution is illustrated in Figure 4-1, Table 3-1 and Table 4-1. Two variants of the model have been delivered. Variant 2 includes a surface layer Z1, which represents the uppermost 0.6 metre of the regolith and the uppermost 0.1 metre of bedrock outcrops (Table 4-1). This layer can be used to model processes in the soil and uppermost sediments. The first variant (1) of the model does not include the Z1-layer. The relations between the surface distribution of the regolith types and modelled underlying stratigraphy in the RDM are described in Table 4-2.

The model presents the geometry of the upper level for each layer and in addition the lower level of Z1 and Z6, as elevation above sea level (in the Swedish national elevation system from 1970, RH 70 system). Furthermore, the model also illustrates the thickness of each layer. The model has a spatial resolution of 20×20 m^2. 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 of whether 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).

Table 4-1. The nine regolith types represented by Z-layers, which are included in the Regolith Depth Model (RDM).

Layer	Regolith type (English term)	Jordart (Swedish term)	Comment
Z1*	Surface layer	*Ytlager*	The layer is only present in Variant 2 of the RDM and represents the uppermost regolith which is affected by surface processes, e. g. soil forming processes in the terrestrial parts or sedimentation/transport/erosion in the limnic/marine parts. Z1 is present within the entire modelled area. On bedrock outcrops, the layer is 0.1 m and 0.6 m in areas where the regolith is thicker than 0.6 m. If the total modelled regolith depth is 0.6 m, Z1 will be the only layer (The total regolith depth is never less than 0.6 m in areas with regolith). The layer can be connected to a GIS application such as the map of QD or soil type map and assigned properties in accordance to the properties of the deposits.
Z2	Peat	*Torv*	
Z3c	Artificial fill	*Fyllning*	This layer corresponds to material which has been artificially deposited by human.
Z4a	Clay gyttja and gyttja	*Lergyttja*	This layer also represents postglacial clay having a lower organic content than clay gyttja.
Z3a	Postglacial sand/gravel	*Postglacial sand/grus*	In the model this layer is only present in areas shown as postglacial sand or gravel on the regolith map, i.e. postglacial sand and gravel covered by other deposits (e.g. peat) are not shown in the model. In the terrestrial area Z3a also includes a few deposits with recent fluvial sediments.
Z4b	Glacial clay	*Glaciallera*	
Z3b	Glaciofluvial sediments	*Isälvsmaterial*	Corresponds to glaciofluvial eskers
Z5	Till	*Morän*	
Z6	The uppermost bedrock	*Den översta delen av berggrunden*	This layer has a constant depth of 0.6 m and represents the upper part of the bedrock, calculated from the interpolated Z5.The layer could be used to represent a high-conductive layer observed in many of the hydraulic tests in Forsmark.

*Present in Variant 2 but not in Variant 1.

Table 4-2. The stratigraphical distribution of the Z-layers, which are shown in the Regolith Depth Model (RDM). The stratigraphy represents the regolith types overlying the bedrock (from left to right). The regolith has been further subdivided into domains representing specific stratigraphies which are shown in Table 4-3.

Regolith type on the map of regolith	Stratigraphy	Comment
Till/Clayey till (Z5)	Z5	
Glacial clay/Glacial silt/ Clay (Z4b)	Z4b/Z5	
Postglacial sand and/or gravel (Z3a)	Z3a/Z4b/Z5	
Clay gyttja/Gyttja (Z4a)	Z4a/Z4b/Z5	
Artificial fill (Z3c)	Z3c	
Peat (Z2)	Z2/Z4a/Z4b/Z5	Peat areas bordering areas with water laid sediments (clay or sand)
Peat (Z2)	Z2/Z5	Peat areas not bordering areas with water laid sediments (clay or sand)
Glaciofluvial sediment [1] (Z3b)	Z3b	Z3b laying directly upon the bedrock surface
Glaciofluvial sediment [1] (Z3b)	Z3b/Z5	Z3b is resting upon till.

[1]In certain areas the glaciofluvial deposits are overlain by glacial clay (Z4b) and in some places also by clay gyttja (Z4a). These areas are exclusively situated in the marine area.

4.2 Areal distribution of regolith stratigraphy domains

The map of regolith contains numerous surfaces representing different types of regolith. Many of these surfaces lack stratigraphical observations. Based on the regolith map the area was subdivided into fourteen domains (Figure 4-2). Each domain represents one type of regolith and, since several types of regolith may occur at one site (Figure 4-1) several domains can be present at one site. The stratigraphy of the domains is distributed in accordance with the conceptual model (Figure 4-1 and Table 4-3). The domains were produced to secure that all stratigraphical units shown in Figure 4-1 are represented in the RDM. Figure 4-2 shows the surface distribution of the fourteen domains. Areas with bedrock outcrops lack regolith and are not included in the domains. The domains are distributed in the same stratigraphical order as the regolith (see Table 4-2). For example domain 1 (Till) is present in the whole marine area except where bedrock outcrops occur. This is because till is the oldest deposit, which is underlying all other types of regolith.

Different types of data were used to model the thickness of the layers in the domains (see Chapter 2). A study of the data showed that the regolith layers are generally thicker in the marine area compared to the terrestrial area (including the lakes). To take this into account in the modelling, two different domains representing the same regolith were defined for the marine and terrestrial areas (Figure 4-2). As an example, glacial clay in the terrestrial area is represented by a different domain than in the marine area.

In the terrestrial areas there are numerous small surfaces with water laid deposits. Stratigraphical observations have shown that these deposits often are situated directly upon the till and lack the complete stratigraphy illustrated in Figure 4-1. In areas on land where the aggregated area of sand (Z3a), peat (Z2), clay gyttja (Z4a) and glacial (Z4b) clay is smaller than 2 ha these deposits are consequently interpreted as situated directly upon the till. These small areas are represented by domain 10 in the modelling. There are however a few areas, smaller than 2 ha, where the deposits are distributed in accordance with Table 4-2. These small areas have observations confirming the occurrence of all stratigraphical units. Areas with peat, which do not border on water laid sediments, are interpreted as resting directly upon the till regardless of the size of the peatland.

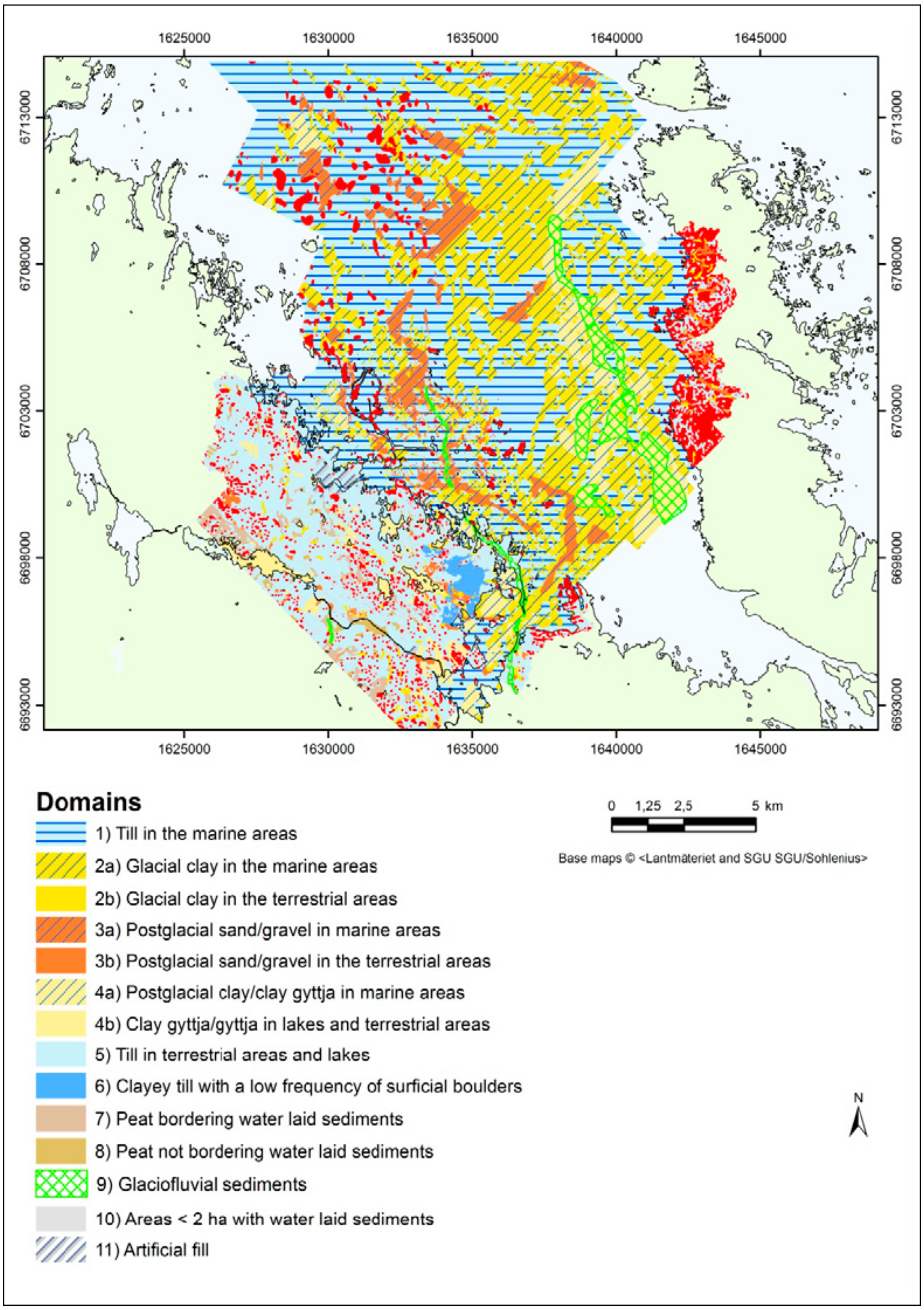

Figure 4-2. *The model area with the surface distribution of the fourteen domains used to delineate the different regolith types during the development of the RDM. Each domain represents a certain type of regolith with a specific stratigraphy. The domains are superimposed upon each other and several domains may consequently occur at one site. The red areas represent areas with outcrops that are excluded from the domains.*

Table 4-3. The fourteen domains used to delineate the different regolith types during the development of the RDM. The geographical distribution of the domain areas is shown in Figure 4-2. Areas on the regolith map that are smaller than 0.1 ha are ascribed to the surrounding domain (often till). Note that several domains can be present at one site. For example Domain 1 (Till) is present in the whole marine area except where bedrock outcrops occur. M=Marine area, L=Lakes, T=Terrestrial area.

Domain	Regolith type	Surface type	Stratigraphy	Comment
1	Till in the marine area	Marine	Z5	Present in the whole marine area except where bedrock outcrops occur.
2a	Glacial clay in the marine area	Marine	1) Z4b/Z5 2) Z4b/Z3b/Z5	In certain areas there is a layer with glaciofluvial sediments (Z3b) between Z4b and Z5.
2b	Glacial clay in the terrestrial area	Lake/Terrestrial	Z4b/Z5	In aggregated areas larger than 2 ha[2].
3a	Postglacial sand or gravel in the marine area	Marine	Z3a/Z4b/Z5	
3b	Postglacial sand or gravel in the terrestrial area[1]	Lake/Terrestrial	Z3a/Z4b/Z5	In aggregated areas larger than 2 ha[2].
4a	Postglacial clay/ clay gyttja in the marine area	Marine	1) Z4a/ Z4b/Z5 2) Z4a/Z4b/Z3b/Z5	In certain areas there is a layer with glaciofluvial sediments (Z3b) between Z4b and Z5.
4b	Clay gyttja/gyttja in the terrestrial area	Lake/Terrestrial	Z4a/Z4b/Z5	In aggregated areas larger than 2 ha[2].
5	Till in the terrestrial area	Lake/Terrestrial	Z5	Present in the whole T/L area except where bedrock outcrops occur.
6	Clayey till in the terrestrial area	Terrestrial	Z5	In areas with a low frequency of superficial boulders.
7	Peat	Terrestrial	Z2/Z4a/Z4b/Z5	Peat areas larger than 2 ha that border areas with water laid sediments.
8	Peat	Terrestrial	Z2/Z5	Peat areas larger than 2 ha that do not border areas with water laid sediments.
9	Glaciofluvial sediments	T/M	1) Z3b 2) Z3b/Z5	In parts of the marine area there is till (Z5) between Z3b and the bedrock.
10	Small areas with water deposited sediment or peat	Lake/Terrestrial	Deposits shown on the regolith map as Z4a Z4b, Z3a or Z2 are directly underlain by till (Z5)	Areas smaller than 2 ha.
11	Artificial fill	Terrestrial	Z3c	

[1]Recent fluvial sediments are included in this group.

[2]There are a few areas, smaller than 2 ha that have been attributed to Domain 3b. There are observations from these small areas showing a stratigraphy in accordance with Domain 3b.

In the marine area the density of data is generally high (Figure 2-2) and the thicknesses of the regolith layers were determined by interpolation (Kriging). In the terrestrial area (including lakes) the data density is generally low (Figure 2-3 and Figure 2-4) and it was therefore not possible to use data directly from the observation points when interpolating the thickness of the regolith layers. Instead the average thickness of each layer was first calculated by the use of data from the terrestrial area (Table 4-4). These average values were evenly distributed and thereafter used together with data from observations for interpolating the thickness of the regolith layers in areas lacking dense data from observations. It has been shown that the clayey till in the terrestrial areas has generally larger regolith depths than the till in general. The clayey till is therefore represented by a specific domain (Figure 4-2). There are no data showing the thickness of artificial fill and the value presented in Table 4-4 should be regarded as a rough estimate. Landforms entirely built up by regolith, such as eskers, are modelled in a special way, to avoid too thin regolith depths (see below).

Table 4-4. The average depth of the regolith layers in the terrestrial area. These values were used for interpolating the thickness of the regolith layers in terrestrial areas lacking depth information. In areas with several regolith types the average thicknesses were summarised according to the table above. Note that the average depth was not used for modelling the thickness of glaciofluvial deposits (see below). N = numbers of observations.

Regolith type		Average depth (m)	Standard deviation	N	Comment
Sandy and silty till	Z5	4.18	2.77	114	This value is only based on data from drillings, geophysical data was not used.
Clayey till	Z5	5.51	2.85	18	This value is only based on data from drillings, geophysical data was not used.
Glaciofluvial sediments	Z3b	Average depth was not used	–		In terrestrial areas where glaciofluvial deposits comprise a positive landform a special interpolation method was used (see text).
Glacial clay	Z4b	0.98	0.87	315	61 of these observations have depths < 0.5 metre.
Postglacial clay	Z4a	0.99	0.53	137	Only values >0.5 metre. There are numerous observations from sites with thin Z4a layers. These values would have given too low average values and were therefore excluded.
Postglacial sand	Z3a	0.60 m	–	–	This value is based on the estimation that the sand layer is thicker than 0.6 metre in areas mapped as sand.
Peat	Z2	1.11	0.47	24	In domain 10 a peat depth of 0.60 meter was used.
Artificial fill		3.00	–	–	This value is an estimate without data support, first was used by Hedenström et al. (2008). In terrestrial areas where artificial fill comprises a positive landform a special interpolation method was used (see text).

4.3 Construction of databases used for interpolation of raster surfaces

4.3.1 General description of data management

Data used for interpolation of raster layers representing the bedrock surface (Z5), clay gyttja (Z4a), glacial clay (Z4b), postglacial sand/gravel (Z3a), glaciofluvial sediments (Z3b), artificial fill (Z3c) and peat (Z2) used in the Regolith Depth Model (RDM) are of different origin and quality (Table 2-2). In order to generate a good result in the interpolation, data of lower quality were removed and data of higher quality kept in areas with overlapping data (see ranking in Section 2.5). The method for construction of databases used for interpolation of raster surfaces was based on judgment of test interpolations and knowledge of how the interpolation procedure works.

The marine geological data obtained by SGU (Elhammer and Sandkvist 2005, Nyberg et al. 2011) are divided in different areas based on the type of survey (Figure 2-5). The distance between survey lines in the regional area is sometimes more than 1000 m compared to around 100 m in the detailed area. The uneven spatial distribution of data may affect the result of interpolations. In the previous digital elevation model (DEM, Strömgren and Brydsten 2008) this distribution resulted in a ribbed pattern along the survey lines in the regional area. For the DEM used in the present RDM, a new method was developed to avoid this pattern and get a smoother and more realistic surface (Strömgren and Brydsten 2013).

The DEM (Strömgren and Brydsten 2013) was used as upper surface in the RDM. In the marine area data from Elhammer and Sandkvist (2005) and Nyberg et al. (2011) was used for interpolating both the DEM and the RDM. In order to generate smoother, more realistic surfaces, this data was handled in the same manner in the production of the layers in the RDM as in the production of the DEM. The similarities in the method used for the DEM and the RDM are listed below:

- Some data along the survey lines in Areas 5 and 7 in Figure 2-5 were excluded, and the data used for the model has a separation of approximately 50 m.
- Data from Area 6 in Figure 2-5 was recalculated to average values for 5 m cells.
- The interpolation method used in the production of the DEM was also used for the RDM.

Moreover, almost no average values for the different regolith types were used in the marine area, i.e. the marine area is mostly modelled by direct use of data from geophysical observations.

4.3.2 Modelling of areas with outcrops

In the previous RDM (Hedenström et al. 2008) the area with outcrops was overestimated, especially in areas with many small outcrops. The outcrops modelled in the previous RDM were produced from a conversion from the regolith map (ESRI shape format) to ESRI Raster format. In order to obtain a modelled outcrop area closer to the area shown on the regolith map (Figure 3-1) a new method for modelling the outcrop area was used in the current RDM.

In the first step, outcrop surfaces from the regolith map were divided into four different classes depending on the area. These classes range from relatively large areas to quite small areas. Several different combinations of areas were tested during the method development. The areas shown in Table 4-5 (column 1) were chosen since they gave the smallest difference between modelled area and outcrop area from the regolith map, when used in the next step of the outcrop modelling described below.

In the next step, a conversion of a raster layer representing the extension of the RDM with a 20 m cell size (20×20 m) to ESRI Shape format was done. The resulting shape file was used with the "Intersect" tool to obtain the outcrop surfaces from the regolith map. From the area of outcrops within each 20 m cell, calculations were performed in an iterative process to find the best fit between the regolith map and the outcrops area for the 20 m cells used in the RDM. This process was performed for all four area classes (column 1 in Table 4-5). The aim of these iterative calculations was to minimise the difference between the modelled outcrop surface and the total outcrop surface from the regolith map (column 4 in Table 4-5). An example of this procedure is illustrated in Figure 4-3. In Table 4-5 the deviation in percent between the modelled outcrop area (column 3) and the outcrop area from the regolith map (column 4) is shown (column 5). However, some outcrops from the regolith map with areas less than 29,000 m^2 (the smallest area class for outcrops in Table 4-5) were not represented since the intersected areas were smaller than or equal to 188 m^2 (the area calculated in the iterative process described above). All these small outcrops were therefore assigned one 20 m cell in the RDM. The 20 m cell with the largest outcrop area was chosen to represent these small outcrops. Finally, all 20 m cells modelled as outcrops were merged to one file in ESRI Shape format.

The modelled outcrops that were included in the Z5 database (Table 4-6) were assigned regolith depth zero in the model, i.e. the bedrock surface corresponds to the elevation of the DEM (Strömgren and Brydsten 2013).

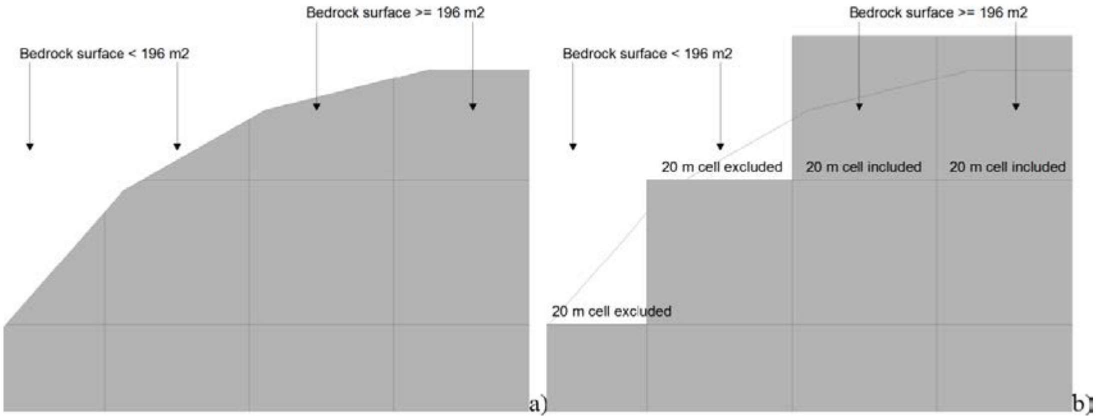

Figure 4-3. *Schematic illustration showing part of an intersected outcrop surface with an area < 75 000 m² and ≥ 29 000 m² (a). All outcrop areas < 196 m² within a 20 m cell were excluded from the RDM (b). All outcrop areas ≥ 196 m² were included as a 20 m cell characterised as outcrop in the RDM.*

Table 4-5. Areas used for modelling of the outcrop areas in the RDM (the unit for all areas is m²): (1) area of outcrop from regolith map, (2) smallest represented outcrop area from regolith map within a 20 m cell, (3) total modelled outcrop area, (4) total outcrop area on the regolith map and (5) deviation in percent between modelled outcrop area and corresponding area on the regolith map.

1. (m²)	2. (m²)	3. (m²)	4. (m²)	5. (%)
≥125 000	≥ 203	15 927 600	15 914 169	+0.073
≥75 000 and <125 000	≥ 200	3 064 000	3 061 469	+0.24
≥29 000 and < 75 000	≥ 196	6 354 000	6 343 882	+0.13
<29 000	≥ 188	8 484 400	8 671 828	+4.61
<29 000[1)]	None	586 800		
All areas		**34 416 800**	**33 991 348**	**+1.25**

[1)] All merged outcrops <29 000 m² not represented by modelled outcrops were assigned one 20 m cell modelled as outcrops.

Table 4-6. Databases used in the interpolation of bedrock surface (Z5). References to observations points are shown in Figure 2-5. The interpolation was performed in two steps. The average regolith depth values were calculated from observations shown in Table 4-4. In the first step, no average regolith depth values or data representing outcrops were used. In the second step the marine geological data obtained by SGU (Elhammer and Sandkvist 2005, Nyberg et al. 2011) was replaced by elevation data produced in the first interpolation. Outcrops, average regolith depth values for the terrestrial area (Table 4-4) and some average regolith depth values for shallow bays were also included in the database used in the second interpolation.

Data source	Interpolation step 1 (number of points)	Interpolation step 2 (number of points)
Data from interpolation step 1		437,259
Average regolith depth values (terrestrial area)		124,914
Average regolith depth values (marine area)		2,541
Seismic and sediment echo sounding data (Area 6 in Figure 2-5)	50,590	
Seismic and sediment echo sounding data (Area 4 in Figure 2-5)	83,378	
Seismic and sediment echo sounding data (Area 5 and 7 in Figure 2-5)	5,671	
Outcrops		86,015
Other data reaching bedrock	8,108	7,326
Total no of points	**147,747**	**658,055**

4.3.3 Database for modelling the bedrock surface

For some areas, data from different studies are available. For modelling the bedrock surface (the Z5 database) in these areas the data with the highest ranking was used (Section 2.5). In the marine area data from area 4, 5 and 7 (Figure 2-5) within 50 m from data shown in area 5 (Figure 2-5) was excluded from the database used for modelling the bedrock surface. Data within Area 5 and 7 and within 50 m from Area 4 was also excluded from the Z5 database. Data from drillings in fine grained sediment (Table 4-7) situated less than 30 meters from data with higher ranking number was also excluded from the Z5 database.

In the terrestrial area, points converted from the DEM (Strömgren and Brydsten 2013) within the domains described in Table 4-3 were given average values (Table 4-4) for the regolith depth according to which domain they were located in. These average regolith depth values were recalculated to elevations by subtraction from the corresponding elevations in the DEM (Strömgren and Brydsten 2013). All average values within 30 m from measurement data or data corresponding to outcrops were removed. The aim was to interpolate the bedrock surface for the marine area without including any average values. However, some test interpolations showed that it was necessary to include average regolith depth values (Table 4-4) in certain parts of the shallow bays. These areas have a low density of data and the regolith depths obtained from interpolations were considered as too small compared to other surrounding areas.

The interpolation was performed in two steps, which was necessary to minimise the use of average regolith depth data. Data used in these two steps is shown in Table 4-6. In the first step no average regolith depth values or data showing outcrops were used. Test interpolations including outcrop data resulted in an unrealistically thin regolith depths close to the outcrops, since the impact of the outcrops was too large on the interpolation result. Data within 30 m from outcrops was not included in the Z5 database used in the first step of the interpolation.

Outcrops were included in the second step and measurement data in the marine area was replaced by elevation data converted to points from the raster layer produced in the first interpolation. All points within 50 m from points corresponding to outcrops were excluded from the Z5 database used for the final interpolation. In the parts of the shallow bays where the total regolith depth was modelled as too thin, around 2,500 elevation points from the first interpolation was also replaced by average regolith depth values.

In the terrestrial area both measurement data and average regolith depth values were used. However, average regolith depth values within 30 m from measurement data or data corresponding to outcrops were excluded from the Z5 database used for the final interpolation.

Table 4-7. Data used for the RDM in the marine area. Data sources and the number of observations used for the first interpolation of the lower level of postglacial sand/gravel (Z3a), clay gyttja (Z4a), glacial clay (Z4b) and the final interpolation of glaciofluvial sediments (Z3b). References to observations points and studied areas are shown in Figure 2-5.

Data source	Postglacial sand/gravel (Z3a) N	Clay gyttja (Z4a) N	Glacial clay (Z4b) N	Glaciofluvial sediments (Z3b) N
Seismic and sediment echo sounding data (Area 6)	21,096	4,677	31,711	1,542
Seismic and sediment echo sounding data (Area 4)	30,716	2,428	60,826	
Seismic and sediment echo sounding data (Area 5 and 7)	1,265	1,138	3,688	591
Data from drillings in fine grained sediments	10	120	142	
Total no of points	**53,087**	**8,363**	**96,367**	**2,133**

4.3.4 Databases for modelling the thickness of the regolith layers

Similar to the databases for Z5, databases were constructed for interpolation of raster surfaces for the lower level of clay gyttja (Z4a), glacial clay (Z4b), postglacial sand/gravel (Z3a), glaciofluvial sediments (Z3b), and peat (Z2). Data used in these databases are described in Table 4-7 and Table 4-8. In the marine area two interpolations were necessary also for most of these layers, for the same reasons as mentioned for the bedrock surface. However, only one interpolation was necessary for Z2 and Z3b, since Z2 is mostly modelled from average regolith depth values and Z3b only cover small areas.

The outer boundaries of Z4a, Z4b, Z3a and Z2, obtained from the regolith map, were divided every 20 m by "extension points" where the thicknesses of the layers were set to zero, see Table 4-8. Data for the outer boundaries was not included in the first interpolation, since these data would have had too large weight in the interpolation procedure, resulting in too thin regolith some distance from these outer boundaries. Only measured data was used in the first interpolation (Table 4-6). In the second interpolation, measured data in the marine area was replaced by elevation data converted to points from the raster layers produced in the first interpolation for all Z-layers shown in Table 4-8. In the second interpolation average regolith depth values (Table 4-4) for the terrestrial area and for some small areas in shallow bays, and data representing outcrops and the outer boundaries of the Z-layers shown in Table 4-8 were also included. The same rules were applied as when constructing the Z5 databases regarding buffer distance between different data sources.

The lower level of peat (Z2) was interpolated in one step using mostly average regolith depth values (Table 4-8). The lower level of glaciofluvial sediments (Z3b) in the marine area was interpolated in one step using marine geological data obtained by SGU (Elhammer and Sandkvist 2005, Nyberg et al. 2011) shown in Table 4-7 within the extension of Z3b.

No average depth values were used for modelling the thickness of glaciofluvial sediments (Z3b) in the terrestrial area where Z3b is represented by eskers that constitute landforms entirely built up by regolith. Modelling the bedrock surface beneath these eskers, using average depth values would have resulted in a convex shape of the bedrock surface below the eskers, which is not in accordance with the general knowledge of the regolith distribution in the area. Instead, the bedrock surface below Z3b was interpolated using average depth values of the regolith layers on either side of the esker (illustrated in Figure 4-4). This was done in the final interpolation of the bedrock surface (lower level of Z5) for the RDM using data shown in Table 4-6.

The lower level of Z3c (artificial fill) was modelled using two different methods. In Figure 4-5 the dark blue colour shows areas with artificial fill where average depth values for Z3c were used to calculate the level of the bedrock surface. It should be noted that in areas with artificial fill there are no data from observations showing the level of the bedrock surface.

Table 4-8. Data sources and number of points (N) used for the second and final interpolation of the lower level of postglacial sand/gravel (Z3a), clay gyttja (Z4a), glacial clay (Z4b) and peat (Z2). The average regolith depth values were calculated from observations shown in Table 4-4.

Data source	Postglacial sand/gravel (Z3a) N	Clay gyttja (Z4a) N	Glacial clay (Z4b) N	Peat (Z2) N
Data from interpolation step 1	38,758	49,587	244,144	
Average regolith depth values (terrestrial area)	6,594	21,844	34,307	13,196
Average regolith depth values (shallow marine area)		598	983	
Outcrops	86,015	86,015	86,015	86,015
Extension points	15,516	15,578	63,518	7,674
Data from drillings in fine grained sediments and peat	1	72	98	27
Total no of points	**146,884**	**173,694**	**429,065**	**106,912**

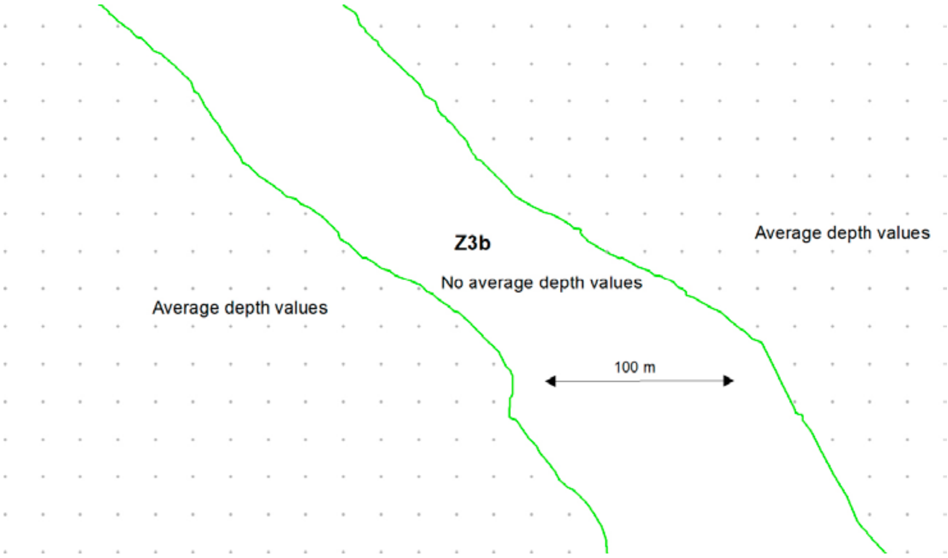

Figure 4-4. *Schematic illustration from the terrestrial area where the bedrock surface (Z5) in an area with glaciofluvial sediments (Z3b), constituting an esker, was interpolated using average depth values of the regolith (Table 4-4) on either side of the deposit. This method was used since the esker is a positive landform entirely built up by regolith. If average values would have been used for modelling the esker the resulting bedrock surface beneath the esker would have followed the topography of the esker, which is not realistic.*

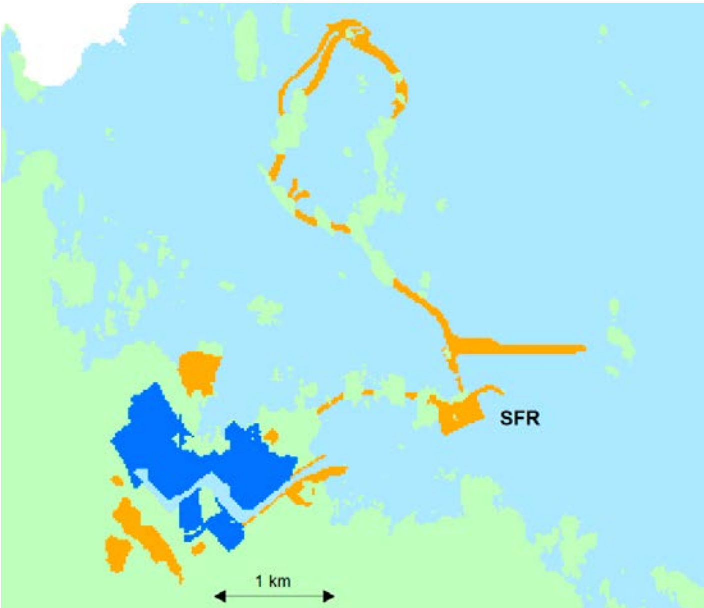

Figure 4-5. *This map shows all areas modelled as Z3c except for two small areas situated in another part of the RDM. The lower level of Z3c was calculated using average depth values in the dark blue areas. The lower boundary surface of Z3c was calculated with an interpolation between surrounding average depth values for other regolith types (see Figure 4-4) in the orange areas. The orange areas were modelled in the same way as the glaciofluvial sediments in the terrestrial area (Figure 4-4).*

The bedrock levels in the dark blue marked areas (Figure 4-5) with artificial fill shown in the resulting RDM should therefore be regarded as assumptions. The orange colour in Figure 4-5 shows areas where the lower level of Z3c was calculated with the same method as used for the glaciofluvial eskers (see Figure 4-4), i.e. an interpolation between average depth values of surrounding regolith. This was done in areas where the artificial fill constitutes landforms, which are interpreted as entirely built up by regolith. The interpolation of the lower level of Z3c was done in the final interpolation of the bedrock surface (Z5) for the RDM using data shown in Table 4-6.

4.4 Interpolation of data to obtain the RDM

Using the databases described in the previous section, raster surfaces for the bedrock surface (lower level of Z5) and the lower level of Z4a, Z4b, Z3a, Z3b, Z3c and Z2 were produced. The interpolations from irregularly spaced point values to regularly spaced raster layers were done using the software ArcGis 9.3.1 Geostatistical Analysis extension. Ordinary Kriging was chosen as the interpolation method (Davis 1986, pp 383–404, Isaaks and Srivastava 1989). A spherical theoretical semivariogram model was used in all interpolations. A smooth interpolation (Gribov and Krivoruchko 2004) was performed in Ordinary Kriging using 20 m cell size. This method was previously used for the marine area in the production of the DEM (Strömgren and Brydsten 2013), which has a similar spatial distribution of input data as used for the RDM. The result of the smooth interpolation was a DEM without artefacts caused by irregular distribution of data.

First the bedrock surface (lower level of Z5) was interpolated. Note that Z5, as the other modelled layers, is present in the whole model area, but is represented by a layer with thickness zero where till is lacking. The raster layers representing the lower level of the regolith layers were validated both with cross validation (one data point was removed and the rest of the data was used to predict the removed data point) and ordinary validation (part of the data was removed and the rest of the data was used to predict the removed data). Both the cross validation and ordinary validation goals produce a standardised mean prediction error near zero, small root-mean-square prediction errors, average standard error near root-mean-square prediction errors, and standardised root-mean-square prediction errors near one.

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. The final choice of parameters and statistics from the cross validations and validations are presented in Appendix 2. Only statistics for the interpolations performed using measured data are shown. Statistics from the final interpolations, where average regolith depth values and elevation values from the first interpolation were used, would not have resulted in reliable statistics and consequently would have underestimated the degree of uncertainty in the interpolated layers. However, all models used for all interpolations are shown in Appendix 2. As described in Section 4.3.4, in the marine area two interpolations were performed for all raster layers except for Z2, Z3b and Z3c.

4.5 Post-processing of interpolated surfaces

After the interpolation procedure was finished, the resulting layers were adjusted to the extent of the RDM, since these raster layers were produced in a larger geographical extension than the RDM. In the next step, the layers were adjusted to follow the stratigraphical order described in Figure 4-1 and Table 3-1. All adjustments were done in ArcGIS 9.3.1 Spatial analyst. The adjustments were performed beginning from the lowermost surface, i.e. the bedrock surface, and upwards in correct stratigraphical order (see Table 3-1). Thin layers were allowed in the model, i.e. no adjustment of the thickness was done. However, the bedrock surface was adjusted to ensure a minimum total regolith depth of 0.6 m, corresponding to Z1, in all areas not modelled as outcrops.

All layers were adjusted not to exceed the upper surface of the RDM as given by the DEM (Strömgren and Brydsten 2013) and adjusted not to exceed the layer(s) next upward. For all layers areas modelled as outcrops were adjusted to the correct topographical levels with the DEM (Strömgren and Brydsten 2013).

In the marine area, other adjustments were necessary for the glaciofluvial sediments (Z3b) before the adjustments described above were performed. The bedrock surface was first subtracted from the raster layer corresponding to Z3b produced in the interpolation. All 20 m cells within the extent of Z3b in the marine area where the interpolated surface was just above or below the bedrock surface were adjusted to the elevation of the bedrock surface, i.e. Z3b is modelled to rest directly upon the bedrock surface in these areas. All other 20 m cells within the extent of Z3b are modelled to show areas where Z3b rests upon a layer of till. The marine geological data obtained by SGU (Elhammer and Sandkvist 2005, Nyberg et al. 2011) also show that Z3b either rests directly upon the bedrock surface or on a layer of till.

Z1 represents the uppermost regolith that is affected by surface processes, e. g. soil forming processes. Z1 was not interpolated but was calculated from other layers. Z1 covers the whole model area and has a depth of 0.6 m in all areas except for outcrops where the depth is 0.1 m (see Section 4.1). The total regolith depth is consequently 0.6 meter or more in all areas covered by regolith.

Z6 is actually located beneath the regolith and is intended to represent the upper 0.6 m of the bedrock. The lower level of Z6 was not interpolated but was calculated as a 0.6 m thick layer situated beneath the bedrock surface (the lower level of Z5).

For the final RDM all raster were recalculated to represent the upper level of each Z-layer. This was necessary for the use of the RDM in further modelling. Note that the upper level of each Z-layer is present in the whole model area. All deposits represented by the Z-layers are, however, not present in the whole model area. In a certain area several Z-layers may consequently have thickness zero and the same elevations.

The calculations of the upper level of the Z-layers were done starting from the lowermost layer and upwards, i.e. the upper surface of till was calculated first. All 20 m cells for the lower level of the Z-layers overlaying till (Z5) were identified. Z5 was covered by different regolith types, i.e. in some parts Z5 was overlain by Z3b and in other parts by Z4b and so on. In areas where no till exists, the upper elevation of outcrops was used as the upper level of Z5 to get a continuous raster surface for the whole model area. All these areas from the different Z-layers were merged to one layer representing the upper level of till (Z5) and outcrops.

The upper level of glaciofluvial sediment (Z3b) was calculated next. This was done using the method used for Z5, i.e. by identifying the regolith types overlaying Z3b. For all other surfaces the upper level of Z5 and bedrock (outcrops) were used to represent the upper level of Z3b. The upper level of Z4b was calculated next. For all surfaces that were not represented by the upper level of Z4b, the upper level of Z3b, Z5 and outcrops were used instead. These calculations were repeated for the remaining Z-layers upwards. Finally, the thickness of each Z-layer was calculated by subtracting the upper surface for the layer with the upper surface of the layer closest downward in the stratigraphy.

5 Results

The resulting RDM shows the total thickness of regolith as well as the thicknesses of the individual regolith layers. The distribution of the layers is shown by different raster, showing either the altitude of the regolith layers in relation to the sea level (Swedish national elevation system from 1970, RH 70) or the thicknesses of the regolith layers.

5.1 Total regolith depth

Figure 5-1 and Figure 5-2 show the total modelled regolith depth in the whole model area and in the central area (within a few kilometres from SFR), respectively. The maximum depth of regolith in the model is about 47 m, and the average depth is 6.7 m with bedrock outcrops included and 7.5 m with outcrops excluded. There is a difference between the average regolith depths in the terrestrial and marine areas, which are 4.0 m and 8.3 m, respectively. The thickness of the regolith often follows the underlying bedrock topography. That means that the thickest layers of regolith are found in areas of low bedrock surface elevation. Consequently, the regolith depths are generally larger in the marine area compared to the terrestrial. The largest regolith depths are found in the clay areas at the floor of Öregrundsgrepen and Kallrigafjärden. The RDM reveals several lineaments in the bedrock surface, e.g. an area with thick regolith which is visible on the sea floor in Kallrigafjärden with a direction towards north-east. Another lineament with a south-eastern direction can be seen at the sea floor south-east of SFR (Figure 5-1). These two lineaments have also been recognised during SKB's characterisation of the bedrock (SKB 2008).

The Esker Börstilsåsen and some artificial fill (e.g. the pier above SFR Figure 4-5) are exceptions from the rule mentioned above, since these deposits comprise morphological landforms entirely built up by regolith, and the upper surface of these deposits does not follow the morphology of the underlying bedrock.

In the terrestrial area the density of data is in general low and the thickness of the regolith layers was mainly interpolated by using average values of existing data (Table 4-4). Compared to the marine area the modelled regolith layers are therefore characterised by small variations in regolith thickness and sites represented by observations are in many places reflected by deviating thicknesses of the Z-layers. In the model several of the cored sites are consequently shown as holes or heaps with thicker or thinner regolith respectively.

Figure 5-2 shows the regolith depths around SFR, which is situated in the central part of the model area. The area bounded by a lilac line in Figure 5-2 was investigated by Nyberg et al. (2011) and constitutes of detailed a map of QD and the highest geographical density of observations concerning stratigraphy and depth of the regolith (Figure 2-2 and Figure 2-5). The confidence in the model is therefore largest for this area.

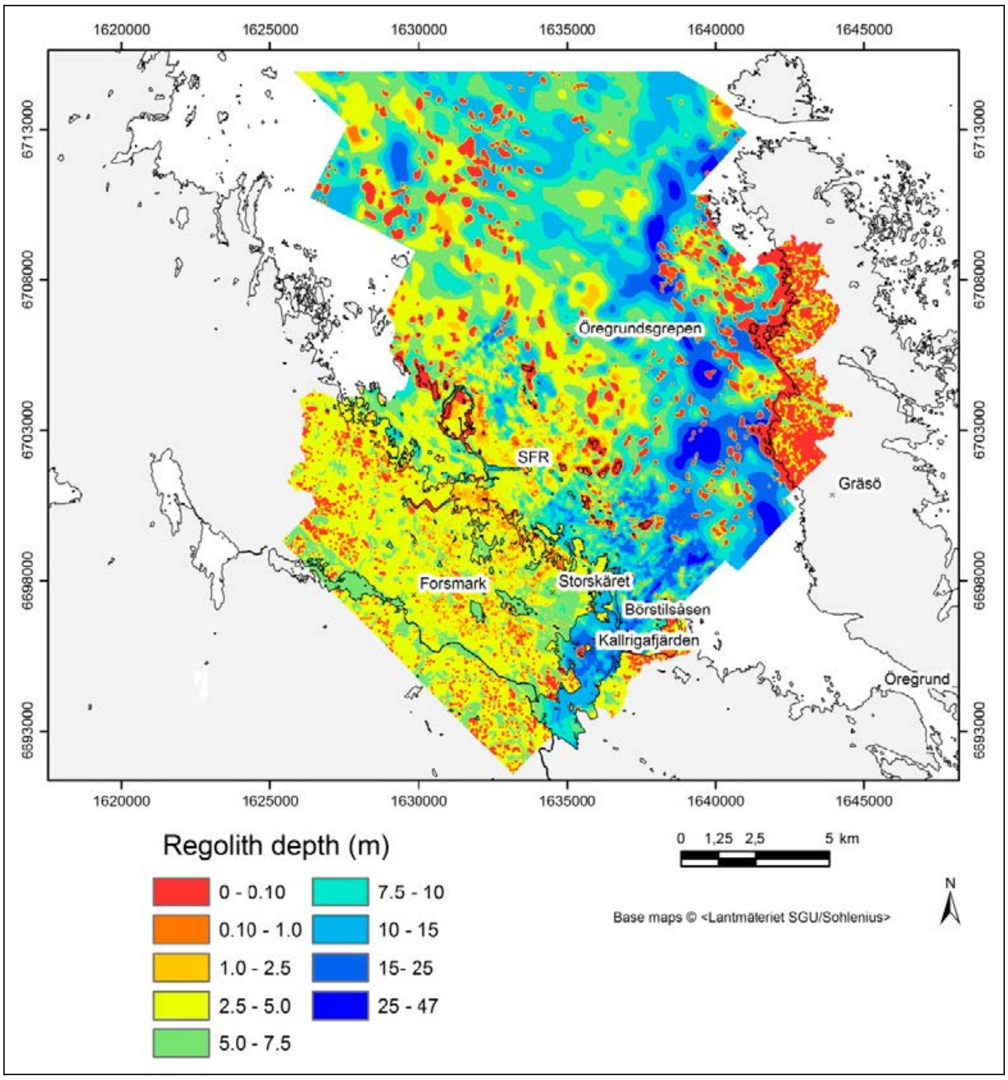

Figure 5-1. *Total modelled regolith depth. The terrestrial areas outside the model area are shaded in grey, whereas areas with water are white. The present shoreline is marked by a black line. Note that water is not depicted within the model area.*

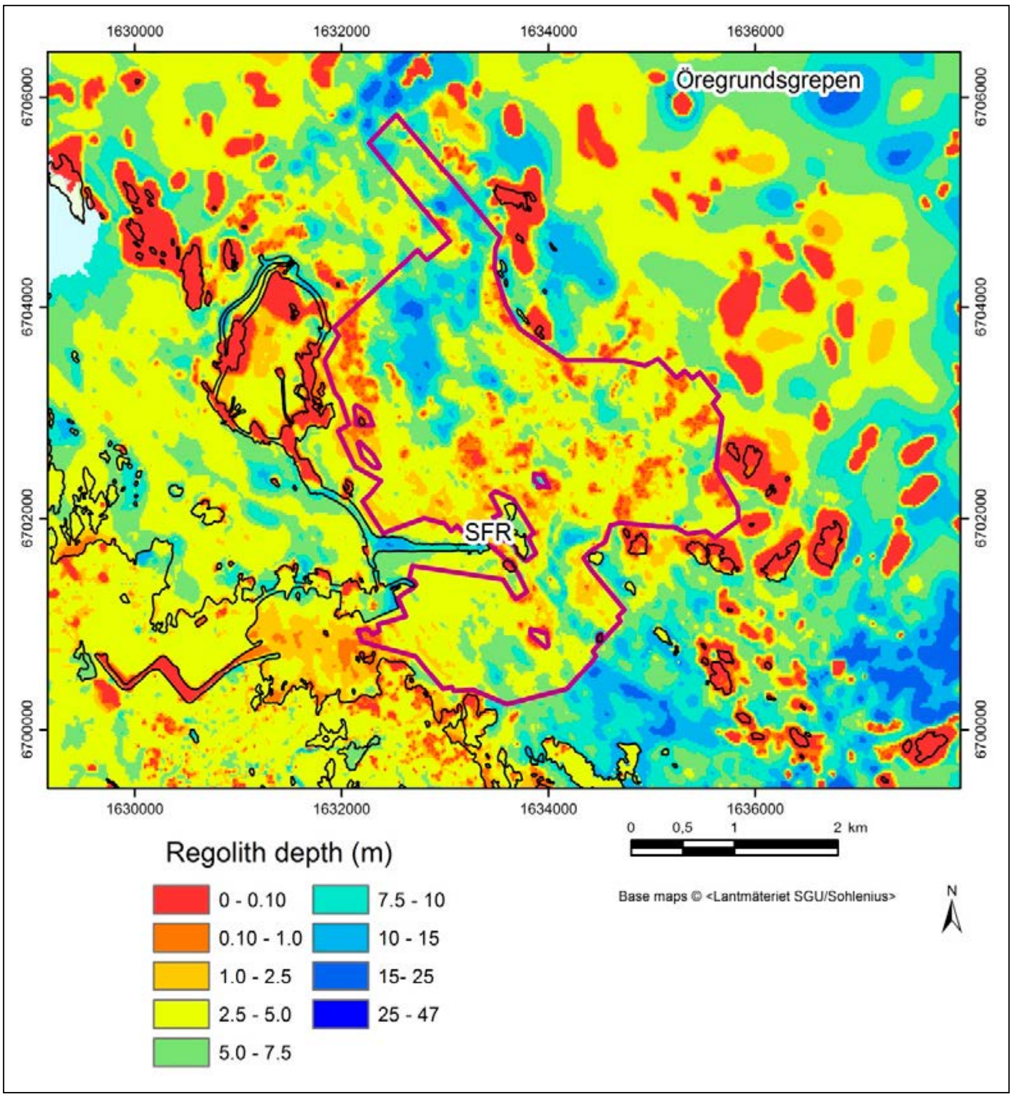

Figure 5-2. *Total modelled regolith depths in the central part of the model area. The shoreline is marked with a black line. The lilac line delineates the area with the highest density of data used for the RDM (Figure 2-5). That area was investigated during a marine geological survey (Nyberg et al. 2011).*

5.2 Vertical profiles

Altogether 14 stratigraphical profiles were drawn along selected lines (Figure 5-3) and show the interpolated thickness and stratigraphical distribution of the regolith layers represented by the Z-layers. The lines were selected to represent the different geological settings within the model area. Some lines were also selected to illustrate how the quality and quantity of data used for the modelling reflect the resulting RDM. It should be noted that the scale on the y-axis is up to 50 times enhanced compared to the scale on the x-axis, i.e. the thicknesses of the regolith layers are strongly exaggerated in relation to the length of the profiles. The distribution of QD in the surroundings of the profiles is shown on separate maps in Appendix 1. One figure also shows the observation points that are situated around a profile (Figure 5-4).

In the area above SFR the density of data with high quality is generally high and the profiles give a realistic picture of the thickness and distribution of the regolith layers (see Figure A1-1, Figure A1-2, Figure A1-3 and Figure A1-4 in Appendix 1). In the terrestrial area the regolith layers were in large parts modelled by using interpolations with the average thickness of each layer (Table 4-4) as recorded from observations in the area. The approximations involved in this procedure are obvious in some of the profiles, e.g, the profile from Lake Fiskarfjärden (Figure 5-4), where the observed regolith thickness diverges from the average values used in the RDM. In that area the observed thicknesses of clay are larger than the average, giving rise to small areas with clay depths considerably larger than in the surroundings. In the RDM the till is thinner below the small areas where observations have resulted in thick clay layers in the model (Figure 5-4), which is unlikely.

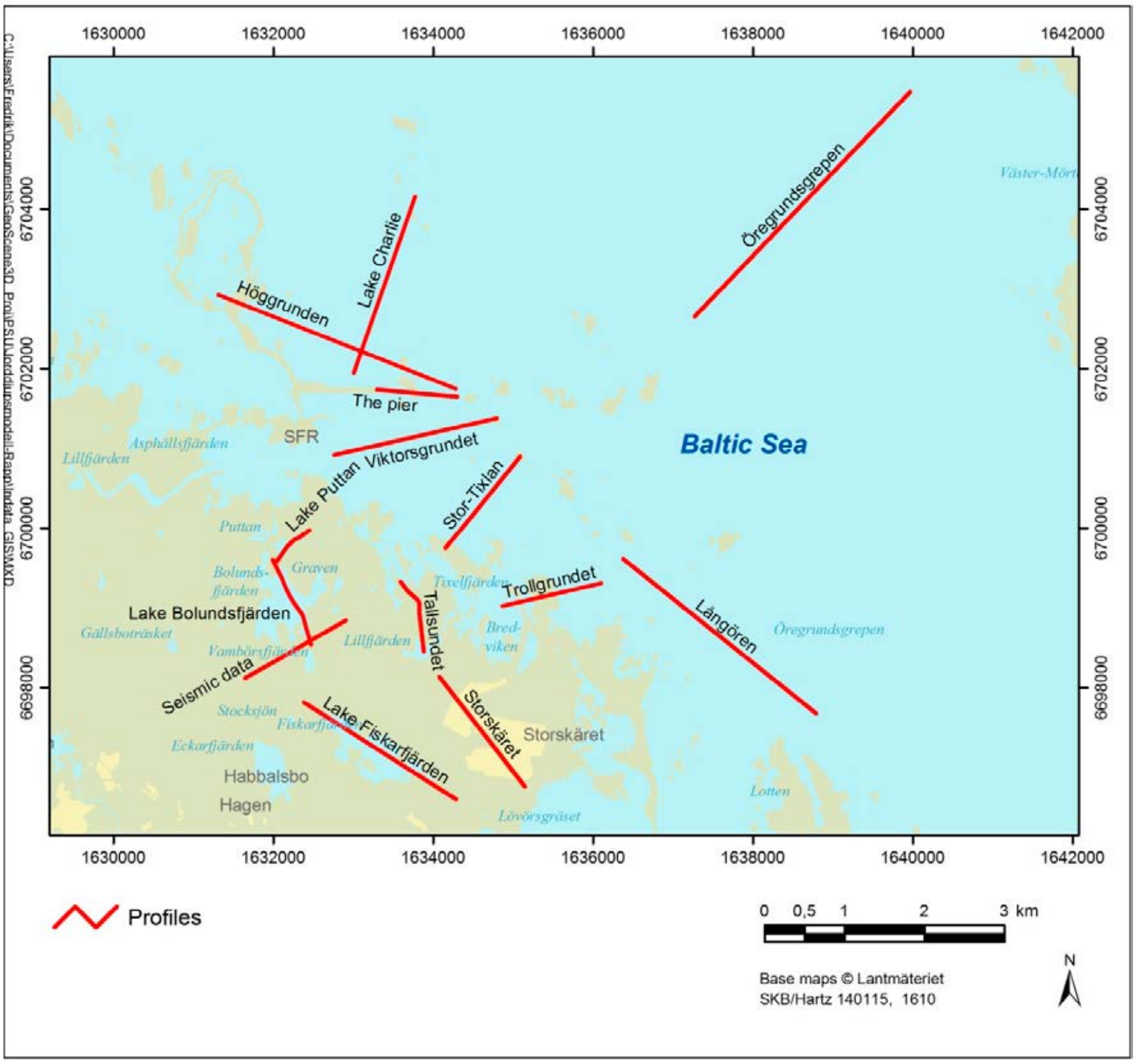

Figure 5-3. The locations and names of the stratigraphical profiles presented in Figure 5-4 and Appendix 1.

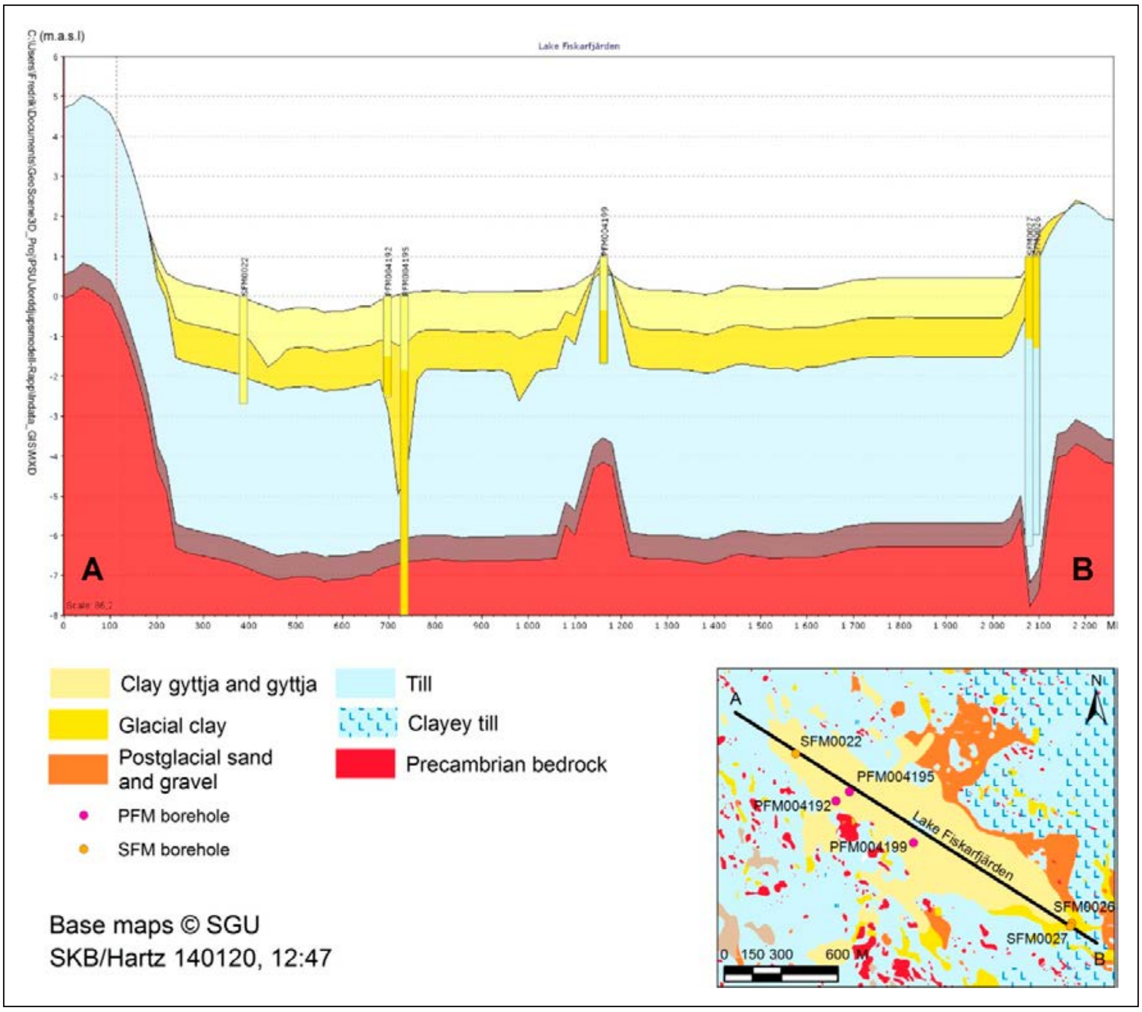

***Figure 5-4.** Profile from Lake Fiskarfjärden showing the stratigraphical distribution of regolith in the lake. The calculated average values of the regolith layers (Table 4-4) were used for interpolating regolith depths along large parts of the profile. Sites with observations used as input to the model are shown along the profile. The observations denoted PFM are results from corings with a hand driven corer. It is not possible to penetrate to the till with that method. Observations denoted SFM are from drillings, which show the depth of till. It is obvious that the results from the observations diverge from the average values. The regolith types are explained in the figures below and the Z-layers representing these regolith types are shown in Table 3-1 and Table 4-1.*

At the transition from one domain to another, e.g. from clay to till, the thicknesses of the regolith layers often change abruptly. This can be observed by studying the raster layers demonstrating the thickness of the regolith layers, and is most obvious in areas with a low density of data. However, the variations in thickness shown in the profiles have been smoothened and do not fully reflect the abrupt variations in the RDM.

The esker and the pier are landforms that are entirely built up by regolith, and were interpolated with a specific method (see Section 4.3.3). The results of that interpolation are illustrated by Figure A1-3 and Figure A1-11 in Appendix 1.

Areas with clayey till are characterised by thicker till layers than other till areas, as observed when comparing Figure A1-10 in Appendix 1 with the other profiles. The relatively thick till layers around Storskäret can also be seen in Figure 5-1, which shows the total regolith depths in the area.

5.3 Raster included in the Regolith Depth Model

The RDM was delivered as 37 layers in ESRI raster format and can be found in SKB GIS database (N-STH-SDE APP2).The thickness and upper level of all Z layers (Table 4-1) are represented by raster layers. All raster layers include the whole model area even though the regolith layers represented by the Z layers are not present in the whole areas. The thickness of a specific Z-layer is consequently zero in the parts of the model area where corresponding regolith type is absent. Two variants of the model have been produced, where Variant 2 includes the uppermost regolith layer (Z1), which is affected by surface processes. The upper levels of the raster layers are presented in metres above the present sea level (according to the Swedish national height system 1970, RH 70). There are also two raster layers showing the lower levels of Z1 and Z6 (in metres above the present sea level). The upper level of the bedrock corresponds to the upper level of Z6 (the uppermost bedrock) and is represented by a specific raster. In addition to the raster layers showing the thicknesses of the individual Z layers (in meters) the total thickness of all regolith is represented by one specific raster. At a certain site it is possible to illustrate the stratigraphical distribution and the thicknesses of the regolith layers by adding the upper level of all Z layer in accordance with the general stratigraphical distribution of the regolith layers (Figure 4-1).

6 Discussion and conclusions

6.1 Uncertainties in the RDM

The quality of the RDM varies with the density and quality of the input data (see Chapter 2). The most crucial part of the RDM is situated above and around SFR. This sub-area has a high density of data with high quality (Nyberg et al. 2011, Figure 5-2 and e.g. Figure A1-1 of the present report), showing both the total thickness and the thicknesses of the individual regolith layers (Z-layers in the RDM). In most of the terrestrial areas, interpolations by the use of average thicknesses of the individual Z-layers (Table 4-4) were used to produce the RDM. This method was used since the density of data is low in the terrestrial area. However, in some areas the thicknesses of the layers may differ significantly from the average. This is illustrated by the measuring lines with data from ground geophysics, which in some places are clearly shown in the RDM, illustrating the discrepancy between measured data and average values. This is further illustrated in Lake Fiskarfjärden, where the clay thicknesses are larger than the average at most of the sites that have been cored (Figure 5-4). In other areas, e. g. Lake Bolundsfjärden, the thickness of certain layers are thinner than the average values (Figure A1-7 in Appendix 1).

The modelled thicknesses of the regolith layers often change steeply at transitions between two domains (e.g. at the transitions from till to clay). These abrupt changes in thickness are too commonly occurring to be realistic. This is, however, not fully illustrated in the profiles (Appendix 1) where the changes in regolith thicknesses have been smoothed when producing the profiles. Furthermore, the thickness of till (Z5) is at some sites smaller in areas where the till is overlain by clay than in areas where till is the only regolith type (e. g. Figure A1-13 in Appendix 1 from Långören in the marine area). This is not a likely distribution of the till, which would be expected to be at least as thick in clay covered areas as in other till areas. The reason for the steep change of e.g. clay at the domain boundaries can at least partly be explained by low density of data in combination with the interpolation method, which obviously gives too large clay thicknesses close to the outer limit of the clay occurrences.

In the marine area the regolith thickness was estimated by the use of interpolations of data from observations, whereas, as mentioned above, interpolations with average values of the regolith layers were used in the terrestrial area, including lakes and some shallow bays. One effect of this is that the increase in regolith thickness often is very sharp at the transition from land to marine areas. The regolith thickness is on average larger in the marine area than on land, but the increase is not likely to be as sharp as shown in the RDM when going from the terrestrial to the marine area (see e.g. Figure A1-5 from Stor-Tixlan in Appendix 1). One additional reason for the steep transition between land and sea is that there is almost no data on total regolith depths in the shallowest marine areas, i.e. the transition area between the terrestrial and marine areas.

The quality of input data was evaluated for the ranking of data (Section 2.5). It is, however, difficult to quantify the uncertainty in especially the geophysical interpretations, since drillings are missing in large areas. The regolith layer thicknesses in the marine area are modelled from interpretations of seismic and sediment echo soundings only. There are no drillings available to confirm the thickness of the regolith cover.

6.2 Comparison with earlier RDM from the area

The RDM presented here is improved in several ways compared to earlier RDM versions (Hedenström et al. 2008, Vikström 2005). The most important differences are listed below.

- The present RDM comprises a larger geographical area, and includes parts of the Island Gräsö and also larger areas of the sea floor in the northern part of the model area.
- The DEM, which is used as input to the RDM, has been improved, especially in parts of the marine area, e. g. in Area 5 (Figure 2-5), where most data is distributed along lines with a separation of 1 km. In the present DEM the sea floor surface is less ribbed in Area 5 due to the use of a different interpolation method, modified from Strömgren and Brydsten (2013). Compared to the earlier RDM (Hedenström et al. 2008), this resulted in less ribbed regolith depths in that area. The false lineaments that were present in the earlier RDM are consequently absent.
- In the area around SFR (Area 6 in Figure 2-5) the present RDM is based on considerably larger dataset concerning both regolith and bathymetry data, which gives a higher confidence in the model for that area.
- In the marine area the present model is almost completely based on interpolations of data from observations. The earlier model was constructed by the use of average values in the parts of the marine area that had a low data density. The result of the interpolation method used in the present RDM is regolith depths less affected by the uneven distribution of data, and the present RDM gives consequently a more realistic topography of the upper bedrock surface. In Hedenström et al. (2008), the SGU survey lines in Öregrundsgrepen were clearly reflected in the resulting RDM giving the regolith depths a ripped appearance. This appearance was, however, partly an effect of the quality of the DEM (see above).
- In earlier models the distribution of clay and gyttja in lakes was illustrated by the use of three lenses (Hedenström et al. 2008). In the present model the same Z-layers were used in the lakes as in the remaining parts of the model area. This makes the model more consistent. However, the clay thickness in some of the lakes may have been under- or overestimated in the present model, which can be seen by diverging thicknesses along some of the profiles (see Figure 5-4 and Figure A1-7 in Appendix 1).
- The areas with outcrops are less exaggerated compared to the RDM by Hedenström et al. (2008). In this previous model, the total area with outcrops is 38% larger than on the map of regolith. In the present model this difference is only 1%.
- The bedrock surface below positive landforms in the regolith cover (including artificial fill) is more realistically modelled compared to former RDM versions, where the bedrock surface followed the ground surface (e.g. below Esker Börstilsåsen and the pier above SFR).
- The RDM used new data showing that glaciofluvial deposits are present in the marine areas. These deposits were not represented in earlier RDMs.
- In the terrestrial area, small sub-areas with clay and sand/gravel are represented in the present RDM. These deposits were almost absent from the terrestrial parts of earlier RDMs, where they were modelled as consisting of till.
- In the terrestrial area the difference between the present and former RDM is generally small. The differences between the RDMs are larger in the marine area due to the improved interpolation method used for the present RDM.
- The present RDM shows smaller regolith depths in shallow bays compared to earlier RDMs. Data showing the total regolith depths is almost lacking in these areas and it is consequently not possible to determine whether the present model is more realistic in predicting regolith thicknesses in the shallow bays.

6.3 Conclusions

The Regolith Depth Model (RDM) illustrates the geometrical distribution of the most commonly occurring regolith types, including the uppermost bedrock. The properties of the regolith layers (e.g. hydraulic conductivity) can be attributed by the user of the model.

The regolith thickness and the distribution of the regolith types are largely determined by the bedrock morphology, and the thickest layers are situated in bedrock depressions. Low laying areas are characterised by a large proportion of thick clay layers whereas till and outcrops dominate in high topographical areas. The maximum depth of regolith in the model area is about 47 m, and the average depth is 6.7 m with bedrock outcrops included. There is a general difference between the regolith depths in the terrestrial and marine areas, which are 4.0 m and 8.3 m, respectively.

The present RDM has been improved in several manners compared to earlier RDM versions. That is mainly thanks to a larger dataset with high quality data from the marine areas close to SFR. Furthermore, the RDM presented here was produced by an interpolation method giving a more realistic geometrical distribution of the regolith layers, especially in the marine area. The present RDM demonstrates some features that were not represented in earlier RDM versions. The most prominent new feature is a large glaciofluvial deposit underlying the clay in the marine area. Furthermore, an extension of a glaciofluvial esker ("Börstilsåsen"), earlier recorded on land, was recorded also on the sea floor.

The RDM has relatively large uncertainties in areas with low density of data and there are large areas, e.g. shallow marine areas, which lacks data showing the total depths of regolith. Some of these areas may be possible to model more realistically even without the addition of new data.

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Appendix 1

Stratigraphical profiles

In Figures A1-1 through A1-14 below, the stratigraphical distribution and thicknesses of the regolith layers are illustrated in 14 profiles produced using the program GeoScene3D (ftp://mapserver.dk/Website/GeoScene3D/Help/GeoScene3D.html). The locations of the profiles are shown on one overview map (Figure 5-3) and on 14 detailed maps showing the regolith in the surroundings of the profiles. Note that the scale on the y-axis is up to 50 times smaller compare to the x-axis, i.e. the thicknesses of the regolith layers are strongly exaggerated in relation to the length of the profiles. The regolith types are explained in the figures below and the Z-layers representing these regolith types are shown in Table 3-1 and Table 4-1.

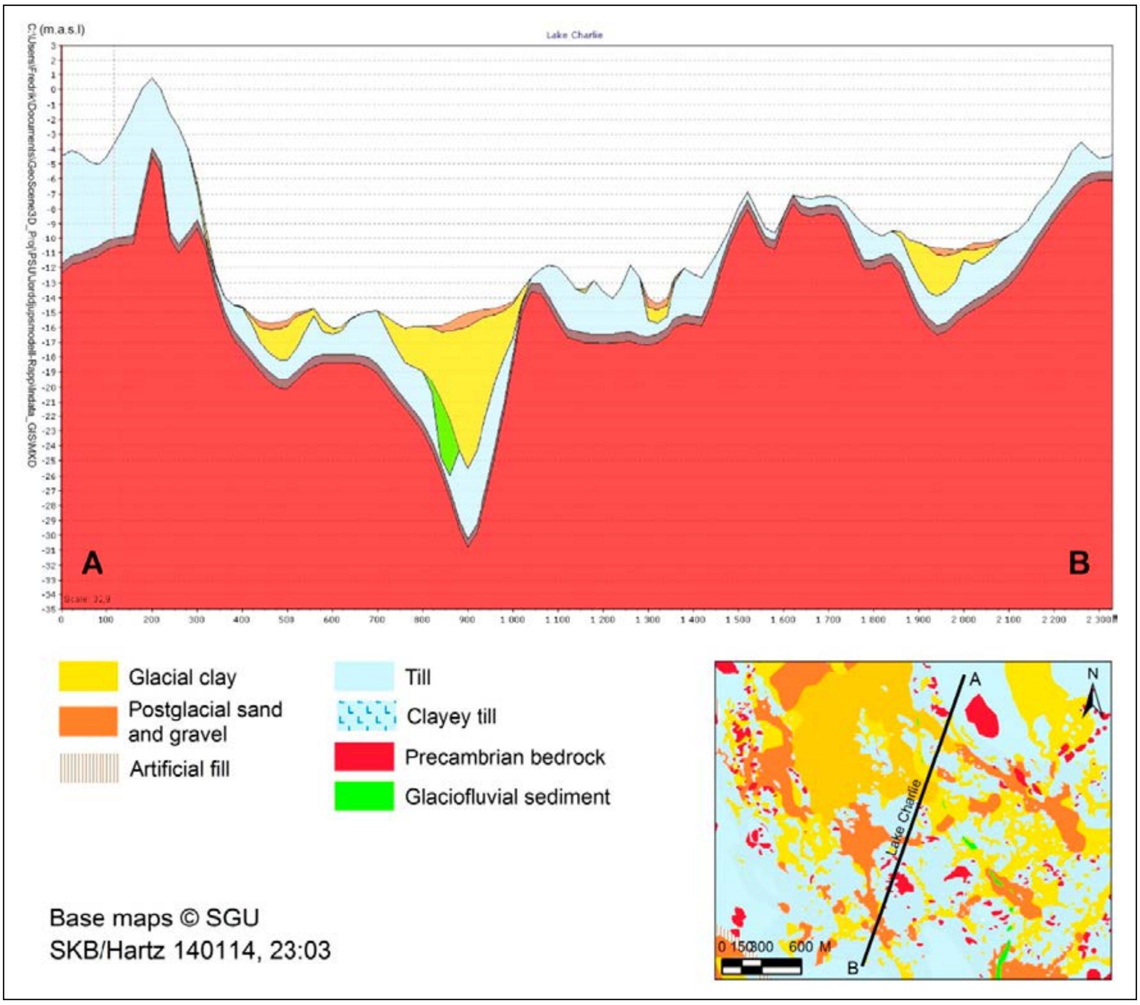

Figure A1-1. Vertical profile showing stratigraphy and total regolith depth along the profile "Lake Charlie" (Figure 5-3). The y-axis shows the altitude in relation to the sea level (m.a.s.l.). This profile illustrates the stratigraphy at the present sea floor in an area which has a high density of data with a high quality (Nyberg et al. 2011). The area with the largest water depths is situated in an area that in the future will be covered by a lake.

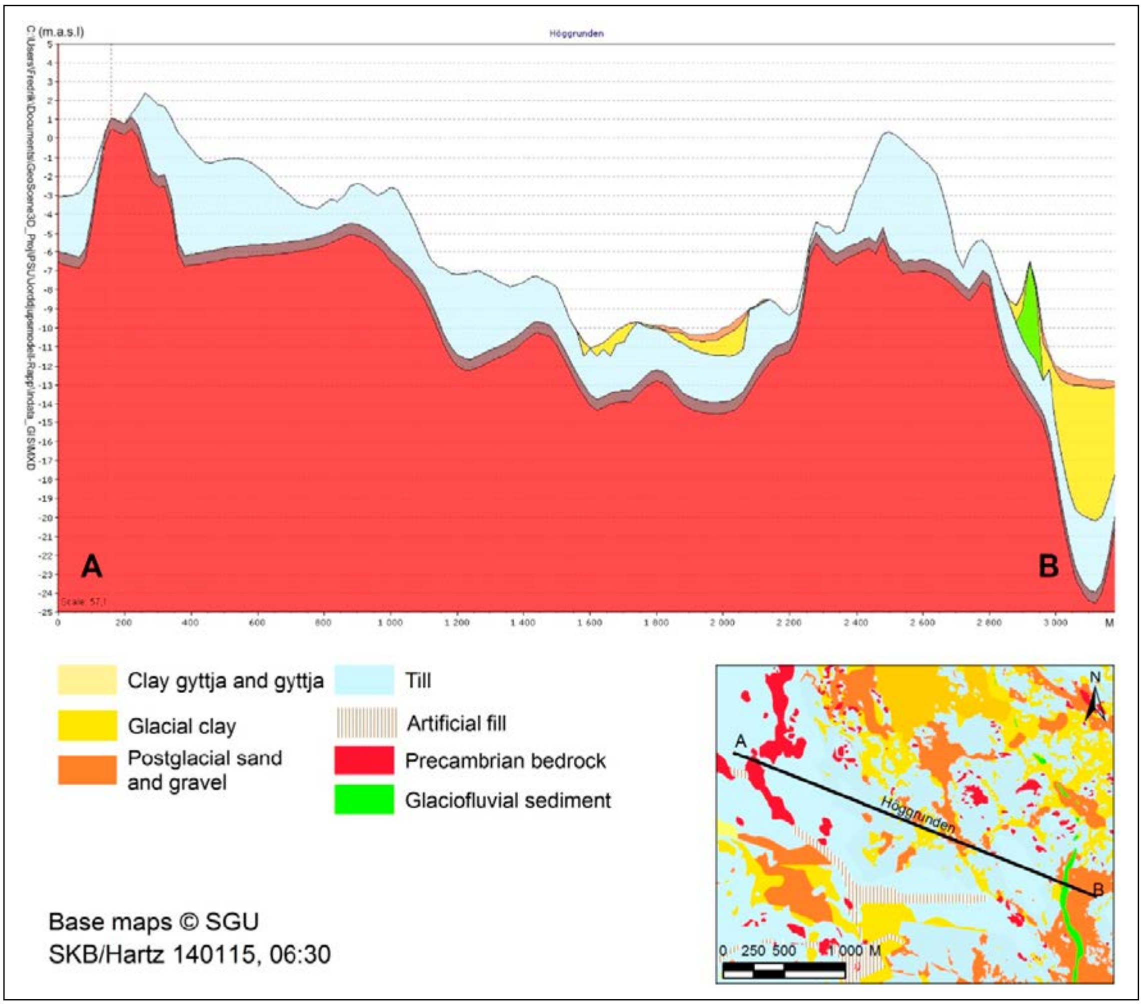

Figure A1-2. *Vertical profile showing stratigraphy and total regolith depth along profile "Höggrunden" (Figure 5-3). The altitude in relation to the sea level (m.a.s.l.) is shown on the y-axis. Most of this profile illustrates the stratigraphy at the present sea floor in an area which has a high density of data with a high quality (Nyberg et al. 2011). The profile crosses, however, two small islands where no data about regolith depths is available (The parts of the profile with positive values on the y-axis).*

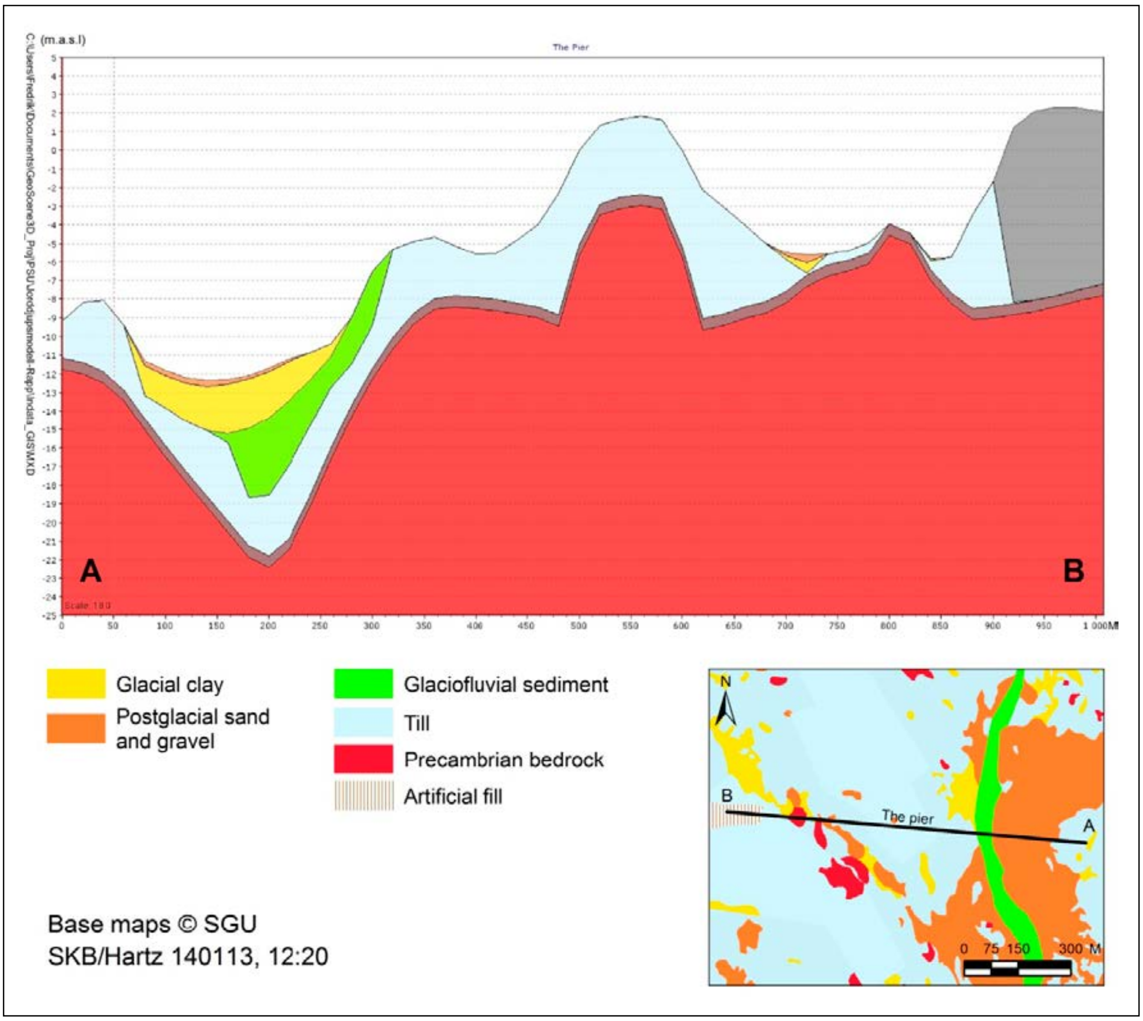

***Figure A1-3.** Vertical profile showing stratigraphy and total regolith depth along the profile "The pier" (Figure 5-3). The altitude in relation to the sea level (m.a.s.l.) is shown on the y-axis. The pier is built up by artificial fill (symbolised with grey in the profile), which constitutes a landform entirely built up by regolith. Such landforms were modelled with a dedicated approach (see Section 4.3.3).*

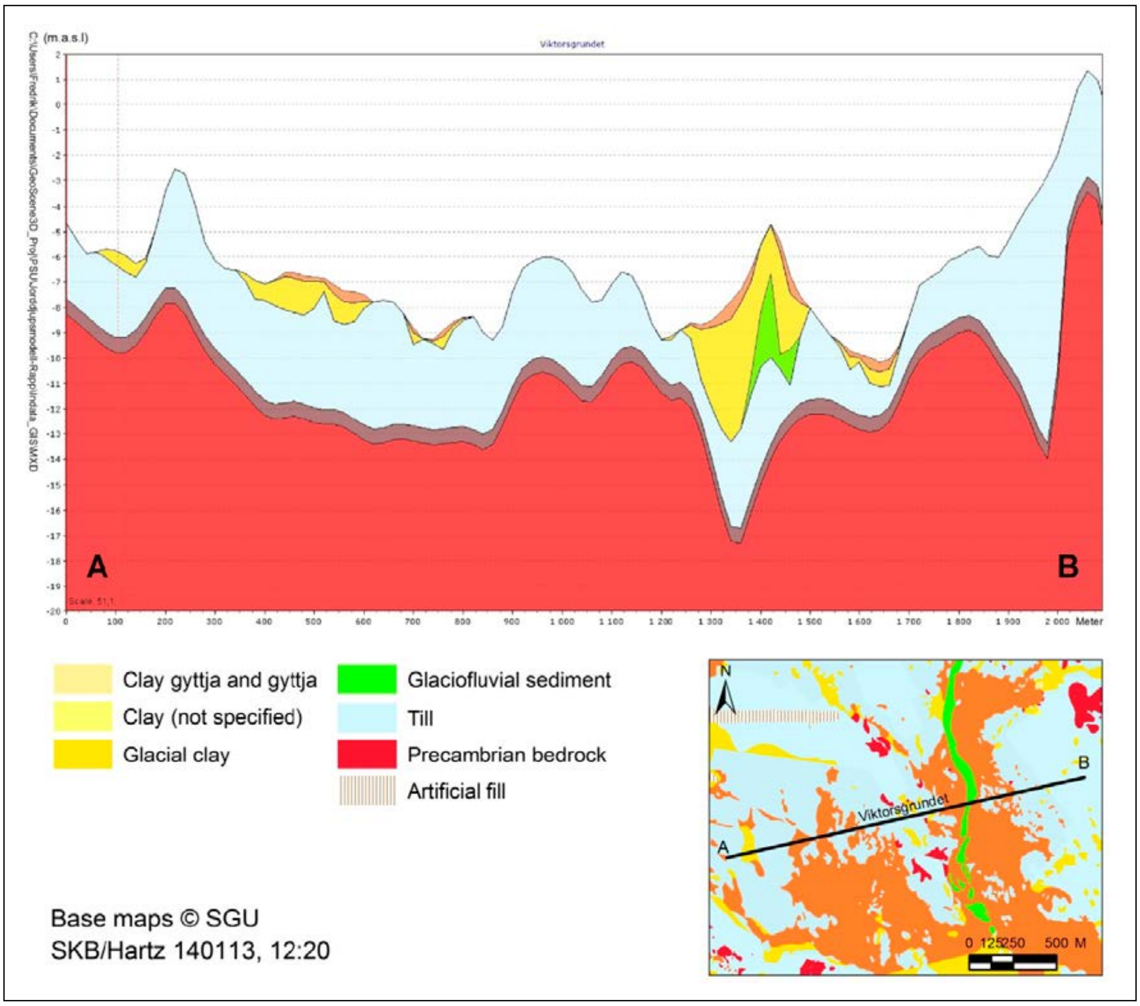

Figure A1-4. *Vertical profile showing stratigraphy and total regolith depth along the profile "Viktorsgrundet" (Figure 5-3). The altitude in relation to the sea level (m.a.s.l.) is shown on the y-axis. The profile is almost entirely situated at the sea floor in an area with a high density of data with high quality (Nyberg et al. 2011). The glaciofluvial esker (green) is denoted "Börstilsåsen" and was not recorded on the sea floor in earlier versions of the RDM.*

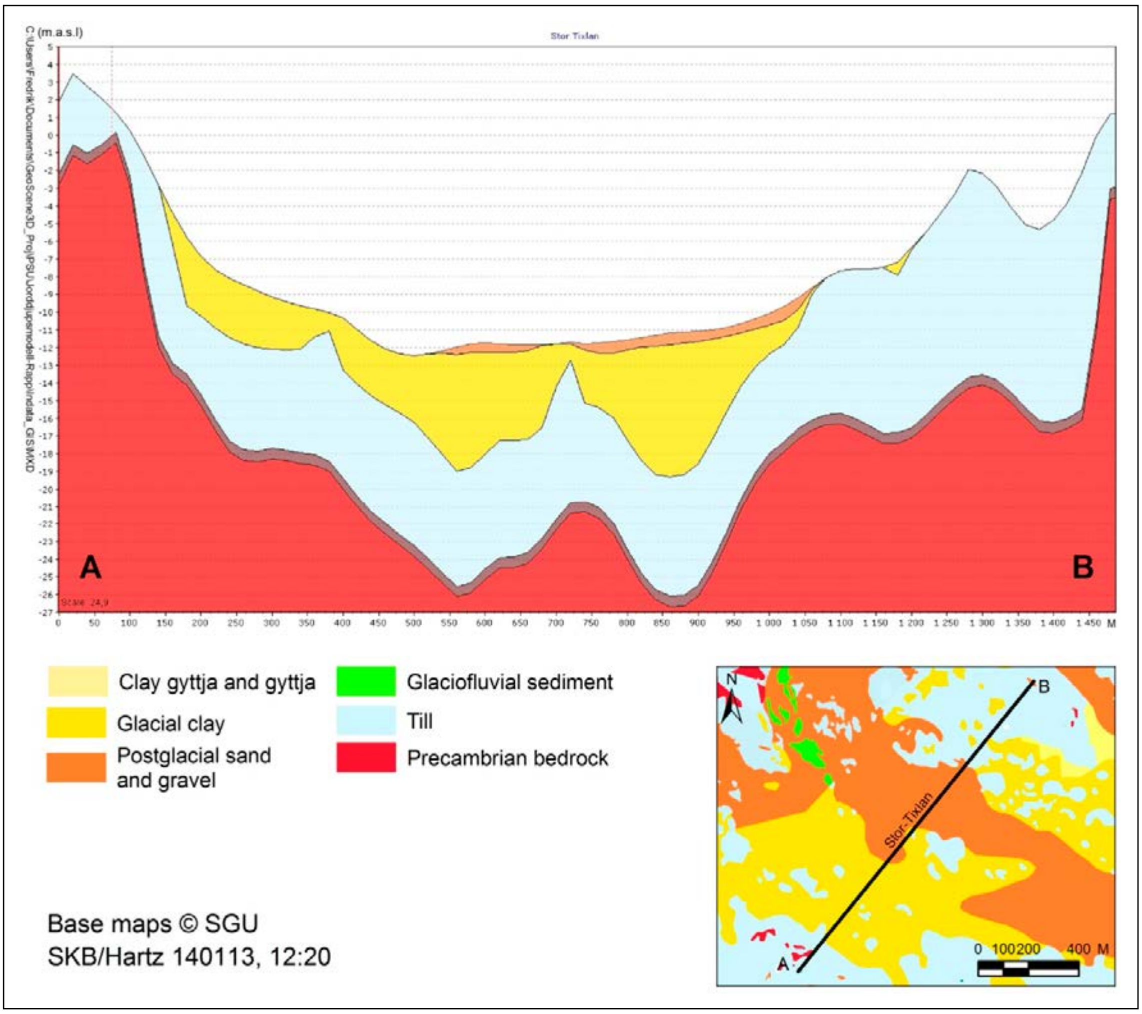

__Figure A1-5.__ Vertical profile showing stratigraphy and total regolith depth along profile "Stor-Tixlan" (Figure 5-3). The altitude in relation to the sea level (m.a.s.l.) is shown on the y-axis. Except parts with positive values on the y-axis most of the profile is situated at the sea floor. The islands Stor-Tixlan and Häggöran on the left and right ends of the profile respectively are characterised by significantly thinner regolith depths compared to surrounding marine areas. However, the model probably exaggerates the difference in regolith thickness between marine and terrestrial areas (see Chapter 6).

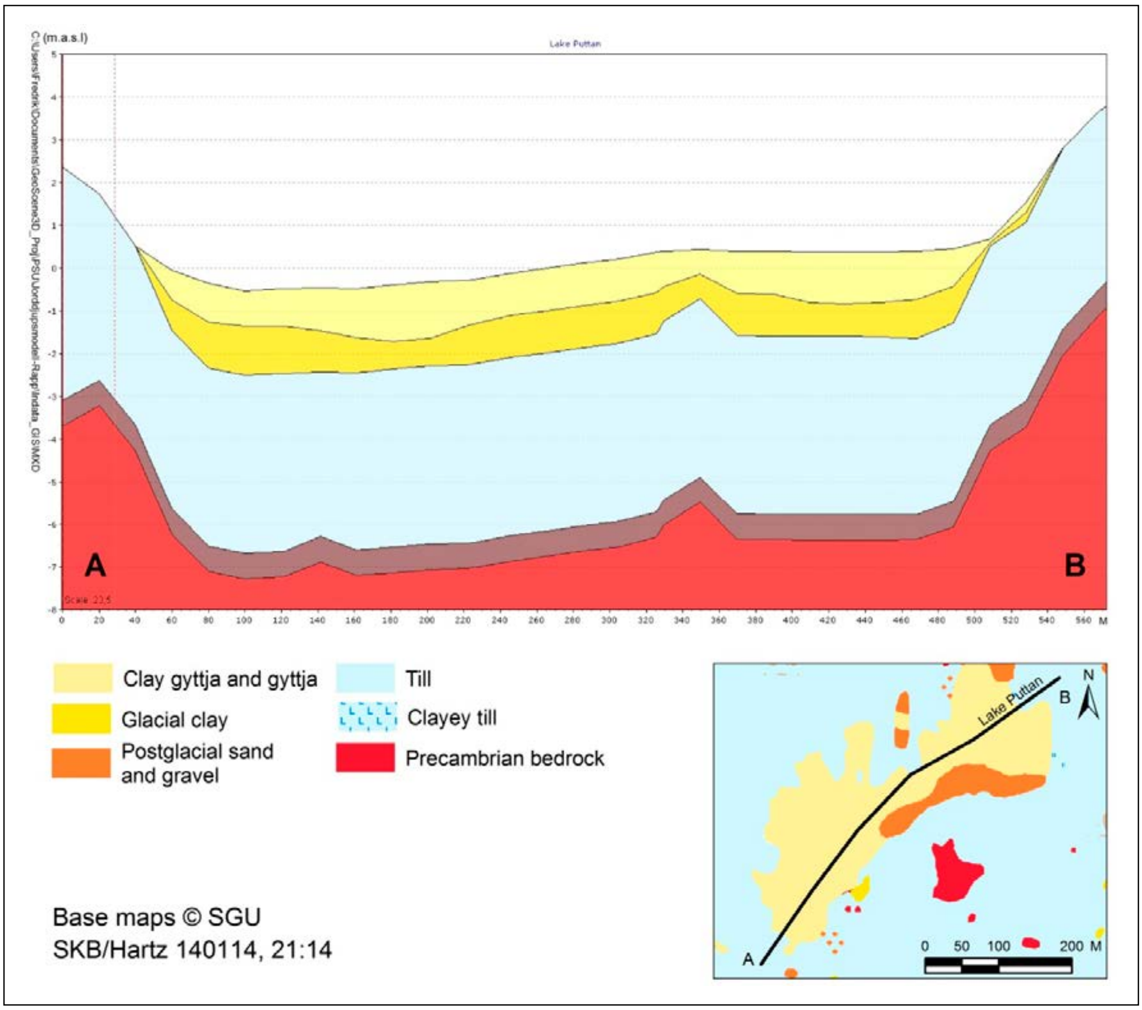

Figure A1-6. *Vertical profile showing stratigraphy and total regolith depth along the profile "Lake Puttan" (Figure 5-3). The altitude in relation to the sea level (m.a.s.l.) is shown on the y-axis. There are only a few observations from Lake Puttan and the thicknesses of the regolith layers are therefore mainly based on interpolation with average values.*

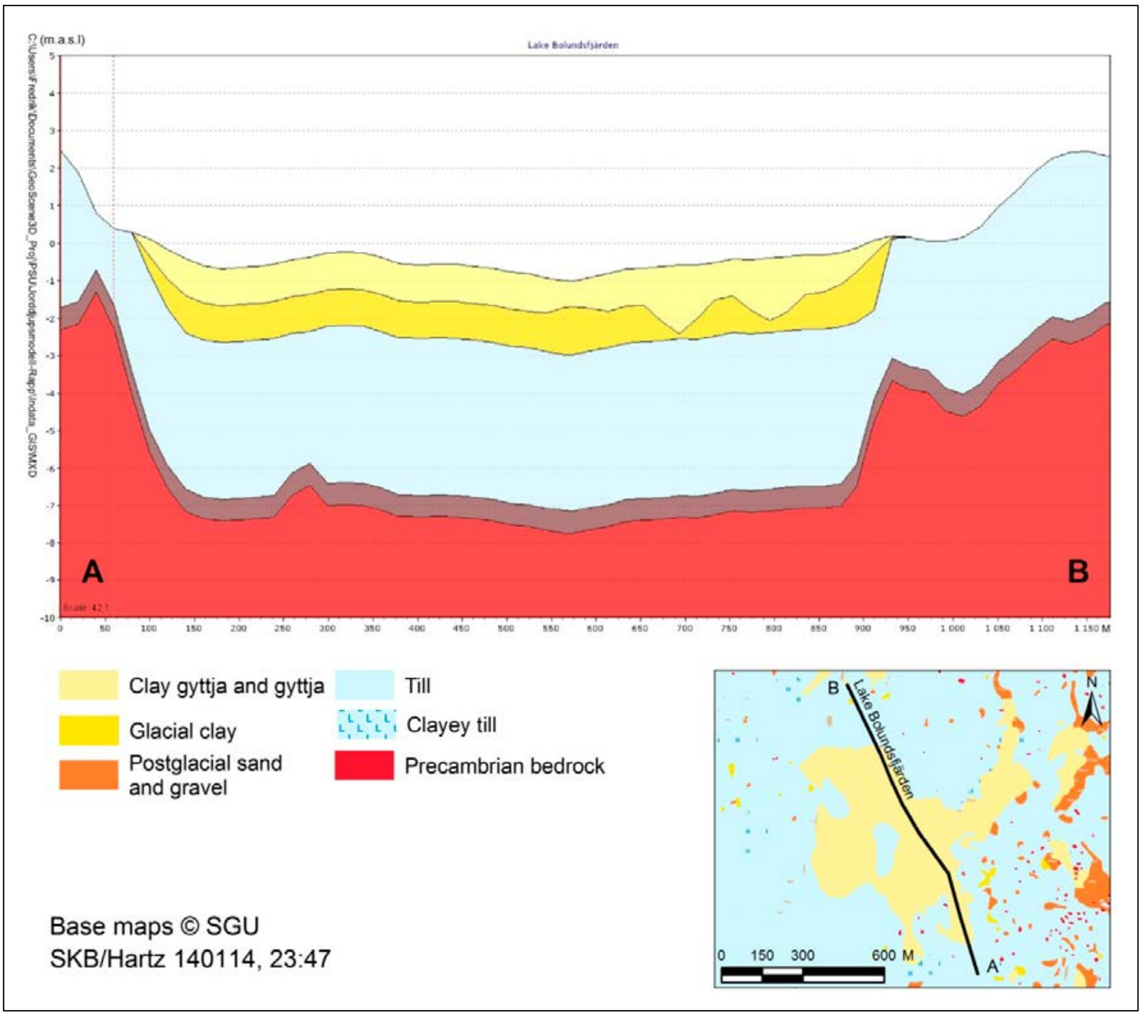

Figure A1-7. Vertical profile showing stratigraphy and total regolith depth along profile "Lake Bolundsfjärden" (Figure 5-3). The altitude in relation to the sea level (m.a.s.l.) is shown on the y-axis. The profile is interpolated by the use of average values in combination with results from drillings through the clay layers. The observations from this lake suggest that the RDM overestimates the layer with glacial clay, which is missing in large parts of the lake. Lake Bolundsfjärden is situated within domain 4b (Figure 4-2), which according to the general stratigraphy is underlain by glacial clay.

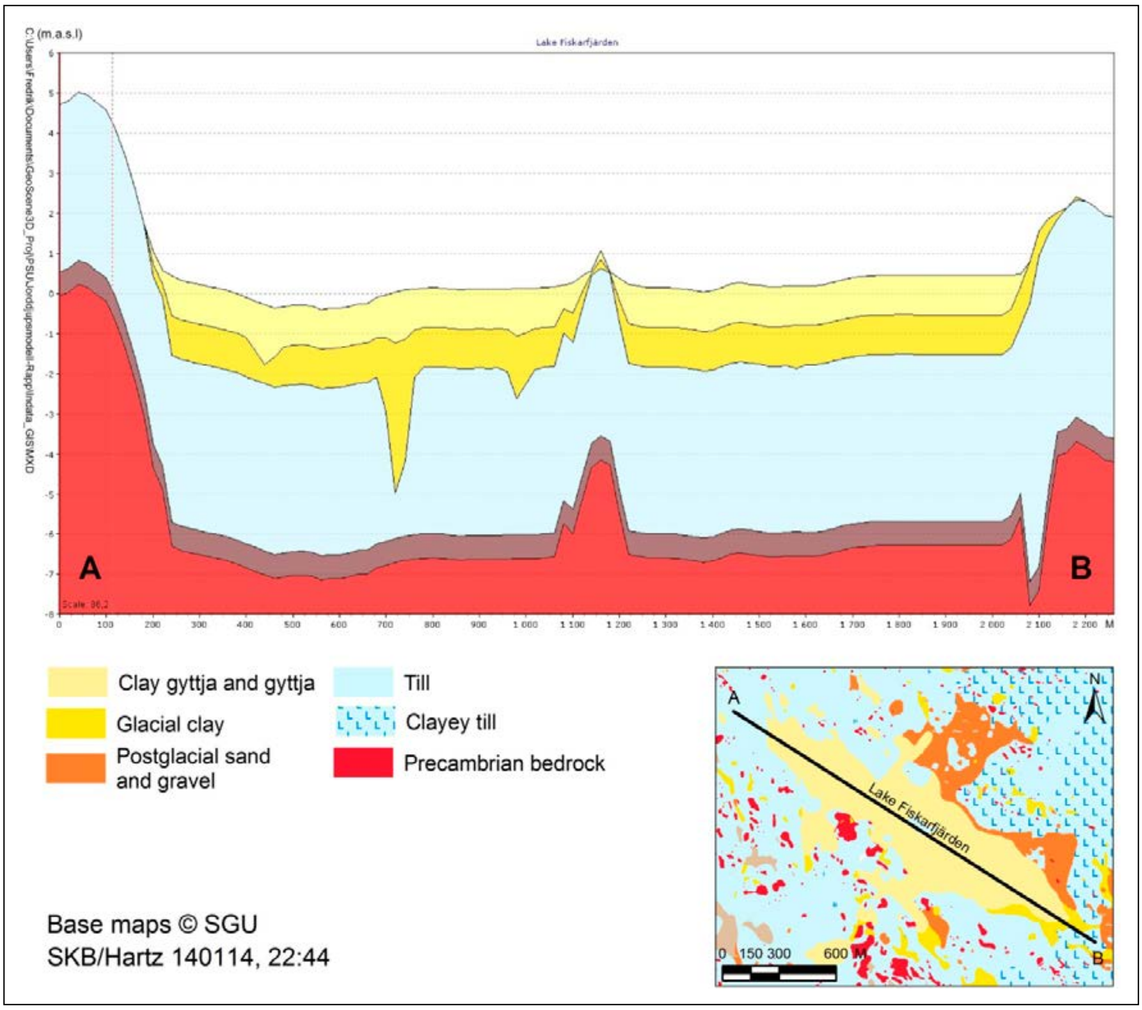

Figure A1-8. Vertical profile showing stratigraphy and total regolith depth along profile "Lake Fiskarfjärden" (Figure 5-3). The altitude in relation to the sea level (m.a.s.l.) is shown on the y-axis. The profile is further discussed in Section 5.2.

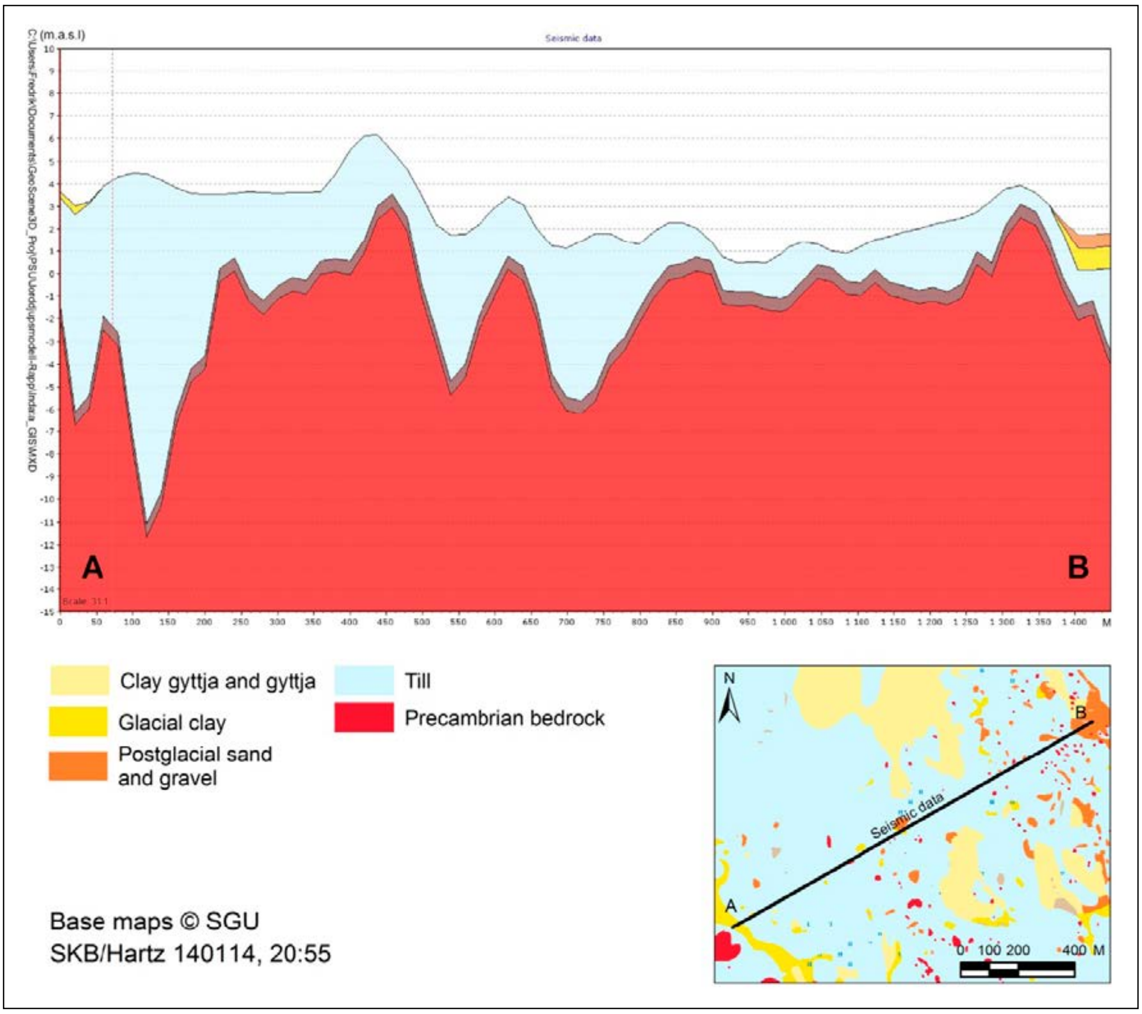

Figure A1-9. Vertical profile showing stratigraphy and total regolith depth along the profile "Seismic data" (Figure 5-3). The altitude in relation to the sea level (m.a.s.l.) is shown on the y-axis. This profile is drawn along a line where refraction seismic measurements were carried out.

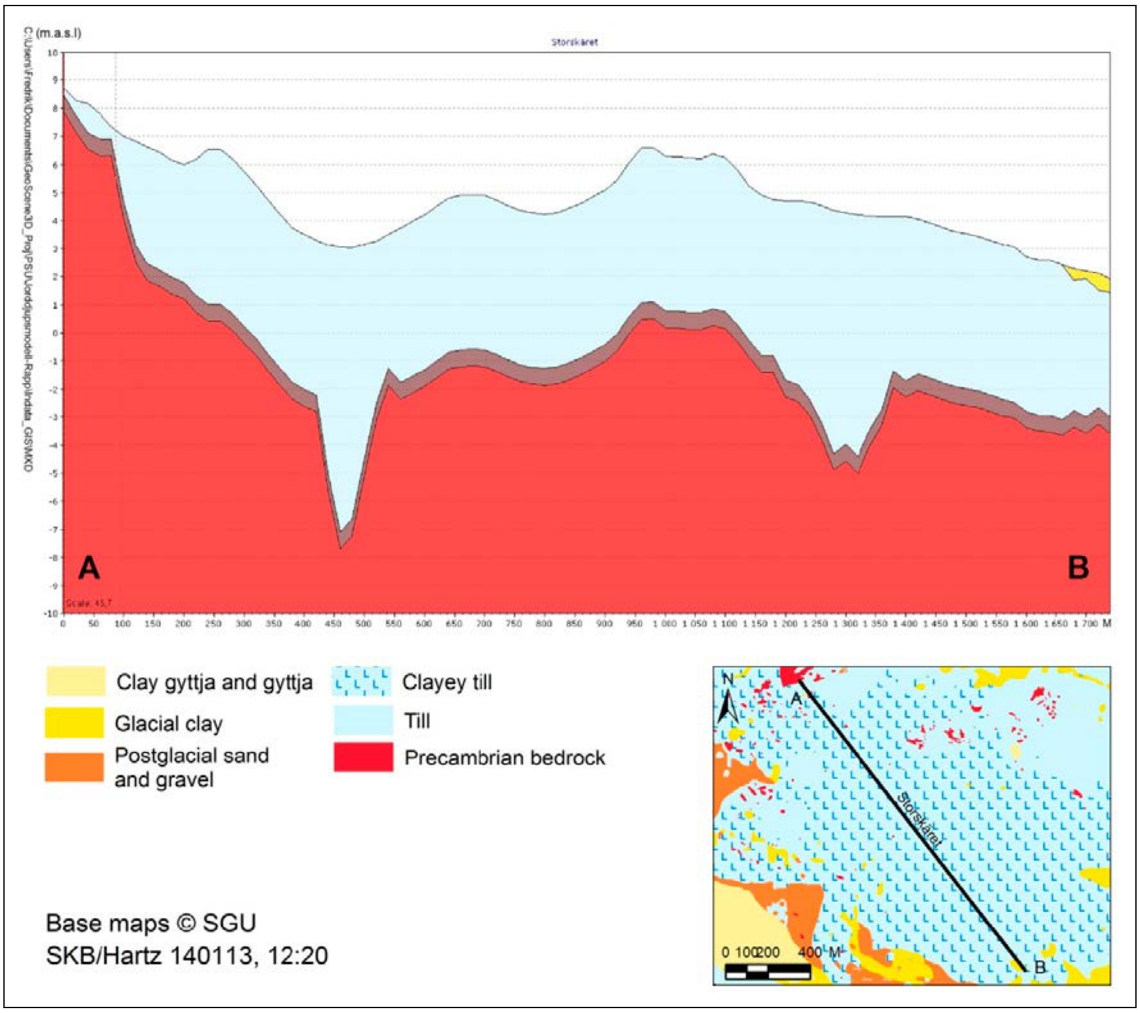

Figure A1-10. *Vertical profile showing stratigraphy and total regolith depth along the profile "Storskäret" (Figure 5-3). The altitude in relation to the sea level (m.a.s.l.) is shown on the y-axis. This profile is characterised by relatively thick layers of till with a high content of clay. The clayey till around Storskäret belongs to domain 6, "clayey till with a low frequency of surficial boulders" (Figure 4-2), which has a larger average till thickness than till in other terrestrial areas.*

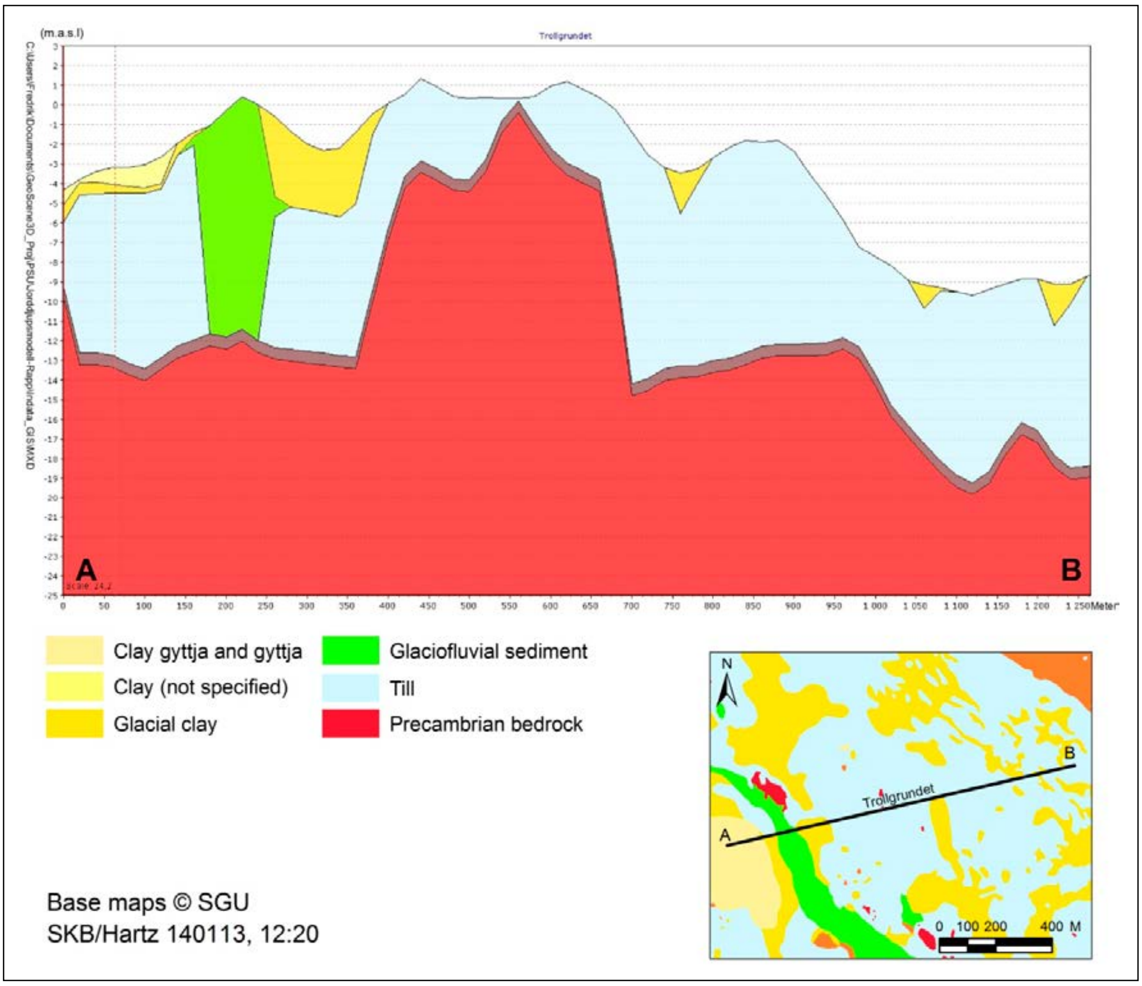

Figure A1-11. Vertical profile showing stratigraphy and total regolith depth along the profile "Trollgrundet" (Figure 5-3). The altitude in relation to the sea level (m.a.s.l.) is shown on the y-axis. The Trollgundet peninsula in the middle of the profile (positive values on the y-axis) is characterised by significantly thinner regolith layers than in surrounding marine areas. However, the model probably exaggerates the difference in regolith thickness between marine and terrestrial areas (see Chapter 6).

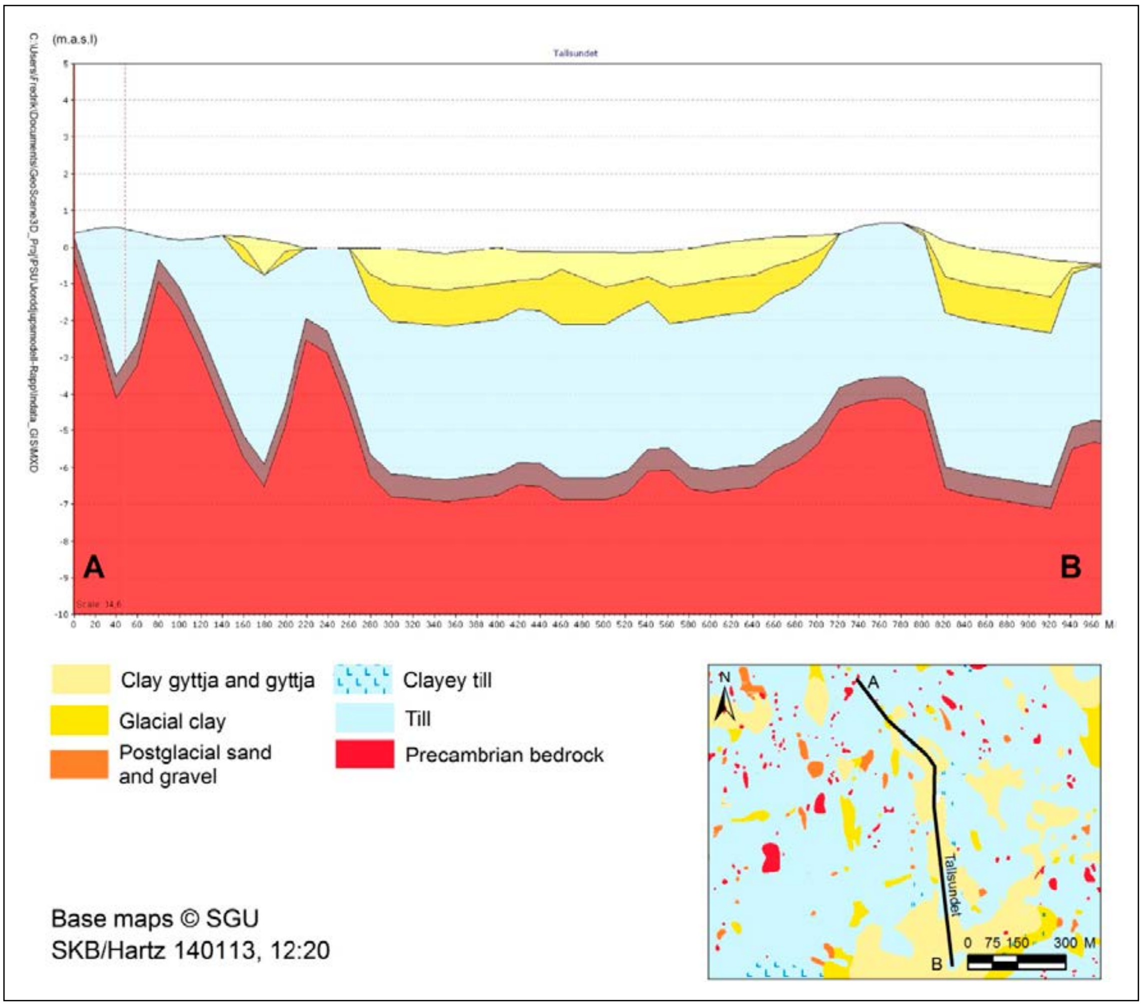

Figure A1-12. Vertical profile showing stratigraphy and total regolith depth along the profile "Tallsundet" (Figure 5-3). The altitude in relation to the sea level (m.a.s.l.) is shown on the y-axis. This profile is situated in an area dominated by shallow waters and fens covered by reed.

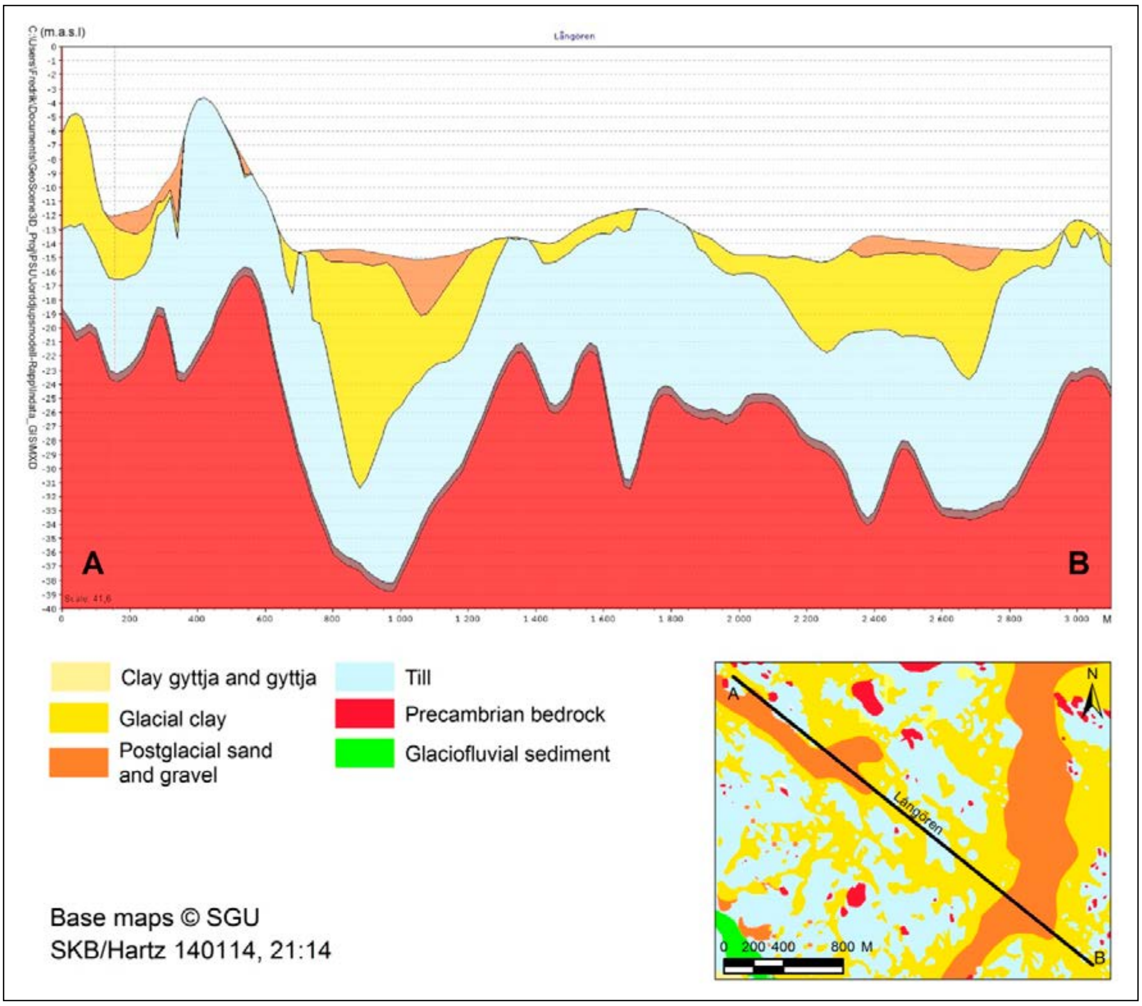

Figure A1-13. *Vertical profile showing stratigraphy and total regolith depth along the profile "Långören" (Figure 5-3). This profile is completely situated at the sea floor in an area with relatively large water depths. The surrounding areas are characterised by a high proportion of clay and sand. The altitude in relation to the sea level (m.a.s.l.) is shown on the y-axis.*

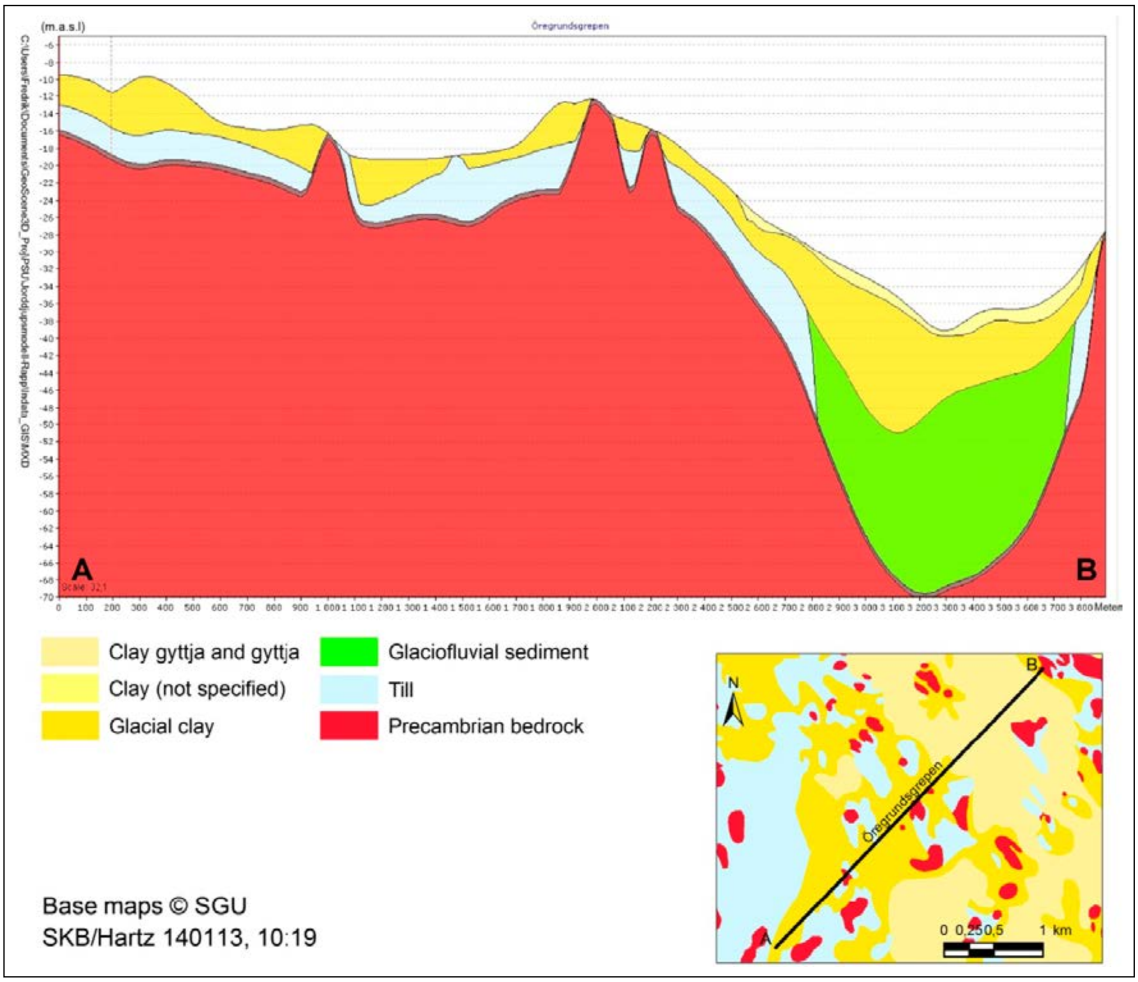

Figure A1-14. Vertical profile showing stratigraphy and total regolith depth along the profile "Öregrundsgrepen" (Figure 5-3). The altitude in relation to the sea level (m.a.s.l.) is shown on the y-axis. This profile is situated at the floor of the sea and crosses the lowest topographical areas of the model area. This area is characterised by a high proportion of clay, which partly is underlain by glaciofluvial sediments. The glaciofluvial deposit was not recorded in earlier versions of the RDM.

Appendix 2

Geostatistical parameters used in production of RDM

In this appendix the models used in Ordinary Kriging for production of regolith layers included in the RDM and statistics from the cross validation and validations of these models are shown. Table A2-1 shows the models used in Ordinary Kriging for production of the bedrock surface (Z5), glacial clay (Z4a), post glacial clay (Z4b) and postglacial sand/gravel (Z3a). Table A2-2 shows statistics from the cross validations of these models and Table A2-3 statistics from the validations of these models.

Table A2-1. Model parameters used in Ordinary Kriging for production of regolith layers included in the RDM. Z5 = bedrock surface, Z4a = glacial clay, Z4b = post glacial clay, Z3a = postglacial sand/gravel, MS = Microstructure, Me = Measurement error, N = Searching Neighbourhood and SF = Smoothing factor. The model equation should be read as follows: Partial sill * Theoretical Semiovariogram (Major Range, Minor Range, Anisotropy Direction) + Nugget value * Nugget.

Layer	Modell	MS	Me	N	SF
Z5	32.051*Spherical(2000,1389.4,146.4) + 16.989*Nugget	16.989 (100%)	0 (0%)	200	1
Z4a	6.297*Spherical(2000,1364.4,4.4) + 0.089*Nugget	0.089 (100%)	0 (0%)	200	1
Z4b	21.956*Spherical(2000,1433.7,157.1) + 4.961*Nugget	4.961 (100%)	0 (0%)	200	1
Z3a	9.137*Spherical(2000,1817.6,162.1) + 0*Nugget	0 (100%)	0 (0%)	200	1

Table A2-2. Cross validation of models used in Ordinary Kriging for production of regolith layers included in the RDM. Z5 = bedrock surface, Z4a = glacial clay, Z4b = post glacial clay, Z3a = postglacial sand/gravel, Mean = mean error, RMS = root-mean-square prediction error, Average SE = average standard error, Mean stand = standardised mean prediction error, RMS stand = standardised root-mean-square prediction error and Samples = number of observations.

Layer	Lag size	Number of Lags	Regression function	Mean	RMS	Average SE	Mean stand	RMS stand	Samples
Z5	200	10	0.939 * × + –1.067	0.00157	1.95148	4.24271	0.00064	0.45575	147704
Z4a	200	10	0.995 * × + –0.063	–0.01571	0.43482	0.43598	–0.01164	0.76005	8363
Z4b	200	10	0.966 * × + –0.492	0.00097	0.89110	2.33645	0.00147	0.37130	96367
Z3a	200	10	0.999 * × + –0.012	–0.00382	0.16926	0.19205	–0.00841	0.86955	53087

Table A2-3. Validation of models used in Ordinary Kriging for production of regolith layers included in the RDM. Z5 = bedrock surface, Z4a = glacial clay, Z4b = post glacial clay, Z3a = postglacial sand/gravel, Mean = mean error, RMS = root-mean-square prediction error, Average SE = average standard error, Mean stand = standardised mean prediction error, RMS stand = standardised root-mean-square prediction error and Samples = number of observations.

Layer	Lag size	Number of Lags	Mean	RMS	Average SE	Mean stand	RMS stand	Samples
Z5	200	10	–0.01617	2.41006	4.28323	–0.00288	0.55216	73873
Z4a	200	10	–0.04329	0.72228	0.46171	–0.01994	0.87795	4181
Z4b	200	10	0.01162	1.13805	2.37477	0.00602	0.46247	48184
Z3a	200	10			0.21116	–0.01306	0.91936	26543