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Baseline Forsmark – Depth and stratigraphy of regolith

Johannes Petrone

Gustav Sohlenius

Jonas Ising

SVENSK KÄRNBRÄNSLEHANTERING AB

SWEDISH NUCLEAR FUEL
AND WASTE MANAGEMENT CO

Box 3091, SE-169 03 Solna
Phone +46 8 459 84 00
skb.se

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Johannes Petrone, Svensk Kärnbränslehantering AB

Gustav Sohlenius, Jonas Ising
Geological Survey of Sweden

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 500 km^2 and includes terrestrial areas as well as regolith underlying lakes and the sea bay between the mainland and the Gräsö Island (Öregrundsgrepen).

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 the stratigraphy. Over 20 000 data points were used to model the total regolith depths. A clear majority of these data emanates from marine geological surveys.

Data used in an earlier version of the RDM was re-evaluated and re-analysed and to a large extent used in the RDM presented in this report. In addition, a new and improved DEM was used that is based on data from the whole terrestrial area and new bathymetric information. Earlier RDMs were modelled entirely using ArcGIS whereas the RDM presented here was produced by using the program SubsurfaceViewer MX®, which in contrast to ArcGIS is constructed for interpretation and modelling of geological data in 3D. Data was post-processed using ArcGIS spatial functions. SubsurfaceViewer makes it possible to apply general knowledge and understanding of the stratigraphical distribution of regolith layers to construct and build sections which are then used to model the RDM.

A general stratigraphy was first constructed that represents the regolith layers and the uppermost bedrock. All data, including the DEM and geological data, was imported to SubsurfaceViewer. More than 700 sections were drawn along and between imported data. The geographical distributions of the regolith layers were then interpreted. Finally, a regional model of regolith thickness and prevalence was constructed in SubsurfaceViewer and post-processed in ArcGIS.

The maximum depth of regolith found within the model area is more than 50 m, and the average depth in the area is 4.2 m with bedrock outcrops included and 4.5 m with outcrops excluded. The regolith thickness and the distribution of the regolith types are largely determined by the bedrock morphology and in effect the topography. The lowest laying bedrock areas, with some major lineaments, are situated in the deeper marine areas between the mainland and the island of Gräsö and are characterised by thick regolith layers of clay and till or glaciofluvial sediment. The higher laying terrestrial areas have a higher frequency of outcrops and are characterised by thinner regolith layers, mainly till.

Sammanfattning

En jorddjupsmodell (regolith depth model, RDM) har tagits fram, som visar som visar tjocklek och stratigrafisk fördelning av de i Forsmarksområdet vanligast förekommande jordarterna. Med jordarter avses de löst konsoliderade avlagringar vilka överlagrar berggrunden. Modellområdet är ca 500 km^2 och innefattar dels landområden och dels områden där jordarterna ligger under sjöar eller marint vatten i Öregrundsgrepen.

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 seismik och sedimentekolod för att modellera både jordarternas totala mäktighet och stratigrafi. Totalt användes data från närmare 20 000 datapunkter 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 detaljerad maringeologisk undersökning kring SFR. Tidigare jorddjupsmodeller togs fram med ArcGIS medan den modell som presenteras här tagits fram med programmet SubsurfaceViewer MX®, som till skillnad från ArcGIS är anpassat för att tolka och modellera geologisk information i 3D. Lager har sedan efterbearbetats i ArcGIS med spatiella verktyg. SubsurfaceViewer gör det möjligt att använda generell kunskap om de geologiska avlagringarnas stratigrafi tillsammans med data för att konstruera 3D-modeller.

En generell stratigrafi togs först fram som representerar de olika jordarterna samt den översta delen av berggrunden. Därefter importerades all data, inklusive DEM och geologisk information, till SubsurfaceViewer. Fler än 700 sektioner har tolkats mellan datapunkter med information om jordlagrens tjocklek. Underlag har även tagits fram som redovisar de olika lagrens geografiska utbredning. Jordlagrens utbredning och mäktighet modellerades sedan och efterbehandlades slutligen i ArcGIS.

Det största modellerade jorddjupet inom modellområdet är över 50 meter, och det genomsnittliga jorddjupet i detta område är 4,2 meter då hällar inkluderas och 4,5 meter då hällar exkluderas. Jordarternas mäktighet och geografiska fördelning bestäms främst av berggrundens morfologi och således markens och havsbottens topografi. I de djupa marina områdena mellan fastlandet och Gräsö finns markanta lineament och den topografiskt lägst liggande berggrunden. Dessa områden kännetecknas av tjocka jordlager av lera och morän eller glaciofluviala sediment. De högre belägna landområdena kännetecknas av en hög hällfrekvens och tunnare jordlager som främst utgörs av morän.

Contents

1 Introduction

The surface geology and regolith depth are important parameters for understanding and modelling of hydrological and geochemical processes in an 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 surface of the bedrock. The model area (Figure 1-1) extends over almost 500 km^2 and includes marine areas, terrestrial areas and lakes. The model area was delineated based on the locations of the present and future water divides. Two earlier RDM-versions were produced during the site investigations for localisation of a deep repository for high level radioactive waste in Forsmark and one for the extension of the existing SFR facility. These models are described in Vikström (2005), Hedenström et al. (2008) and Sohlenius et al. (2013).

Earlier RDMs were modelled in ArcGIS whereas the present model was made using a software program (Subsurface Viewer) that is adapted for making geological models in 3D. A detailed RDM for the access area of the planned spent nuclear fuel repository in Forsmark has been produced with the same method as the RDM presented here. That model is, however, described in Follin (2019). The RDM:s are used for hydrological and contaminant transport modelling, but also as an input to dynamic regolith depth models that describe the distribution of regolith through time from the latest deglaciation to 40 000 AD (e.g. Brydsten and Strömgren 2013).

The RDM is a geometric model that describes the total regolith depth, subdivided into nine layers (Z-layers) that represent different regolith types. 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 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.

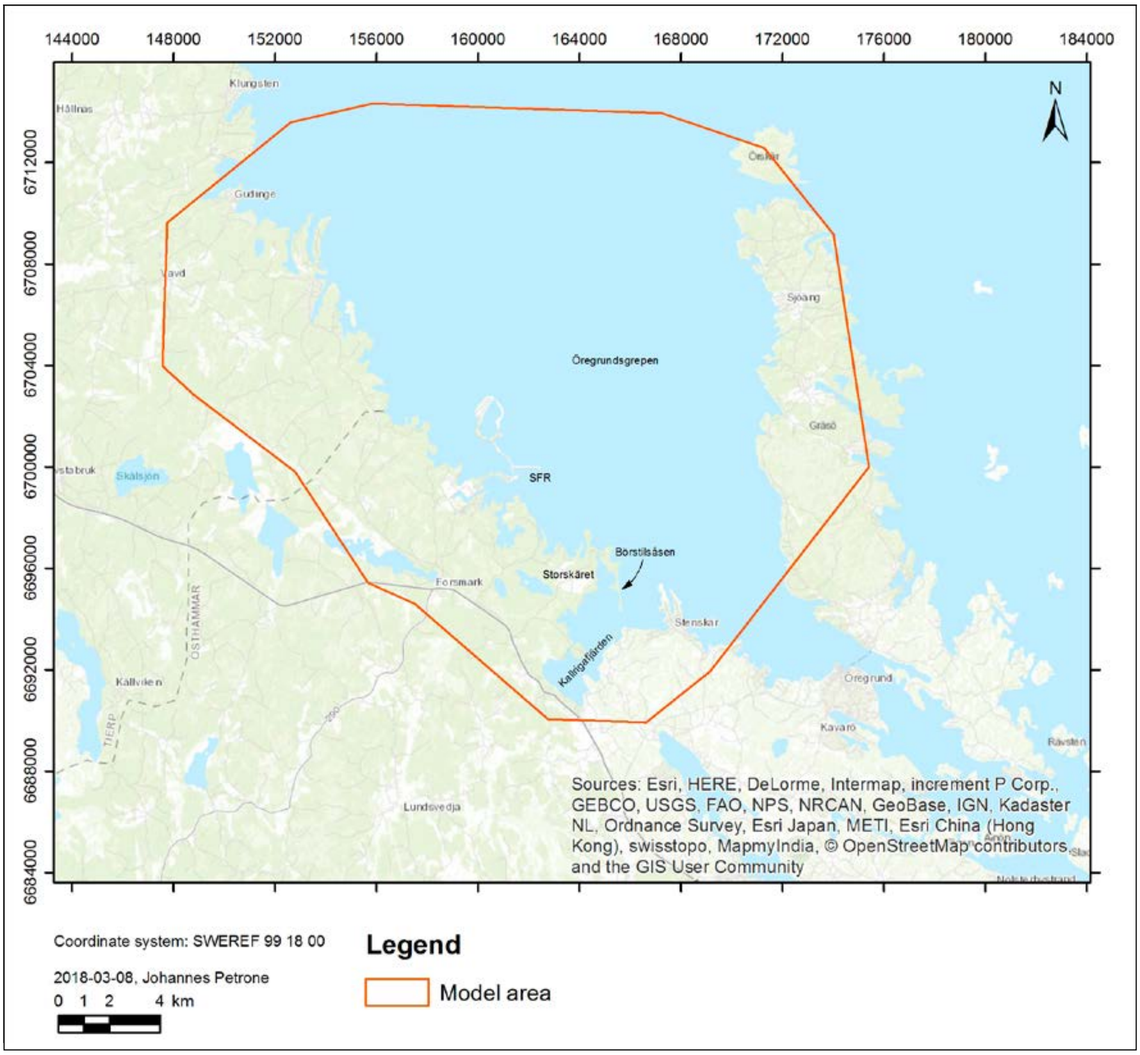

__Figure 1-1.__ The area represented in the regolith depth model (RDM) is delimited by an orange line. The area comprises almost 500 km² and includes terrestrial areas, lakes and marine areas. The latter belong to the Baltic Sea.

2 Input data

Data from many 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 for the extension of the existing SFR facility (e.g. 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, whereas Figure 2-2 shows the various regolith maps used as input to the modelling. Figures 2-3 to 2-5 show the locations of different types of measurements that provide input to the modelling, and hence data points and lines (depending on method employed). Some of the data give information regarding the thickness of the individual regolith layers whereas other data only give information on the total depth of regolith.

Some observations do not reach 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 representations of regolith. The different observation types used in the RDM have different accuracy. 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 (Petrone and Strömgren 2020) and displays the elevation of the ground surface (Figure 2-1). Data from airborne laser scanning, and in the marine area data from nautical charts and depth soundings were used to produce the DEM. The original DEM has a higher resolution in parts of the model area. but the resolution 20×20 m^2 was regarded as high enough 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. Generally, the surface is very accurate where laser data has been used in the model (land areas) and less accurate in the marine areas where only depth sounding has been used to model the surface.

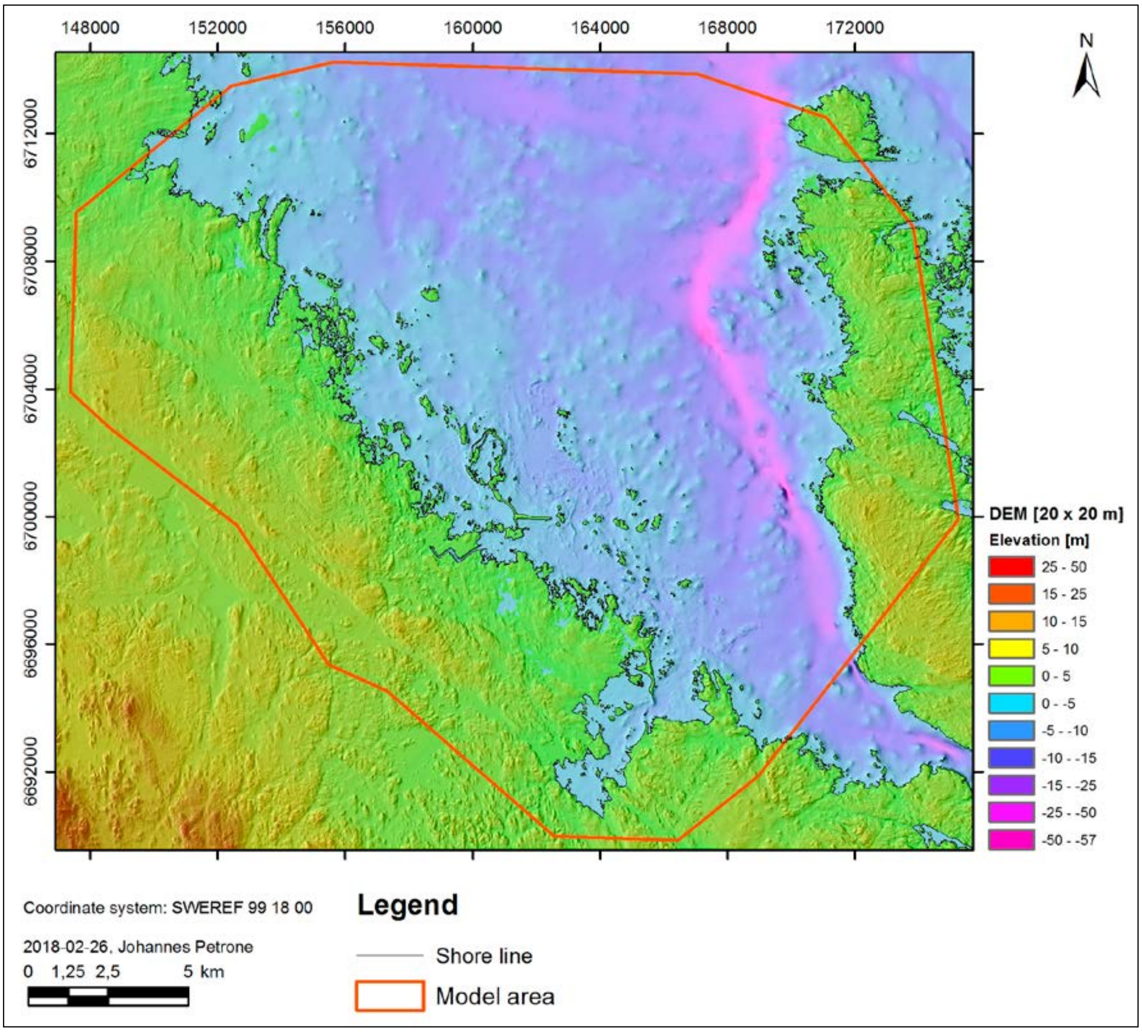

Figure 2-1. *The Digital Elevation Model (DEM) showing the elevation of the ground surface and the sea bathymetry in a 20 × 20 m² resolution (Petrone and Strömgren 2020).*

2.2 Maps of regolith

The map of regolith is a compilation of eight maps, originally produced with different methods (Figure 2-2) 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 and thin layers of peat in wetlands. These thin layers were also used for the RDM. Furthermore, the regolith map shows the distribution of outcrops and artificial fill. During the modelling of regolith depths the regolith maps were used as one input 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 2-2). 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).

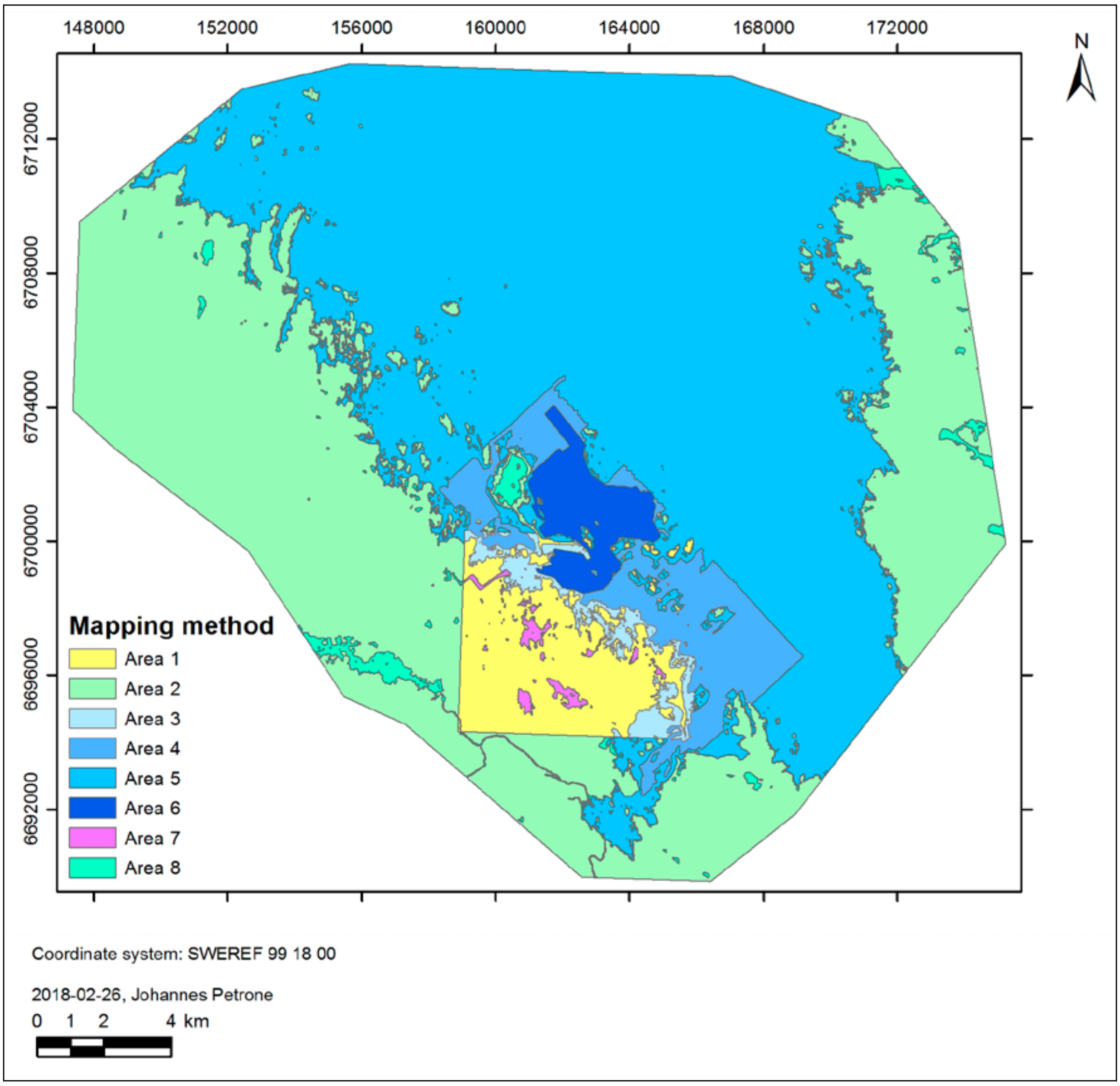

Figure 2-2. *The distribution of the areas represented on the eight different maps of regolith that were used to compile the resulting regolith map used as input to the regolith depth model (RDM). The methods used for mapping the areas are briefly described in Table 2-1 and in the text; Hedenström and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

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 many point observations from the sea ice or using a small boat (Ising 2005). Many of the studied points include determinations of the thickness of regolith layers (Figure 2-2). 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 regolith areas smaller than 50×50 m^2 are not displayed.

Area 4, Area 5 and Area 6 are modelled using data from the marine area, which were collected from boat by SGU. The marina data were used to determine the geographical distribution of regolith as well as the thickness of the regolith layers. In Area 4 geological data were collected along lines with a distance of 100 m between them (Elhammer and Sandkvist 2005). For Area 5 there are data along lines with a spacing of c 1 000 m, collected during the SKB site investigation (Elhammer and Sandkvist 2005) and during 2008 within SGU's mapping programme. All data from Area 5 presented by Elhammer and Sandkvist (2005) was reinterpreted by SGU 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 by 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 comprises lakes and ponds in the central part of the model area. Stratigraphical studies have been carried out at most of these sites (Hedenström 2003, 2004a, b, Sohlenius and Hedenström 2009), and the locations of these studies are shown in Figure 2-2.

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 (e.g. Hedenström 2003), bathymetry from the DEM and interpolation from the surrounding regolith. The regolith map in Area 8 has consequently larger uncertainties than other areas.

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).

In the marine area, sediment echo sounding and seismic data give information on 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 2-5). 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. This is due to problems with double echoes that are 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 (Area 7) obtained by hand coring (Ising 2005, 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). Data obtained from characterisation of regolith in the field 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 2015) gives information about the total depth of regolith (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 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.

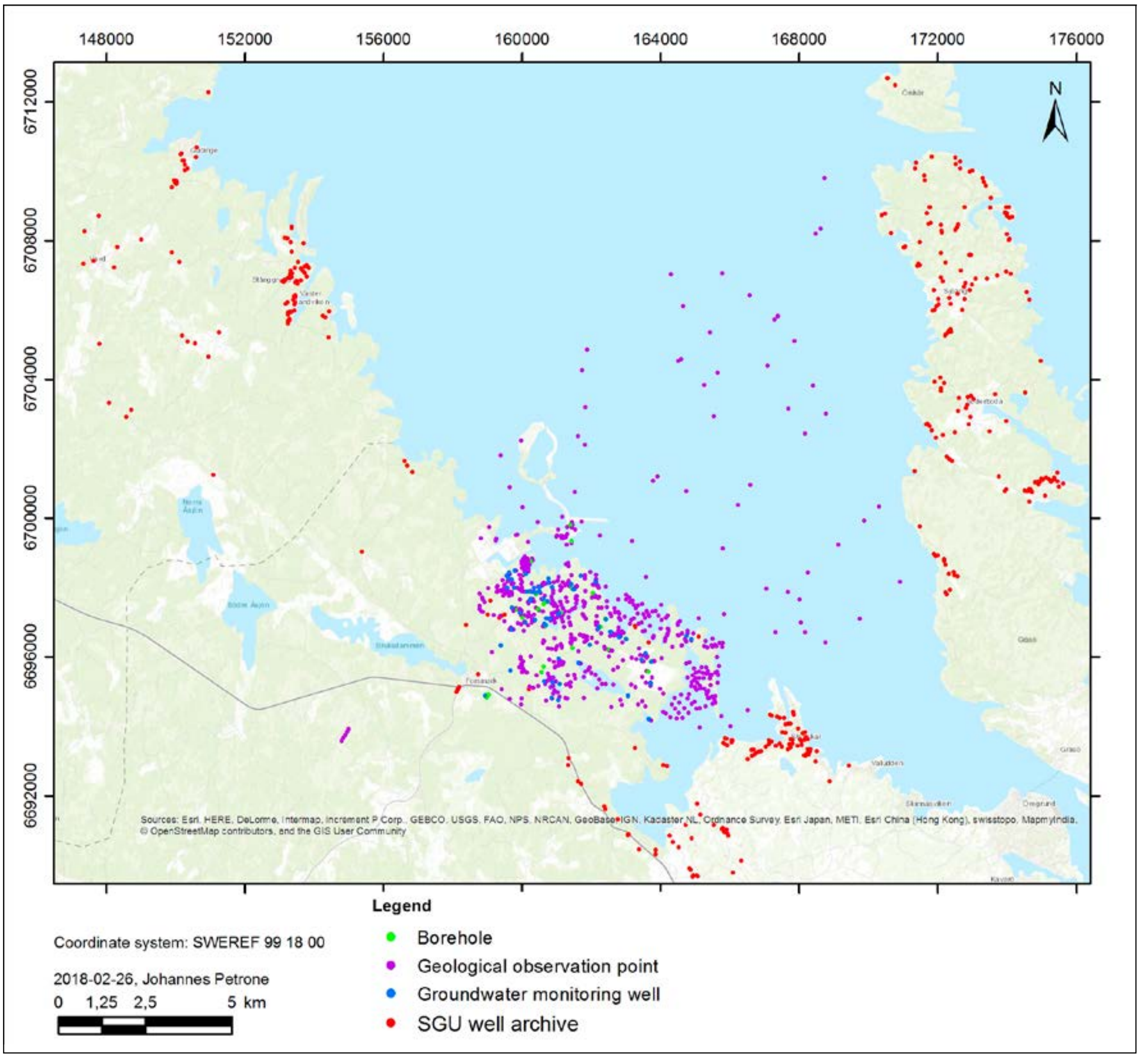

Figure 2-3. *Distribution of stratigraphical data that were used for modelling the total regolith depth and the thickness of the different regolith layers. The number of data points from each investigation is shown in Table 2-2.*

Refraction seismics and continuous vertical electrical sounding (CVES) measurements (Figure 2-4) 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). 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 2-3 and Figure 2-4). The general knowledge of stratigraphy was therefore used to model the distribution of regolith in these areas.

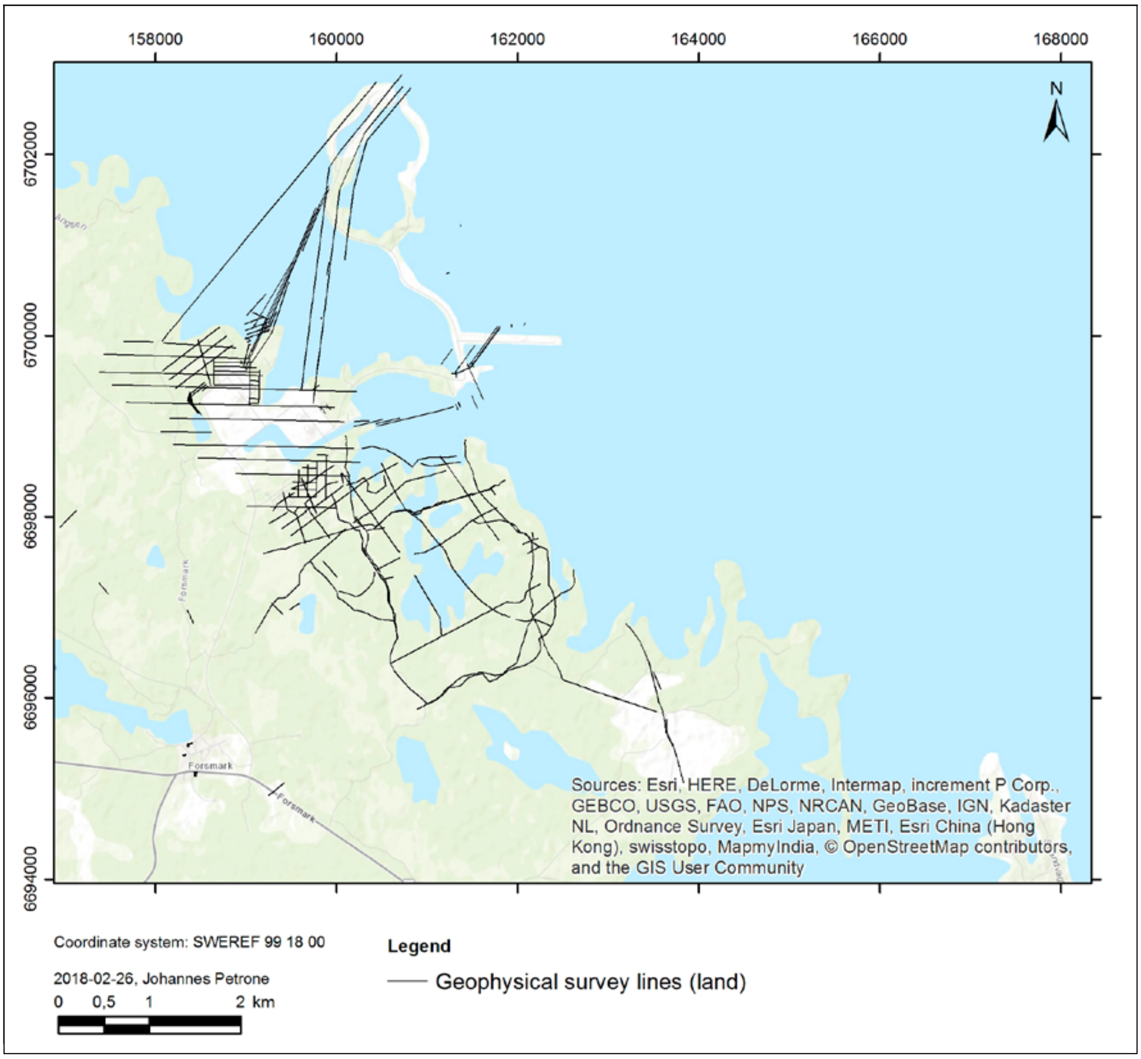

Figure 2-4. *The distribution of data from refraction seismics and continuous vertical electrical soundings (CVES) that were used for modelling the total thickness of regolith.*

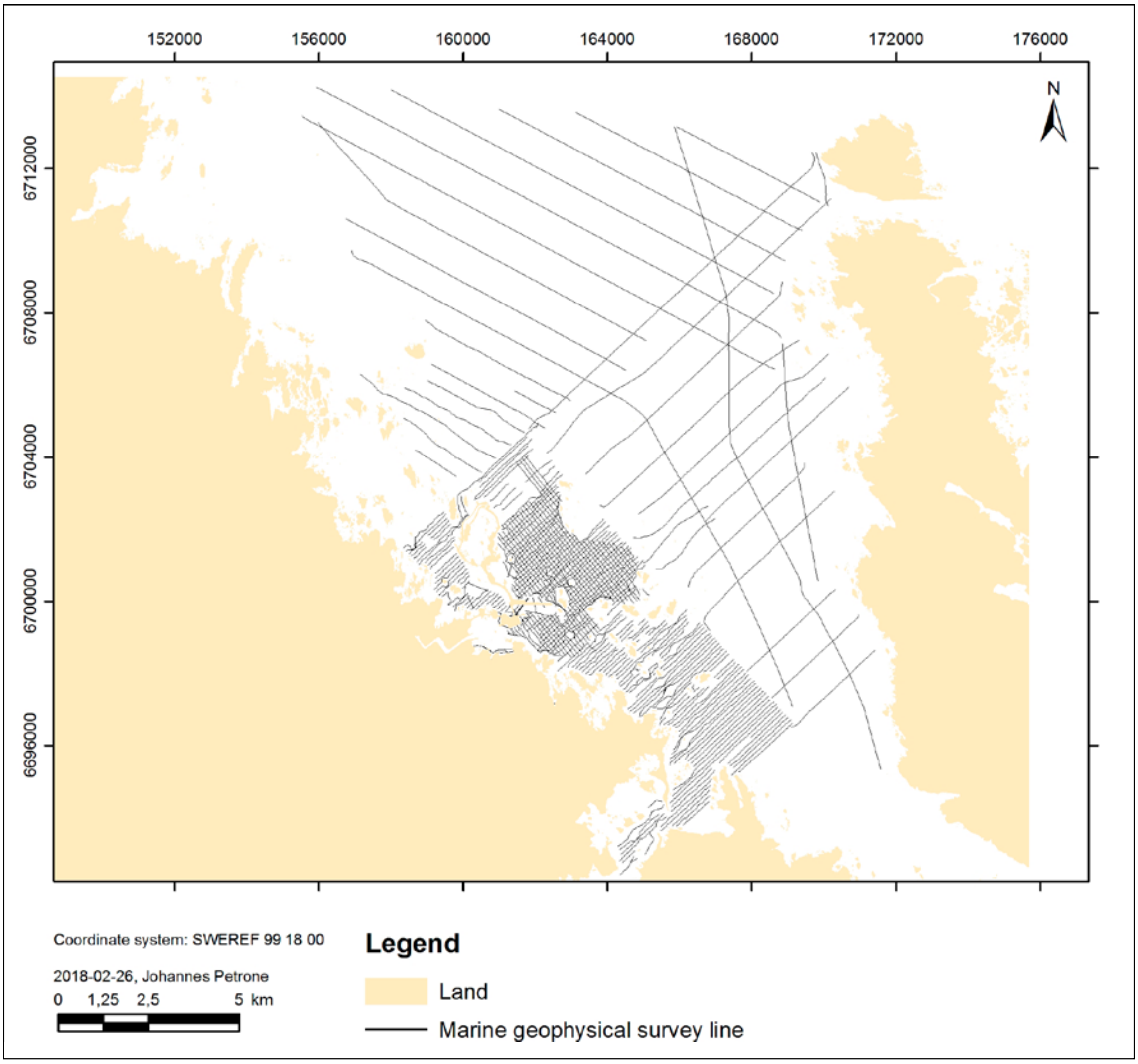

Figure 2-5. *Lines in the marine area along which data from echo and seismic soundings were collected. The results were used for modelling both total regolith thicknesses and the thicknesses of the individual regolith layers.*

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 2-2.

Area	Type of data	Reference (s)
1 (Terrestrial)	Detailed regolith map for presentation in 1:10000.	Sohlenius et al. (2004).
2 (Terrestrial)	SGU map of regolith for presentation in 1:50000.	Persson (1985, 1986), data from SGU´s regolith database.
3 (Marine)	Distribution of regolith in shallow coastal areas.	Ising (2005).
4 (Marine)	Detailed distribution of regolith in coastal areas with water depths between 3 and 6 m. Depth and stratigraphy of regolith obtained along lines with a spacing of 100 m.	Elhammer and Sandkvist (2005).
5 (Marine)	Distribution of regolith at the sea floor in areas with water depths > 6 m. Depth and stratigraphy of regolith obtained along lines with a spacing of 1000 m with data from some additional crossing lines.	The central part of the area was interpreted by Elhammer and Sandkvist (2005) and reinterpreted by Nyberg et al. (2011). The map representing the whole area is available in the SGU database (Nyberg 2016). Data for parts of the area are only available in the SGU database.
6 (Marine)	Detailed distribution of regolith in coastal areas with water depths between 3 and 6 m. Depth and stratigraphy of regolith obtained along a network of lines with a spacing of 100 m.	Nyberg et al. (2011).
7 (Lakes in the central part of the model area)	Interpretation from corings in lakes.	Hedenström (2003, 2004a, b), Sohlenius and Hedenström (2009).
8 (Lakes and shallow bays)	Interpreted from DEM and surrounding regolith.	Interpreted from distribution of surrounding regolith.

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	Reference (s)
DEM	The DEM has a resolution of 20 × 20 m^2 and describes the land surface and the bathymetry of lakes and sea.		Petrone and Strömgren (2020).
Geological maps			
Maps of Quaternary deposits	The map of regolith and bedrock outcrops covering the entire model area. The map is a compilation of eight data sets based on different methods and scale.	Eight different data sets (maps) integrated into one map (Figure 2-2).	Elhammer and Sandkvist (2005), Sohlenius et al. (2004), Persson (1985, 1986), Ising (2005), Hedenström and Sohlenius (2008), Nyberg et al. (2011), data from the SGU database for marine geology.
Corings, excavations and observations			
Boreholes	Boreholes with an estimated bedrock elevation, i.e. cored, percussion and probing boreholes.	44 boreholes	Johansson (2003), Hedenström et al. (2004), Werner and Johansson (2003), Werner et al. (2004, 2006), Albrecht (2007), Hansson et al. (2008).
Groundwater monitoring well	Boreholes with stratigraphical information and in some cases depth to bedrock.	100 boreholes	Johansson (2003), Hedenström et al. (2004), Werner and Johansson (2003), Werner et al. (2004, 2006), Albrecht (2007), Hansson et al. (2008).

Data from the access area of the planned spent nuclear fuel repository	Boreholes and excavations. Most of this data was however not used in the RDM presented here, but is used in a detailed RDM for the access area is presented Follin (2019).	See Follin (2019).	Curtis et al. (2012), Hellgren (2010, 2011), Henriksson (2016).
Geological observation point	Mostly shallow observation points from hand driven corers and excavations with detailed stratigraphy and stratigraphical information from shallow marine areas. Stratigraphical investigations in machine cut trenches are also included in this group of data.	c 700 stratigraphical and/or point observations.	Lokrantz and Hedenström (2006), Sohlenius et al. (2004), Sundh et al. (2004), Fredriksson (2004), Hedenström (2003, 2004a, b), Ising (2005), 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 the SGU database.	390	SGU (2015).
Geophysical data			
Geophysical data (marine survey lines)	Estimated depth to bedrock and stratigraphy.	c 11 000 data points.	Nyberg et al. (2011) interpreted from data collected by Elhammer and Sandkvist (2005).
Refraction seismics	Each observed point along the profiles has a surface elevation and an estimated smoothed bedrock elevation.	7 760	Keisu and Isaksson (2004), Toresson (2005, 2006), Bergman et al. (2004), Bergman (2004).

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 tests that showed that the helicopter data had a too low confidence for the modelling of regolith depths.

The refraction seismics data from the marine area (Keisu and Isaksson 2004) includes data that contradict 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 depth 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 5 and 6 in Figure 2-2.
3. Data from marine geological measurements in Area 4 in Figure 2-2.

4. Data from the SGU archive of wells, since such data often have a low accuracy in 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 the purpose of investigating 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. In addition, there is a general assumption that the direct observations from the field are more reliable than the interpretations from geophysical data.

3 Description of the model area

The model area is situated along the coast of the Baltic Sea and includes both terrestrial areas and areas covered by water, including lakes and sea. The 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. The largest water depths are in the northern part of the model area, west of Island Gräsö, where the water depth is c 50 m (Figure 2-1). The superficial distribution of regolith materials in the model area is shown in Figure 3-1.

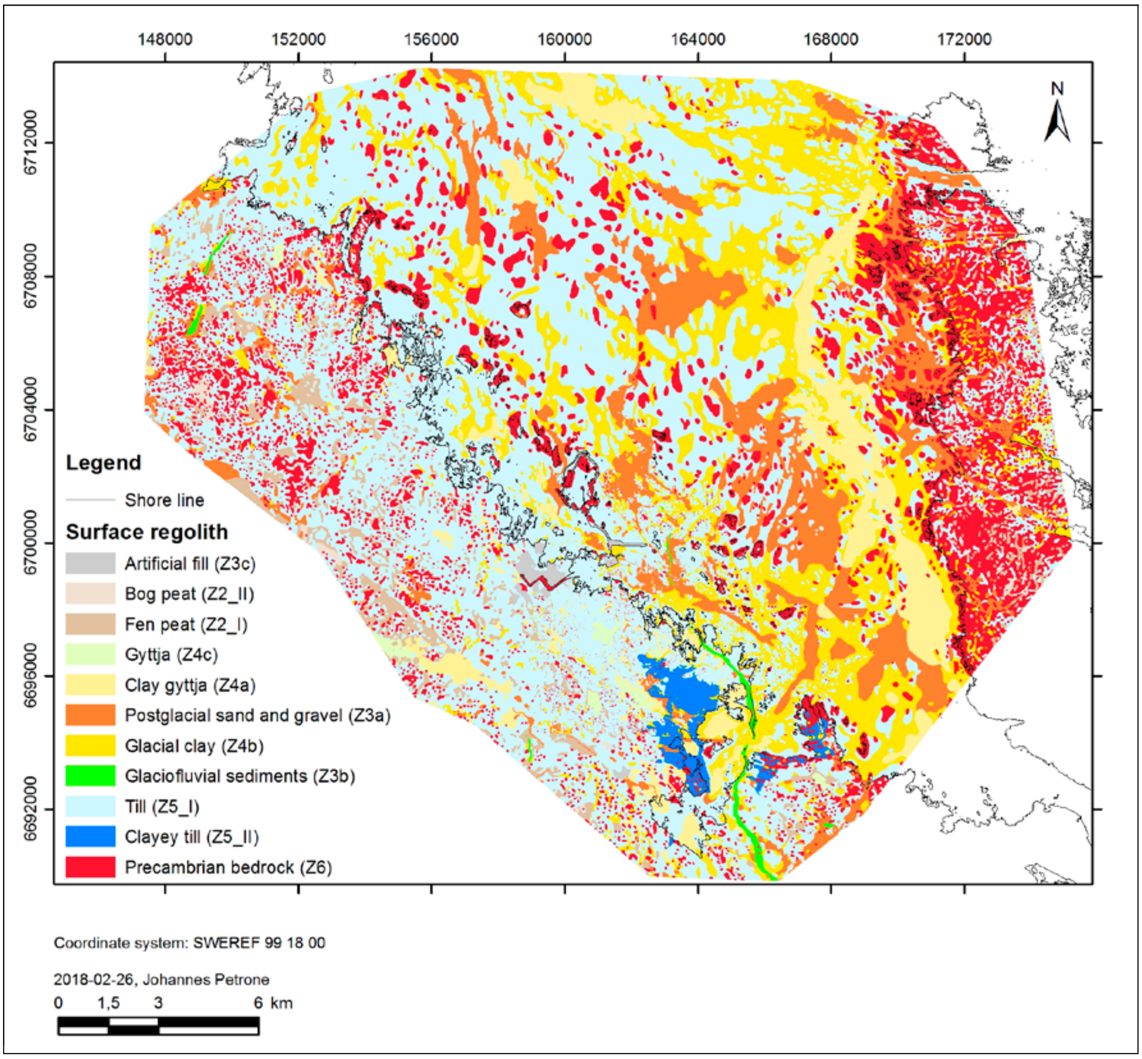

Figure 3-1. *The distribution of regolith in the Forsmark area 0.5 m below the ground surface. It should be noted that the areas presently covered by water (lakes, streams and sea) are presented without the covering water on the map. The map is a compilation of eight maps, originally presented in different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

All known unconsolidated naturally occurring deposits in the Forsmark area were formed during the Quaternary period and are 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 85 % of the ground surface within the model domain. In areas covered by regolith, the contact zone between bedrock and till is characterised by a high hydraulic conductivity (Werner and Johansson 2003) and open fractures (Leijon 2005).

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 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). Most 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 is 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, and is in parts of the area characterised by a high surface frequency of boulders. In the area around Storskäret, clayey till dominates, i.e. till with a clay content > 5 % in the matrix and a low frequency of boulders (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 spatial 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 overlay 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 consisting of remnants from plants 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 repository (Figure 3-1). The artificial fill around the nuclear power plant is assumed to rest directly upon the bedrock surface. 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 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 partly high frequency of exposed bedrock. Certain areas such as the area south of the nuclear powerplant are, however, dominated by till with a low frequency of outcrops. 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 in 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, respectively. 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 Z2 to Z5 in the RDM. In the RDM, Z6 belongs to the bedrock and is consequently not regolith. artificial fill (Z3c) is often resting directly upon the bedrock surface and is never overlaid by other Z-layers. 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.

An additional layer, Z1, was included in earlier RDMs (Sohlenius et al. 2013) to represent the uppermost regolith that is affected by surface processes, e.g. soil forming processes in the terrestrial parts or sedimentation/transport/erosion in the limnic/marine parts. This layer had the same thickness (0.6 m) in all areas covered by regolith. Z1 was not included in the present RDM but can be added if needed for specific modelling purposes. For consistency with earlier models, layer notation for remaining layers has been retained. Furthermore, in the former model Z6 represents the uppermost 0.6 meter of the bedrock, whereas in this model Z6 represents all bedrock. All other Z-layers used in the present model, except Z4c (gyttja), were included also in former RDMs.

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 location. Artificial fill (Z3c) is not shown in the table.

Regolith type	Relative age	Layer in the RDM
Peat	Youngest	Z2_I
Gyttja	↓	Z4c
Clay gyttja		Z4a
Postglacial sand and gravel		Z3a
Clay gyttja		Z4a_I
Glacial clay	↓	Z4b
Glaciofluvial sediments		Z3b
Till	Oldest	Z5_I
Bedrock		Z6

4 Methodology

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

- Based on available data a conceptual model was constructed showing the stratigraphical and geographical distribution of the regolith layers, including the uppermost bedrock.
- All data showing regolith depth and stratigraphy as well as maps of QD and DEM were imported to the SubsurfaceViewer tool.
- Sections based on observation and stratigraphical knowledge were drawn in SubsurfaceViewer.
- Construction of layers showing the geographical distribution of the different regolith layers.
- Due to the large size of the dataset, the model area was split into four areas within SubsurfaceViewer that were interpolated and exported individually.
- The sections and layers were used for producing the lower and upper elevations of the regolith layers.
- The upper and lower elevations of each layer were exported from SubsurfaceViewer (thicknesses of the modelled layers) and were thereafter combined in ArcGIS to cover the entire model area.
- Several post-processing steps were made in ArcGIS to obtain realistic thicknesses and elevations of the regolith layers.
- The model was evaluated, and additional sections were drawn in SubsurfaceViewer to improve the model.
- The final model was then produced in SubsurfaceViewer and post-processed in ArcGIS (as described above).

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) and for the extension of the existing SFR facility (e.g. Nyberg et al. 2011).

The principle of the definition of the layers is illustrated in Figure 4-1. This conceptual model is stored in SKB:s database (a word-file with model-ID: 1712500). 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.

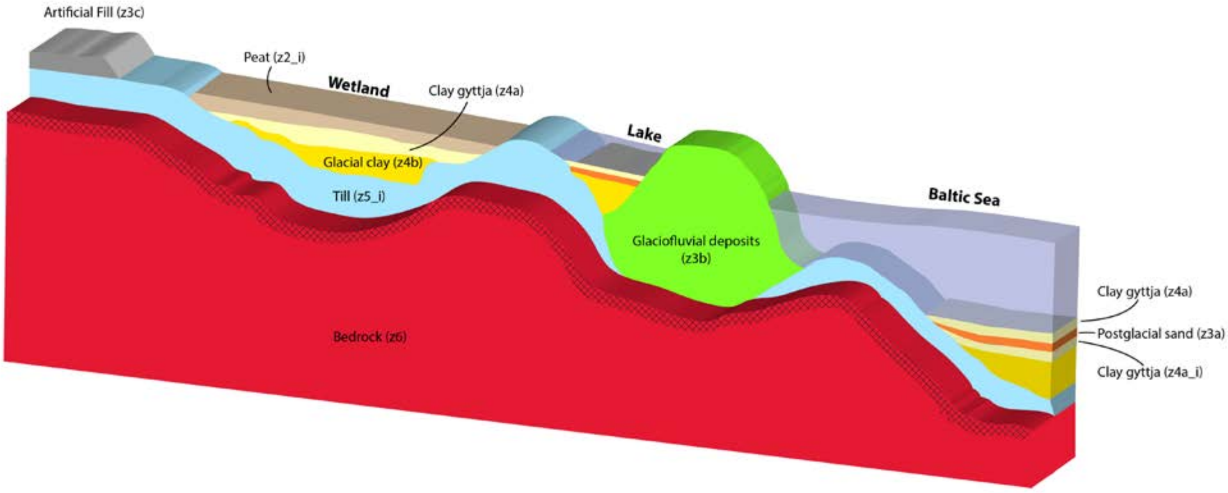

Figure 4-1. *The general distribution of the regolith layers (Z-layers) used in the RDM. The stratigraphy is further explained in Table 3-1 and Table 4-1. This conceptual model is stored in the SKB model database SKBmod as a word-file with SKBmod ID 1712500.*

Table 4-1. The nine regolith types and bedrock (Z6) represented by Z-layers, which are included in the regolith depth model (RDM). The geographical distributions of these layers are shown in Appendix 1.

Regolith type (English term)	Jordart (Swedish term)	Layer	Comment
Artificial fill	*Fyllning*	Z3c	This layer corresponds to material which has been artificially deposited by humans
Peat	*Torv*	Z2_I	Including both fen peat and bog peat
Gyttja	*Gyttja*	Z4c	Sediments deposited in lakes characterised by a high organic content
Clay gyttja	*Lergyttja*	Z4a	This layer also represents postglacial clay that has a lower organic content than clay gyttja
Postglacial sand/gravel	*Postglacial sand/grus*	Z3a	In the terrestrial area Z3a also includes a few deposits with recent fluvial sediments and shingle
Clay gyttja	*Lergyttja*	Z4a_I	In parts of the marine area, clay gyttja occurs below postglacial sand
Glacial clay	*Glaciallera*	Z4b	Including glacial silt
Glaciofluvial sediments	*Isälvsmaterial*	Z3b	Corresponds in the terrestrial area to glaciofluvial eskers
Till	*Morän*	Z5_I	Including sandy, silty and clayey till
Bedrock	*Berggrund*	Z6	

The model is subdivided into ten layers the vertical distribution of which is illustrated in Figure 4-1, Table 3-1 and Table 4-1.

The model presents the geometry of the upper level for each layer as elevation above sea level (in the Swedish national elevation system RH2000). The model was produced using the coordinate system RT90 2.5 gon W. The final model is adapted to the coordinate system SWEREF99. The model has a spatial resolution of 20×20 m^2. Furthermore, the model also contains the thickness of each layer. The lower level for Z5_I (till) was produced from the data showing the total regolith depth, and from the distribution of bedrock outcrops. Thus, the lower level of Z5_I represents the bedrock surface, regardless of whether it is covered by regolith or not.

Table 4-2. The general stratigraphical distributions of the Z-layers, which are shown in the regolith depth model (RDM). The stratigraphy represents the regolith types overlying the bedrock from left (surface) to right (bedrock).

Regolith type on the map of regolith	Stratigraphy	Comment
Artificial fill (Z3c)	Z3c (in some areas underlain by other deposits)	
Peat (Z2_I)	Z2_I/Z4c/Z4a/Z3a/Z4b/Z5_I	All peat is denoted Z2_I Peat areas bordering areas with water laid sediments (clay or sand). All these layers are not present in all peat covered areas, e.g. gyttja was only modelled in peat bordering lakes and at sites where that deposit has been observed
Peat (Z2_I)	Z2_I/Z5_I	Small peat areas not bordering areas with water laid sediments (clay, sand or gyttja)
Gyttja (Z4c)	Z4c/Z4a/Z3a/Z4b/Z5_I	
Clay gyttja, gyttja clay and postglacial clay (Z4a)	Z4a/Z3a/Z4b/Z5_I	
Postglacial sand and/or gravel (Z3a)	Z3a/Z4b/Z5_I Z3a/Z4a_I/Z4b/Z5 (in some marine areas)	Including a few areas with recent fluvial sediments and shingle
Glacial clay/Glacial silt/Clay (Z4b)	Z4b/Z5_I	
Glaciofluvial sediment (Z3b)	Z3b (in some areas underlain by till)	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
Till (Z5_I)	Z5_I	All till is denoted Z5_I

4.2 Stratigraphical profiles in SubsurfaceViewer

The program SubsurfaceViewer MX® (© INSIGHT Geologische Softwaresysteme GmbH) was used for interpreting and modelling the elevation and thicknesses of the regolith layers. The program makes it possible to use the general knowledge of the stratigraphical distribution of regolith layers to construct a model based on available data. SubsurfaceViewer MX was developed from another program, GSI3D (Geological Surveying and Investigation in 3 Dimensions), developed by Hans-Georg Sobish in cooperation with the British Geological Survey (BGS, Kessler et al. 2009). SubsurfaceViewer is now distributed by INSIGHT Geologische Softwaresysteme GmbH and managed by Hans-Georg Sobish. The program GSI3D has earlier been used by SGU (Peterson et al. 2014) to model the stratigraphical distribution of regolith and SubsurfaceViewer is currently used at SGU for the same purpose (Jirner et al. 2016).

For modelling in SubsurfaceViewer several files must be constructed. The GVS-file describes the stratigraphy of the regolith (Z-layers in Table 3-1 and Figure 4-1) in the model area. This file determines in what stratigraphical order the different regolith (Z) layers can occur in the model. The different regolith layers are displayed according to a GLEG-file where the colours of all layers are defined. The regolith was symbolised with the same colours as used on the regolith map (Figure 3-1). Stratigraphical data from the different surveys, (e. g. results from drillings and geophysical studies) were imported in two separate files. The BID-file contains id-numbers, coordinates (x and y) and altitudes in metres above sea level (z). The BLG-file contains id-number and the depth below the DEM of the regolith layers. Some of the geophysical data was imported to SubsurfaceViewer as 3D-shapes. The DEM (Petrone and Strömgren 2020) was imported to SubsurfaceViewer as raster with 20×20 m^2 resolution and the regolith map (Figure 3-1) was imported as a shape file.

In SubsurfaceViewer three windows are displayed (Figure 4-2). In one window, all points with stratigraphical information are shown together with the map of regolith (Figure 4-2). In that window sections can be drawn between the points with stratigraphical data. The section and the points with stratigraphical data are thereafter displayed in a second window, where the distribution of regolith layers along the line is interpreted by using the stratigraphical information and the map of regolith. The different regolith types were delineated by drawing lines along the sections. A third window can be used to visualise the sections in 3D (Figure 4-2).

Some areas in the vicinity of the model area lack stratigraphical data and there the sections were interpreted using the map of regolith and the general stratigraphical knowledge which was obtained from stratigraphical studies in other parts of the model area.

The geophysical data (refraction seismics and CVES) collected along lines were imported as 3D-shapes which thereafter were converted to sections. Most of these sections needed to be modified since they only show the total regolith depths. Regolith layers were therefore added by using the regolith map and the knowledge of the general stratigraphical distribution of regolith. Many of the sections are based on geophysical data and cross areas shown as outcrops on the regolith map. In such areas the regolith depths have been interpreted to be zero.

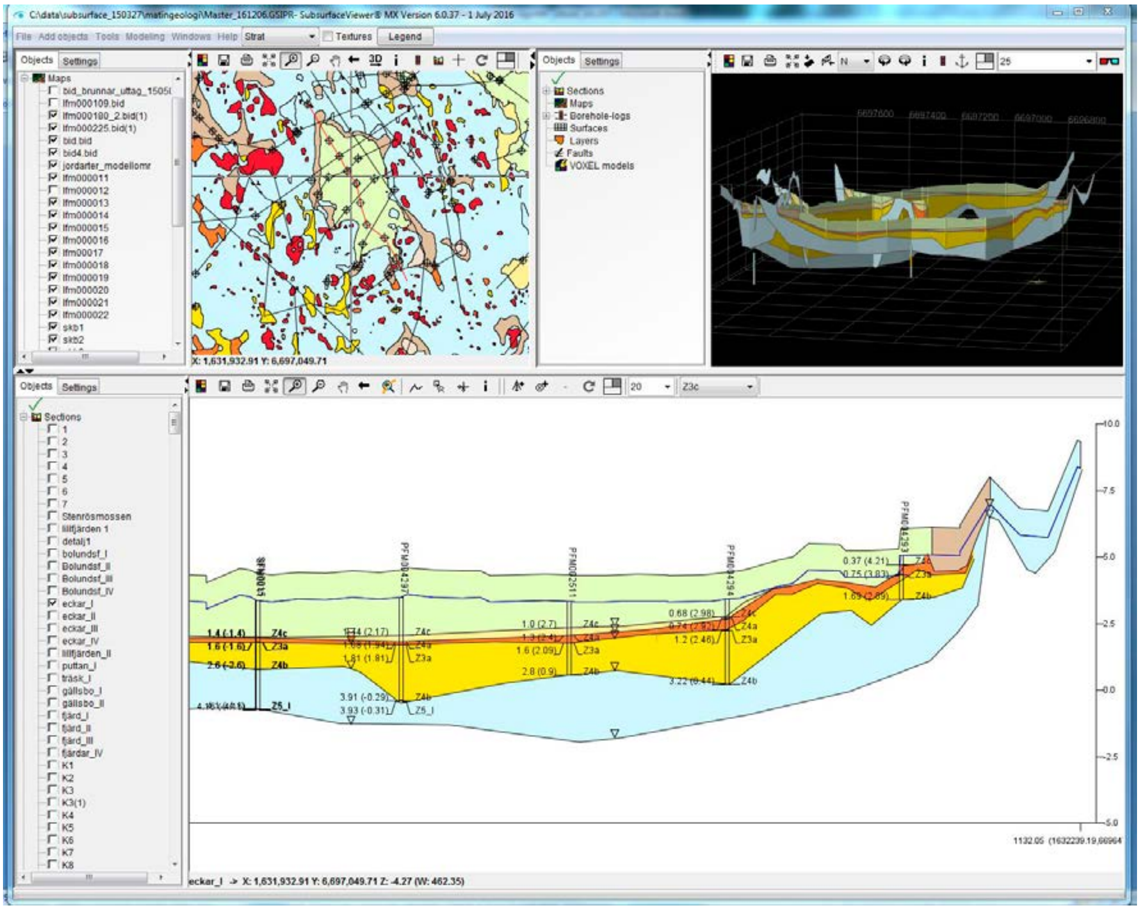

Figure 4-2. *Three windows are available when working with SubsurfaceViewer. The map of regolith and location of stratigraphical observations are shown in the upper left window, which also displays the positions of the sections. The distributions of regolith layers along the sections were interpreted in the lower window, by using the map of regolith together with the stratigraphical observation. The regolith map is shown in the upper part of the sections and the stratigraphical observations are displayed as stacks. The triangles show where sections cross. The regolith is displayed with the same colours in the sections and on the regolith map. All sections can be displayed and studied from different directions in the upper right window.*

In the marine area data was obtained from geophysical data collected along lines. Most of this data were imported as series of BID- and BLG-files, showing the interpreted stratigraphical distributions at points with separations of 25–50 m along the lines. The sections were completed by drawing lines delineating the regolith types. Regolith depth zero was interpreted in areas where the sections cross areas shown as outcrops on the regolith map. In the marine areas, there are some discrepancies between the map of regolith and geophysical data. As an example, there are places where the regolith map shows that the sea floor consists of till whereas geophysical data suggest that the till is covered by glacial clay and postglacial sand. In most cases the data from the geophysical investigation was then used when drawing the sections. However, along some sections the geophysical data suggests the occurrence of water deposited clays in topographically high areas and till in the topographically low areas. This is a highly unlikely distribution of regolith, and in such cases geophysical data was consequently not used when interpreting sections.

When all sections had been interpreted, the crossings between sections were checked to make sure that the distribution and thicknesses of regolith layers were the same in both sections where they cross. At some crossings, there were discrepancies between the sections, and some sections were therefore partly reinterpreted. If a large discrepancy between two sections was observed, both sections were changed equally. However, if there was a discrepancy between a section based on geophysical data and a section based on drillings the results from the drillings were regarded as more reliable, and the section based on geophysical data was consequently reinterpreted. In the sections situated closest to the border of the model area a bedrock layer was entered. This layer reaches below the level of the deepest recorded regolith layer to secure that all regolith in the final model is underlaid by bedrock. The geographical density of sections mirrors the density of data and varies consequently within the model area (Figure 4-3). Lines were also drawn in areas lacking data to secure that all areas were realistically modelled. Altogether, more than 700 sections were interpreted (Figure 4-3).

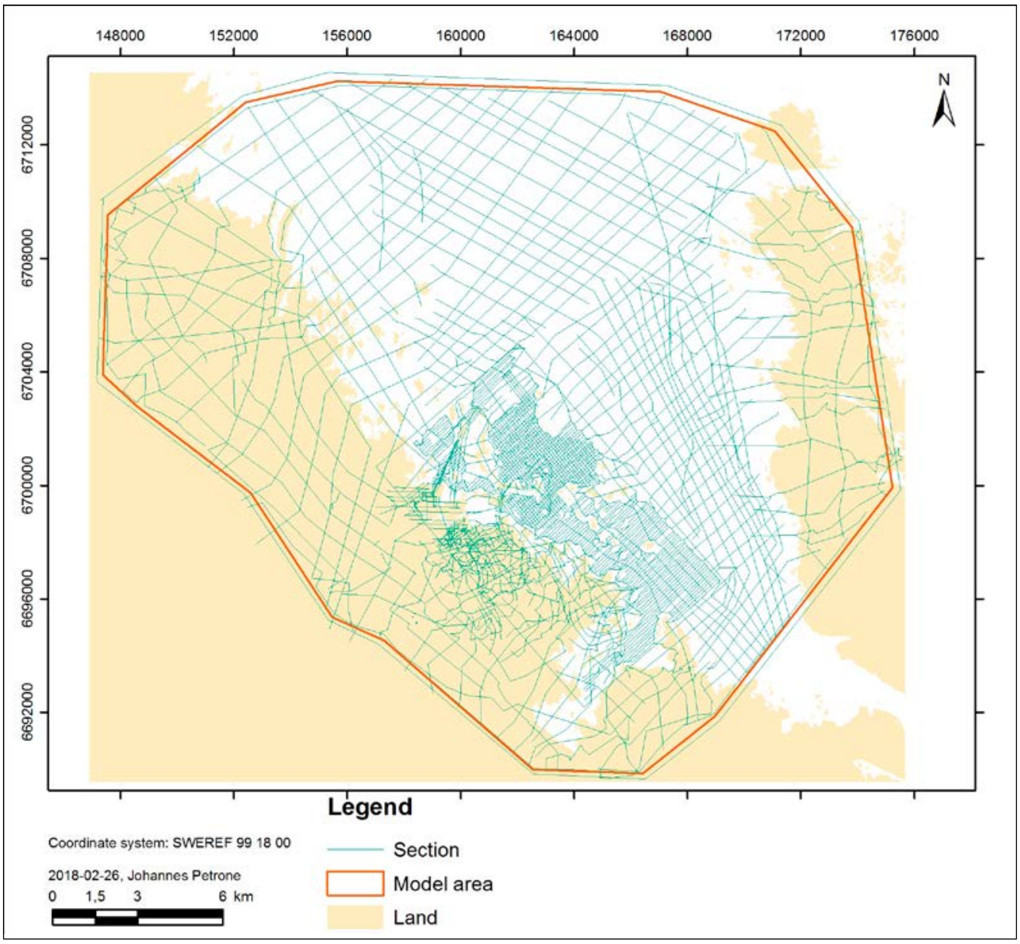

Figure 4-3. *The geographical distribution of the more than 700 sections that were drawn in SubsurfaceViewer. The density of sections reflects the density of available data.*

4.3 Areal distribution of regolith layers used for interpolation

The map of regolith contains numerous surfaces representing different types of regolith. Most of these surfaces lack stratigraphical observations. Based on the regolith map and the sections drawn in SubsurfaceViewer, the areal distribution of each regolith type (layer) used for modelling was determined. Since several types of regolith may occur at one location (Figure 4-1), several layers can be present at that location. Altogether, nine layers were produced to secure that all stratigraphical units shown in Figure 4-1 are represented in the RDM. These layers are equivalent to the nine regolith layers shown in Table 3-1. One additional layer, Z6, represents the bedrock and is present in the whole model area.

The stratigraphy of the regolith layers is distributed in accordance with the conceptual model (Figure 4-1). In some areas, observations confirm that some of the layers in the conceptual model are lacking. As an example, there are areas with gyttja (Z4c) resting directly upon till (Z5_I), lacking the layers of glacial clay (Z4b) postglacial sand (Z3a) and clay gyttja (Z4a) that often are found in such area. Table 4-2 shows the relations between regolith types on the regolith map (i.e. just below the ground surface) and the general stratigraphical distributions from the surface to the bedrock.

In areas where observations contradict the conceptual model, the results from the observations were always used for delineating the layers. In some areas, the interpretations of the sections contradict the map of regolith. One such example is that there are several lake bottoms that according the regolith map consist of clay gyttja (Z4a), which in the sections have gyttja (Z4c) as the uppermost deposit. The interpretation from the sections was then used when constructing the layers and the regolith map will later be updated to be in accordance with these observations. Furthermore, in the marine area, as mentioned above, there are many places where the regolith map contradicts the sections and thereby the interpretation of layers.

In Appendix 1, the surface distributions of the nine regolith layers are shown. In some cases, the layers are partly modelled based on the interpretations from the sections, i.e. the modelled layer is not shown on the map of regolith. In the marine area, there are for example areas with glaciofluvial deposits (Z3b) that are covered by glacial clay (Z4b), and consequently not shown on the regolith map.

In the terrestrial areas, there are numerous small surfaces with water laid deposits and peat. Stratigraphical observations (e.g. Sohlenius and Hedenström 2009) have shown that these deposits often are situated directly upon the till and lack the complete stratigraphy illustrated in Figure 4-1. If the peat according to the map of regolith is not surrounded by water laid sediment, it is assumed that the peat rests directly on the top of the till. Accordingly, it is assumed that the deposits in small areas with water laid sediments rests directly upon till.

4.4 Calculations in SubsurfaceViewer

Delaunay triangulation was used to calculate the upper and lower elevations of each of the nine regolith layers. The thicknesses were thereafter determined as the differences between the upper and lower elevation of each regolith layer. To avoid unrealistically thin or thick layers in the areas between the interpreted sections, minimum allowed thicknesses (Table 4-3) were used for the triangulation of the layers. These values constitute the average values of the recorded thicknesses of each layer. The average values were calculated from observed thicknesses. However, thicker and thinner layers occur along the interpreted sections and at places with observations showing the actual layer thicknesses. The peat (Z2_I) layers in areas at low altitudes (below 5 m) are thinner than peat at higher altitudes. A lower minimum thickness (0.4 m) was therefore used for calculating the peat thickness in these low laying areas. This was, however, done during the post-processing (see below).

Table 4-3. Average thicknesses for nine regolith layers. These values were used in areas between the sections, where data is lacking. A thinner peat thickness was used in areas situated below 5 m.

Regolith type	Layer	Average thickness (m)
Artificial fill	Z3c	1.0
Peat	Z2_l	1.4 (0.4[1])
Gyttja	Z4c	1
Clay gyttja	Z4a	0.5
Postglacial sand	Z3a	0.6
Clay gyttja	Z4a_l	1
Glacial clay	Z4b	1
Glaciofluvial sediment	Z3b	1[2]
Till	Z5_l	4

[1] In areas below 5 m above sea level.
[2] This value has a low impact on the final model due to a high density of interpreted sections in areas with glaciofluvial deposits.

Since the data set was too large, it was not possible to calculate the elevations of the layers simultaneously for the whole area. The area was therefore divided into four subareas that were calculated separately. The layers from the four areas were thereafter exported to ArcGIS (see below) and merged into layers representing the upper and lower elevations for the nine layers in the whole area. The first version of the model was reviewed, and some unrealistic model results were identified. Extra sections were drawn to eliminate these unrealistic results and a final model was thereafter produced. However, there were some unrealistic features that were impossible to correct in SubsurfaceViewer. These features were corrected in ArcGIS during the post-processing (see the section below).

4.5 Post-processing of interpolated surfaces

The thicknesses of the regolith layers were modelled in SubsurfaceViewer. For producing the final model, it was, however, necessary to make some additional work called post-processing. That final work was performed in ArcGIS. The steps taken for each thickness layer during the post-processing are described in detail in Appendix 2. The following post-processing steps were performed in ArcGIS:

- The model area was divided in to four sub-areas that were modelled individually in SubsurfaceViewer. That was necessary since the data-se was too large for modelling in one step. These four areas were later combined in ArcGIS.
- The interpolated layers from SubsurfaceViewer were produced in the coordinate system RT 90 2.5 gon W and height system RH70. The final product was transformed to the reference system SWEREF 99 18 00 and height system RH2000.
- There were unrealistically sharp differences within small distances in the regolith thicknesses within the layers interpolated in SubsurfaceViewer. These sharp transitions were therefore smoothed in ArcGIS.
- At some sites, in the raster from Subsurface Viewer, there were thick layers of regolith within some areas that are represented by outcrops on the map of Quaternary deposits. The regolith thicknesses at these sites were therefore set to 0 in ArcGIS.
- Some of the layers interpolated in SubsurfaceViewer had interpolation errors and interpolation artefacts present, such as lines of null pixels (pixels with no value) in areas where a thickness of that layer had been interpreted (Figure 4-4). Such errors were corrected in ArcGIS.
- The modelled thicknesses for all layers cover the whole model area. The thickness of a layer is set to 0 in areas where the deposit representing the layer are missing. The thickness value of the pixels where a layer was not present was, however, null in the raster produced by SubsurfaceViewer (i.e. not set to 0) and there were consequently holes in the layers that had to be filled in ArcGIS (Figure 4-4).
- The geographical extents of the layers from SubsurfaceViewer were not completely consistent with the extent of the model area. That was corrected in ArcGIS.

- The peat layer (Z2_I) produced in SubsurfaceViewer was too thick in recently uplifted areas, i.e. was too thick close to sea level where thinner peat layers occur. A layer representing peat at low altitudes was therefore produced in ArcGIS.
- The layers produced in Subsurface show the thicknesses of each modelled regolith layer. Layers showing the altitudes (m a.s.l.) of the lowest limit of each layers were produced in ArcGIS (see Appendix 2).

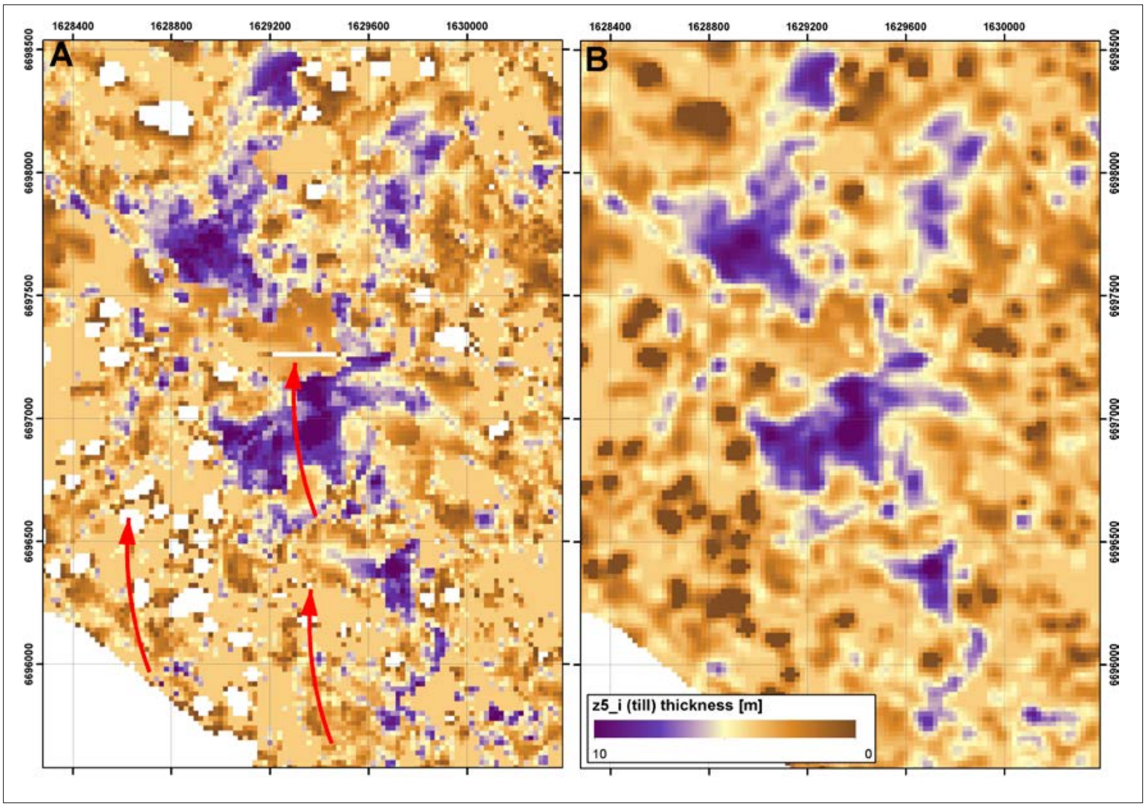

Figure 4-4. *A) Exported thickness of till (Z5_I) from SubsurfaceViewer. The arrows show interpolation artefacts. The two arrows to the right show areas with holes even though a till thickness has been interpreted. The left arrow indicates an area with an outcrop that consequently is lacking till and therefore should be represented by pixels with 0 values. B) Post-processed thickness with corrected pixels where there is no till, as well as smoothing and filling of the pixels.*

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, RH2000) or the thickness of the layers. The projection for all the layers is SWEREF 99 18 00 and the resolution is 20×20 m^2.

The regolith model is available in the SKB model database SKBmod where it has ID 1712498. The model is available in an mxd file (ArcGIS). The conceptual model (Figure 4-1) is presented in a word document that has SKBmod ID 1712500.

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 part of the model area, respectively. The maximum depth of regolith in the model is more than 50 m, and the average depth is 4.2 m with bedrock outcrops included and 4.5 m with outcrops excluded. The thickness of the regolith often follows the underlying bedrock topography. This 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.

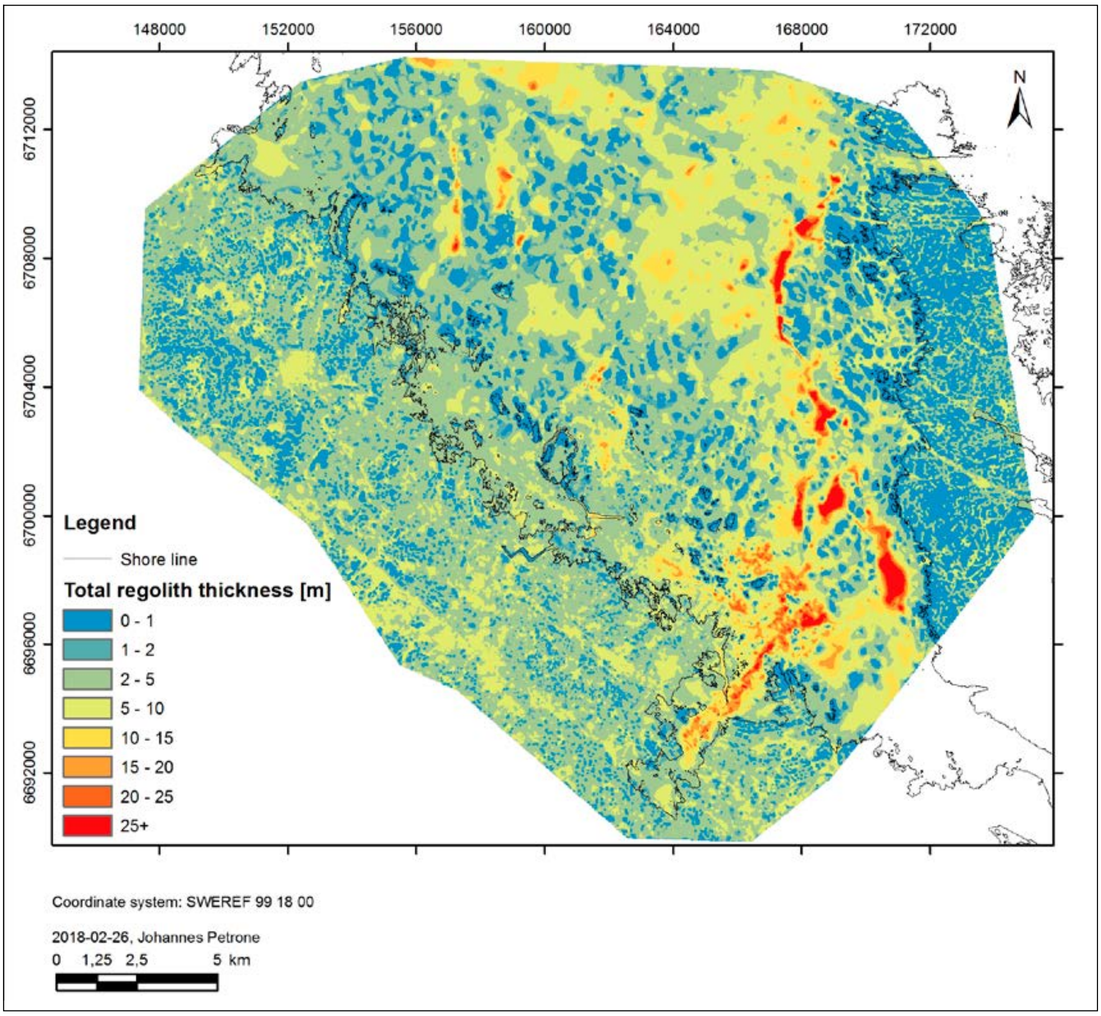

Figure 5-1. *Total modelled regolith depths. The present shoreline is marked by a black line. For orientation, it may be noted that the "w-shaped" object near the shoreline is the intake canal to the nuclear power plant.*

The average regolith depth in the terrestrial area is 3.8 m, with bedrock excluded, and the corresponding value for the marine area is 5.7 m. 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 regolith depth within each raster cell can be regarded as the average depth within the cell. Some small outcrops within Area 1 (Figure 2-2) are not shown as regolith depth zero in the resulting model. This is since these outcrops are much smaller than the resolution of the model (20×20 m^2).

The Esker Börstilsåsen and some areas with artificial fill are exceptions from the rule mentioned above, since these deposits constitute morphological landforms entirely built up by regolith, and the upper surface of these deposits does not follow the morphology of the underlying bedrock. In parts of the terrestrial area, the density of data is in general low and the modelled thicknesses are not supported by data, but by the interpretations made in the sections. These interpretations are based on the thicknesses obtained from data from other parts of the modelled area.

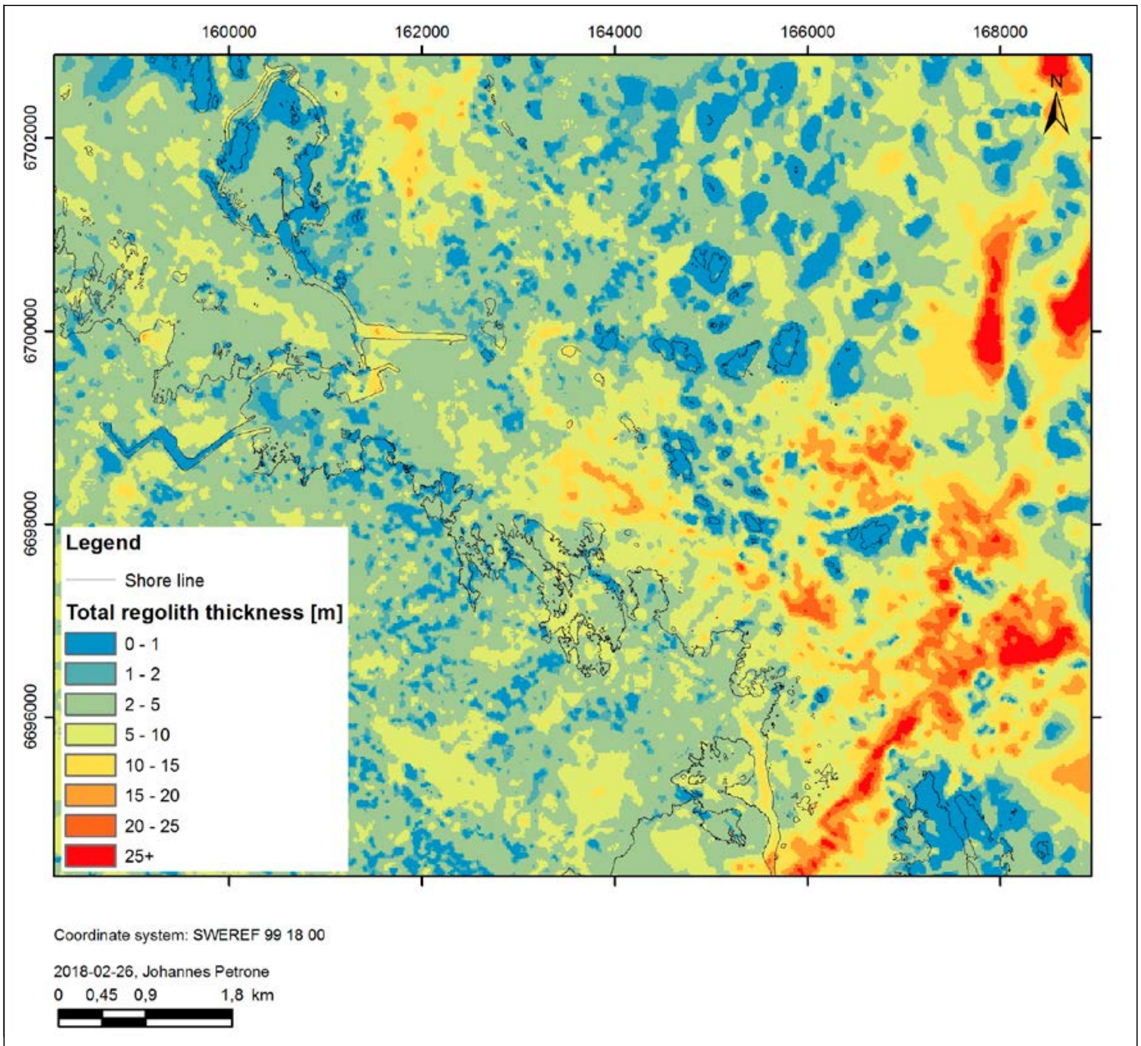

Figure 5-2. *The modelled regolith depths in the central part of the model area. The present shoreline is marked by a black line. For orientation, the "w-shaped" object just above the legend is the intake canal to the nuclear power plant and the SFR peninsula and pier can be identified some distance to the northeast of the canal.*

5.2 Thicknesses of the individual regolith layers

The thicknesses of the regolith layers are dependent on the thicknesses along the interpreted sections but also on the minimum depths used during triangulation of the layers (Table 4-3). In areas with a wide spacing between the sections, the regolith layers commonly have thicknesses close to the average thicknesses between the sections. However, in areas where the sections are situated close to each other the average thicknesses are not reached.

The individual layers can also be converted to thickness (discussed further in Section 5.3) or other formats. Figure 5-3 and Figure 5-4 show two 2 × 1 km^2 cut outs from the model, converted from raster to TIN (Triangulated Irregular Network) and then extruded between layers to create multipatch features for visualization of thickness and topography. Some sections are shown in Appendix 3. The stratigraphical data used for interpretation of the sections are shown in the figures.

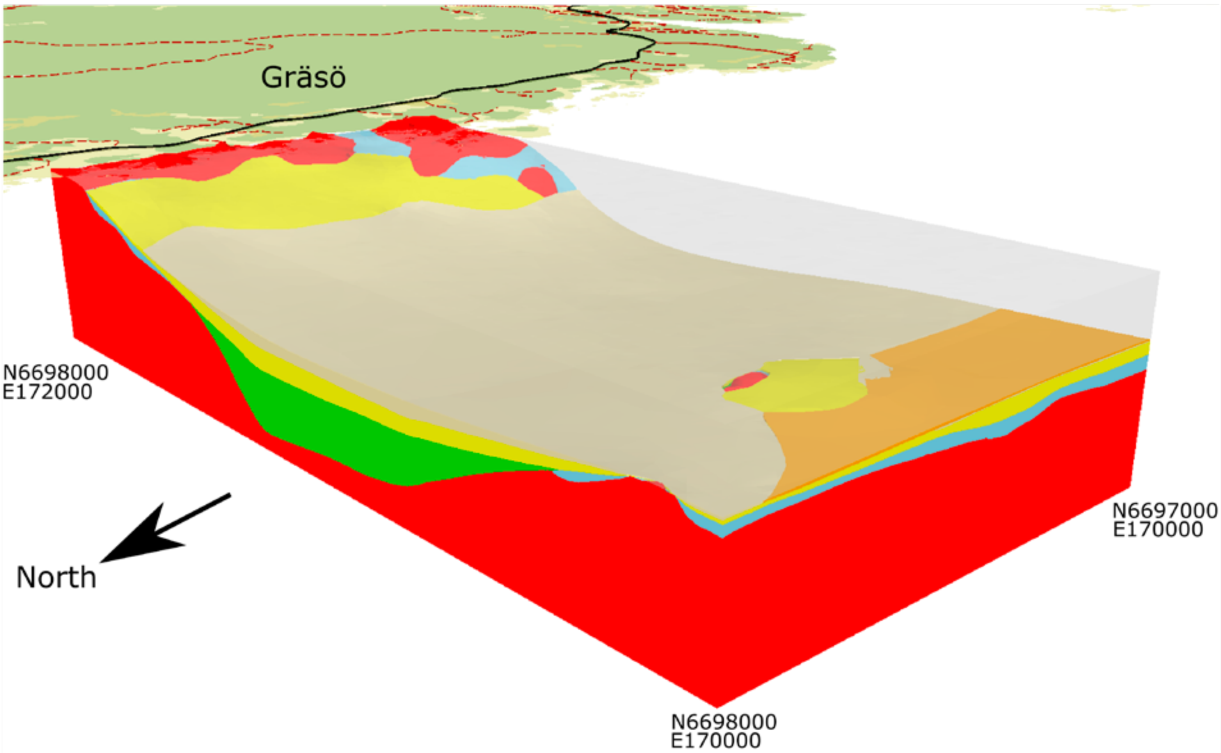

Figure 5-3. *Cut out of a 2 × 1 km^2 block of the model showing the transition between land and sea as well as individual layers and the water body. The layers have a vertical exaggeration of 5. The colours representing the regolith layers are explained in Figure 3-1. Coordinate system: SWEREF 99 18 00.*

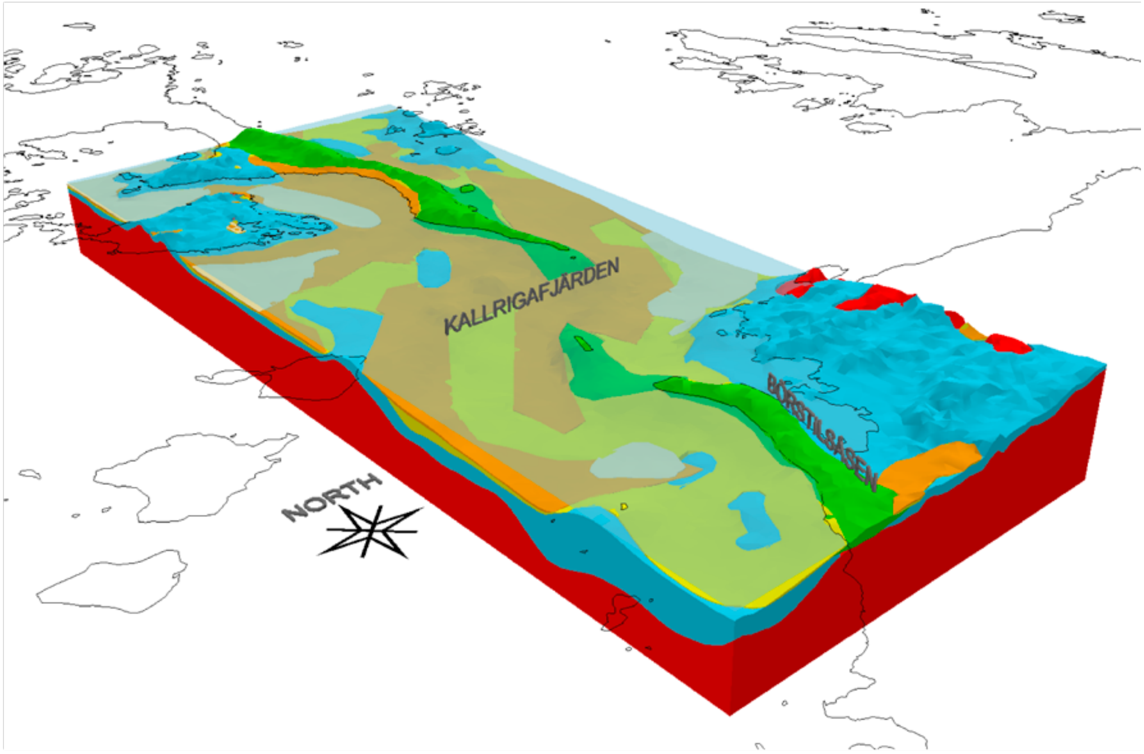

Figure 5-4. *Cut out of a 2 × 1 km² block of the RDM showing the transition between land and sea as well as individual regolith layers and the water body. The shoreline is displayed as a black line. The layers have a vertical exaggeration of 5. The colours representing the regolith layers are explained in Figure 3-1. Coordinate system: SWEREF 99 18 00.*

5.3 Raster included in the regolith depth model

The RDM was delivered as 9 separate layers in ESRI GRID format (see Table 5-1 below). The delivered layers represent the *bottom elevations* of the layers. Further processing of the layers can produce thickness values of each layer as well as top values, according to Table 5-2.

All raster layers include the whole model area even though the regolith 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 the corresponding regolith type is absent. The bottom levels of the raster layers are presented in metres above the present sea level (according to the Swedish national height system RH2000). The upper level of the bedrock corresponds to the bottom level of the till.

Table 5-1. Layers delivered in the RDM. All these layers are stored in the SKB model database in an mxd-file (ArcGIS) with SKBmod ID 1712498.

Regolith class	Regolith class abbreviation	Layer name	Description	Alternative layer property
Artificial fill	Z3c	z3c_b	Bottom elevation of artificial fill	Top elevation of peat
Peat	Z2_I	z2_i_b	Bottom elevation of peat	Top elevation of gyttja
Gyttja	Z4c	z4c_b	Bottom elevation of gyttja	Top elevation of clay gyttja (z4a)
Clay gyttja	Z4a	z4a_b	Bottom elevation of clay gyttja	Top elevation of postglacial sand
Postglacial sand	Z3a	z3a_b	Bottom elevation of postglacial sand	Top elevation of clay gyttja (z4a_i)
Clay gyttja	Z4a_I	z4a_i_b	Bottom elevation of clay gyttja	Top elevation of glacial clay
Glacial clay	Z4b	z4b_b	Bottom elevation of glacial clay	Top elevation of glaciofluvial sediment
Glaciofluvial sediment	Z3b	z3b_b	Bottom elevation of glaciofluvial sediment	Top elevation of till
Till	Z5_I	z5_i_b	Bottom elevation of till	Top elevation of bedrock

Table 5-2. Properties of layers and equations used in further calculations.

Property	Calculation
Thickness of artificial fill	DEM – z3c_b
Thickness of peat	z3c_b – z2_i_b
Thickness of gyttja	z2_i_b – z4c_b
Thickness of clay gyttja (z4a)	z4c_b – z4a_b
Thickness of postglacial sand	z4a_b – z3a_b
Thickness of clay gyttja (z4a_i)	z3a_b – z4a_i_b
Thickness of glacial clay	z4a_i_b – z4b_b
Thickness of glaciofluvial sediments	z4b_b – z3b_b
Thickness of till	z3b_b – z5_i_b
Total thickness of regolith	DEM – z5_i_b
Top elevation of artificial fill	DEM
Top elevation of peat	z3c_b
Top elevation of gyttja	z2_i_b
Top elevation of clay gyttja (z4a)	z4c_b
Top elevation of postglacial sand	z4a_b
Top elevation of clay gyttja (z4a_i)	z3a_b
Top elevation of glacial clay	z4a_i_b
Top elevation of Glaciofluvial sediments	z4b_b
Top elevation of Till	z3b_b

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. The quality of 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 that could be used to check these interpretations are missing in large areas.

Important uncertainties that can be identified are listed below.

- The thicknesses of the regolith layers 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.
- Large parts of the terrestrial areas, including many lakes, lack both stratigraphical data and regolith depth data.
- The thickness of till (Z5_I) is probably too large in Area 4 (Table 2-1). This is shown by larger regolith depths than in surrounding areas (Figure 5-1). Area 6 was modelled using the same type of data as Area 4, but the regolith depths were re-interpreted using newer data. The modelled till depths in Area 6 are not deviating from surrounding areas and can be regarded as more correct.
- The modelled thickness of artificial fill (Z3c) is too small at some places. That is obvious since the distribution of artificial fill, at some places, is reflected as positive landforms in the layer showing the elevation of the uppermost till (Z5_I). One reason for this is that the artificial fill to a large extent occurs as narrow elongated layers along roads. It is possible that the program is unable to correctly model the thickness of layers that are too small compared to the pixel size (20×20 m^2).
- The pixel size is, as mentioned above, too large to visualise all recorded variations in regolith depths. One example is that many of the outcrops mapped in Area 1 (Table 2-1) are much smaller than the pixel size. Many of these outcrops are not shown as regolith depth zero in the model, but as the average regolith depth within the pixel.

Some of the issues described above could probably be improved by using a smaller pixel size in the modelling. In some cases, additional data is needed to improve the model. It is, however, not possible to collect data from all areas with a low data density, but it is important to identify and prioritise such areas that are of importance for general site understanding and safety assessment modelling. More data should be collected in areas of special interest that currently lack data.

In areas with a high density of data (e.g. Area 6), tests could be performed to quantify the uncertainties in the model. This could be done by remodelling a small area not using all available data and thereafter compare the results with the model that used all available data. No such tests have been performed within the work presented here.

6.2 Comparison with earlier RDM from the area

The RDM presented here is improved in several ways compared to earlier RDM versions (Sohlenius et al. 2013, Hedenström et al. 2008, Vikström 2005). The most important differences are listed below.

- The present RDM comprises a larger geographical area and includes larger parts of the Island Gräsö and larger areas of the sea floor in the northern part of the model area.
- The average regolith thickness is c 2.5 m thinner in the present model compared to the previous model (Sohlenius et al. 2013). One reason for that is that larger terrestrial areas, characterised by thin regolith layers and high frequency of exposed bedrock, are included in the model presented here (e.g. the Island Gräsö). Furthermore, the transitions between bedrock and outcrops were sharper in the former model causing thick regolith close to the outcrops. These transitions are smoother in the present model causing thinner regolith layers around outcrops. In the former model the clay layers were also characterised by sharp transitions in thickness between areas with and without clay. That contributed to generally thicker regolith layers in the former model.

- The DEM, which is a major input to the RDM, has been improved, especially in the terrestrial area where the DEM now is completely based on LIDAR data. Also, in the marine area, the DEM is now based on a larger number of observations.
- Postglacial sand (Z3a) and gyttja (Z4c) have been included in the model. This has improved the model, especially for the lakes where all postglacial deposits were shown as one layer in earlier models. Postglacial sand was included in earlier models but only as a surface layer.
- Thin surface layers of peat and postglacial sand have been included in the model.
- The differences in regolith depths between terrestrial and marine areas are less pronounced than in the earlier model, where there is a sharp difference in regolith depth along the present shoreline.
- The present model has a smoother bedrock surface compared to the earlier model, which was characterised by very sharp differences in regolith depth between e.g. outcrops and surrounding areas.
- The SubsurfaceViewer software made it possible to construct a more realistic model in areas with few data, and the model has been improved especially in the lakes and shallow marine areas. The earlier model was based on average regolith thickness values in areas lacking data. The use of sections drawn in SubsurfaceViewer makes it possible to achieve more realistic thicknesses in such areas, even though the average values of each layer are used in areas where there is a wide spacing between the sections.

6.3 Future work

In the future, additional stratigraphical data will be collected from e.g. wetlands with high nature values and during the construction of the planned spent nuclear fuel repository. It will therefore be necessary to update both the RDM presented here and the more detailed RDM for the access area (Follin 2019). Furthermore, the regional RDM presented in this report should be merged with the more detailed RDM covering the access area. This work can be done using SubsurfaceViewer. There is, however, a continuous development of new software for 3D- modelling and it may therefore be necessary or preferable to use a different program for producing future versions of the RDM.

6.4 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-elevation areas. The maximum depth of regolith in the model area is c 50 m and is found in the deeper areas of Öregrundsgrepen, where thick layers of glacial clay and glaciofluvial sediments have been deposited. The average depth with bedrock outcrops included is 4.2 m, and if areas with outcrops are removed from the calculation the average depth to bedrock is 4.5 m.

The present RDM has been improved in several respects compared to earlier RDM versions. This is mainly due to the use of a software program (SubsurfaceViewer) that made it possible to construct a more realistic 3D model using general knowledge concerning the regolith distribution.

The RDM has relatively large uncertainties in areas with low density of data and there are large areas, e.g. shallow marine areas, that lack data showing the total depth of regolith. Some small features, such as small outcrops, are not shown in the model, since the pixel size (20 m) is too large.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.com/publications.
SKBdoc documents will be submitted upon request to document@skb.se.

Albrecht J, 2005. Forsmark site investigation. Study of Quaternary sediments in connection with investigations of bedrock lineaments. SKB P-05-138, Svensk Kärnbränslehantering AB.

Albrecht J, 2007. Forsmark site investigation. Soil stratigraphy based on samples and protocols in the Forsmark area. SKB P-07-01, Svensk Kärnbränslehantering AB.

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

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

Brydsten L, Strömgren M, 2013. Landscape development in the Forsmark area from the past into the future (8500 BC – 40000 AD). SKB R-13-27, Svensk Kärnbränslehantering AB.

Curtis P, Runslätt E, Vestgård J, Bergkvist L, Mærsk Hansen L, Olsson A, Ergun F, 2012. SFK Byggundersökningar. Detaljerad sprickkartering i diken i Söderviken. SKBdoc 1338599 ver 1.0, Svensk Kärnbränslehantering AB. (In Swedish.)

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

Follin S (ed), 2019. Multidisciplinary description of the access area of the planned spent nuclear fuel repository in Forsmark prior to construction. SKB R-17-13, Svensk Kärnbränslehantering AB.

Fredén C (ed), 2002. Berg och jord. Sveriges nationalatlas. 3rd ed. (In Swedish.)

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

Hansson B, Nordén H, Hedman P, 2008. Platsundersökning Forsmark. Kompletterande jord- och bergsonderingar i bostadsområdet. SKB P-08-23, Svensk Kärnbränslehantering AB. (In Swedish.)

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

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

Hedenström A, 2004b. Forsmark site investigation. Stratigraphical and analytical data of Quaternary deposits. SKB P-04-148, Svensk Kärnbränslehantering AB.

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

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

Hedenström A, Sohlenius G, Strömgren M, Brydsten L, Nyman H, 2008. Depth and stratigraphy of regolith at Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-07, Svensk Kärnbränslehantering AB.

Hellgren S, 2010. Rapport Geoteknisk Undersökning, RGEO Forsmark – Projekt Kärnbränsleförvaret. Jord-bergsondering, etapp 1. Östhammars kommun. Tyréns. SKBdoc 1325135 ver 1.0, Svensk Kärnbränslehantering AB. (In Swedish.)

Hellgren S, 2011. Rapport Geoteknisk Undersökning, RGEO Forsmark – Projekt Kärnbränsleförvaret. Byggförberedande undersökningar, etapp 2a och 2b. Östhammars kommun. Tyréns. SKBdoc 1325128 ver 1.0, Svensk Kärnbränslehantering AB. (In Swedish.)

Henriksson H, 2016. Fältrapport/Geoteknik. Fältrapport. Slutrapport 2016-05-20.Tyréns. SKBdoc 1551182 ver 1.0, Svensk Kärnbränslehantering AB. (In Swedish.)

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

Jirner E, Johansson P-O, McConnachie D, Djurberg H, McCleaf Ph, Hummel A, Ahlgren S, Rodhe L, Mikko H, 2016. Jordlagermodellering i 3D – exempel från Uppsalaåsen med hydrogeologisk tillämpning. SGU-rapport 2016:19, Geological Survey of Sweden. (In Swedish.)

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

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

Kessler H, Mathers S, Sobisch H-G, 2009. The capture and dissemination of integrated 3D geospatial knowledge at the British Geological Survey using GSI3D software and methodology. Computers & Geosciences 35, 1311–1321.

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

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

Lundin L, Lode E, Stendahl J, Melkerud P A, Björkvald L, Thorstensson A, 2004. Forsmark site investigation. Soils and site types in the Forsmark area. SKB R-04-08, Svensk Kärnbränslehantering AB.

Nissen J, 2003. Forsmark site investigation. Ground penetrating radar and resistivity measurements for overburden investigations. SKB P-03-43, Svensk Kärnbränslehantering AB.

Nissen J, 2004. Forsmark site investigation. Ground penetrating radar (GPR) and resistivity (CVES) surveys – interpretation of new and previous measurements. SKB P-04-105, Svensk Kärnbränslehantering AB.

Nyberg J, 2016. Maringeologiska kartan. Ytsedimentfördelning. Södra Bottenhavet. (Marine geological map: Sea bed sediments.) Uppsala: Geological survey of Sweden. (SGU K541) (In Swedish with English summary.)

Nyberg J, Elhammer A, Sohlenius G, Kjellin B, Nordgren P, 2011. Results from marine geological investigations outside Forsmark. SKB P-11-39, Svensk Kärnbränslehantering AB.

Persson C, 1985. Jordartskarta 12I Östhammar NO med beskrivning. Uppsala: Geological survey of Sweden. (SGU Ae 73) (In Swedish with English summary.)

Persson C, 1986. Jordartskarta 13I Österlövsta SO/13J Grundkallen SV med beskrivning. Uppsala: Geological survey of Sweden. (SGU Ae 76) (In Swedish with English summary.)

Peterson G, Jirner E, Karlsson C, Engdahl H. 2014. Tredimensionella jordartsmodeller – programvara och metoder. SGU-rapport 2014:33, Geological Survey of Sweden. (In Swedish.)

Petrone J, Strömgren M, 2020. Baseline Forsmark – Digital elevation model. SKB R-17-06, Svensk Kärnbränslehantering AB.

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

SGU, 2015. Brunnsarkivet (Archive of wells). Available at: https://www.sgu.se/grundvatten/brunnar-och-dricksvatten/brunnsarkivet/ [01 November 2015]

SKB, 2008. Site description of Forsmark at completion of the site investigation phase. SDM-Site Forsmark. SKB TR-08-05, Svensk Kärnbränslehantering AB.

Sohlenius G, Hedenström A, 2009. Platsundersökning Forsmark. Stratigrafiska undersökningar i våtmarksobjekt. SKB P-09-18, Svensk Kärnbränslehantering AB. (In Swedish.)

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

Sohlenius G, Strömgren M, Hartz F, 2013. Depth and stratigraphy of regolith at Forsmark. SR-PSU Biosphere. SKB R-13-22, Svensk Kärnbränslehantering AB.

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

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

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

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

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

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

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

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

Werner K, Lundholm L, Johansson P-O, 2006. Forsmark site investigation. Supplementary drilling and soil sampling, and installation of groundwater monitoring wells, pumping wells and BAT filter tips. SKB P-06-89, Svensk Kärnbränslehantering AB.

Appendix 1

The distributions of the regolith layers included in the model are shown in Figures A1-1 to A1-9.

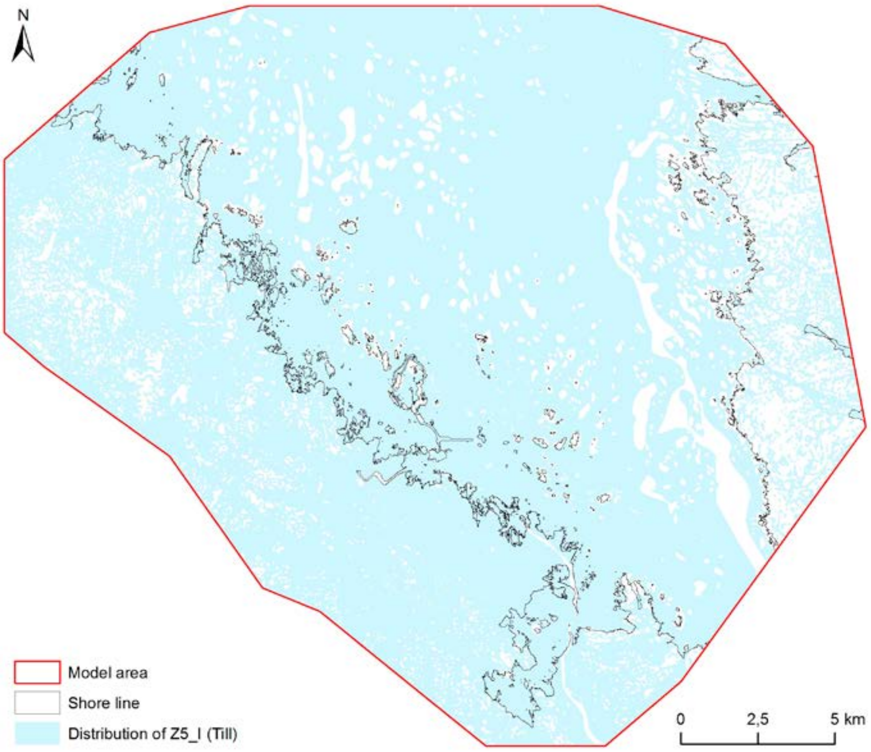

Figure A1-1. *Distribution of till (Z5).*

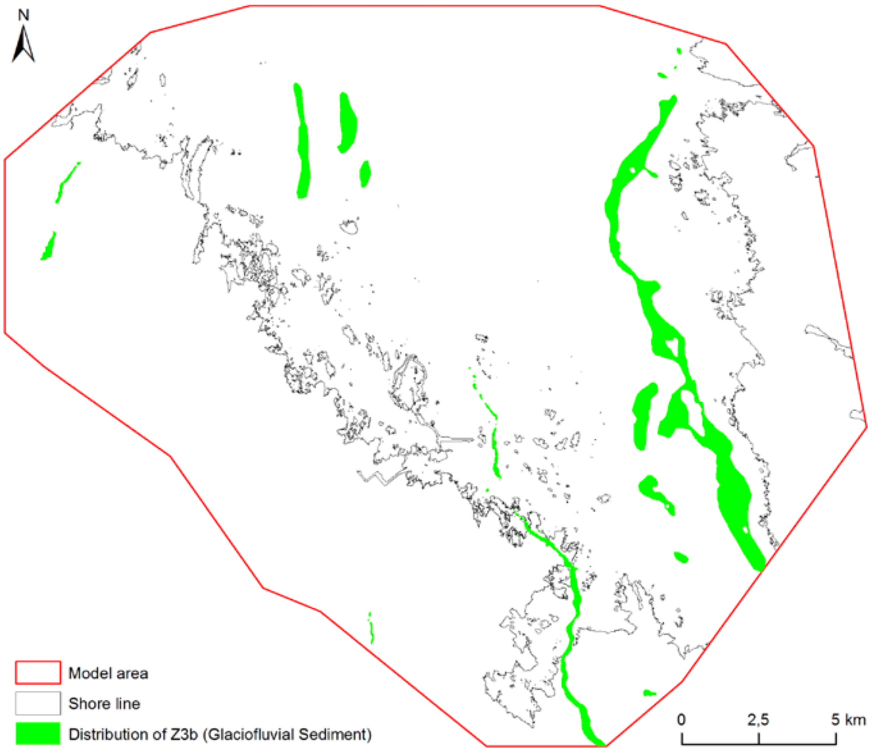

Figure A1-2. *Distribution of glaciofluvial sediments (Z3b).*

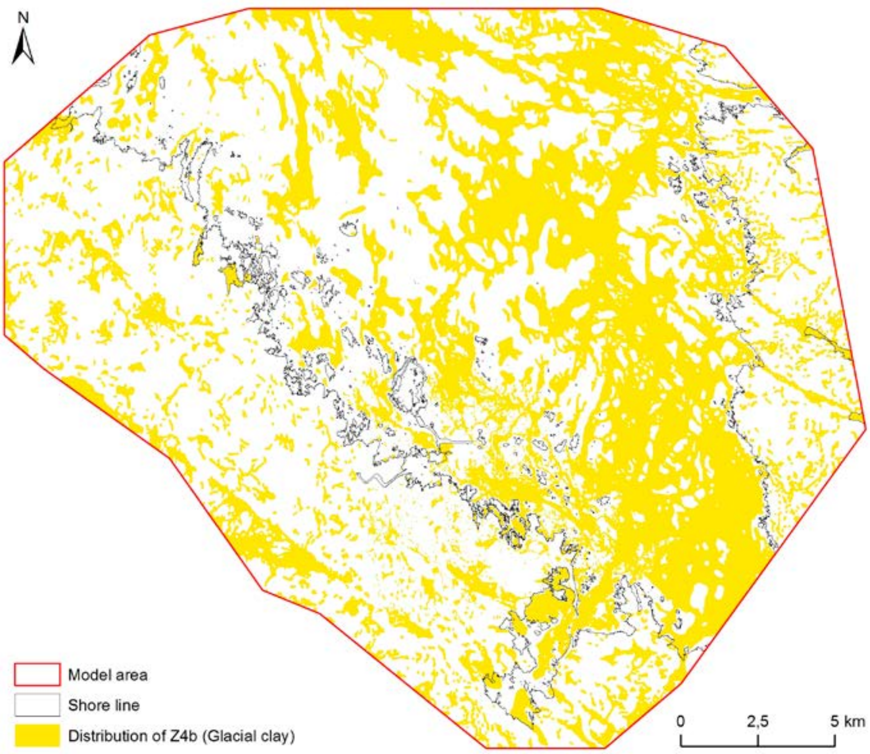

***Figure A1-3.** Distribution of glacial clay (Z4b).*

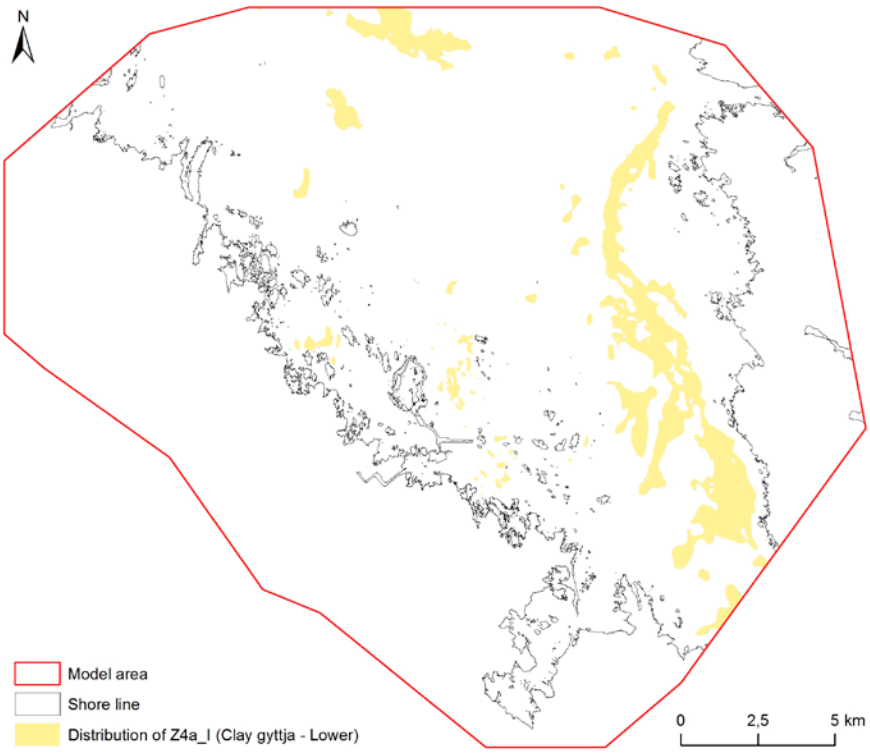

***Figure A1-4.** Distribution of clay gyttja in the marine area (Z4a_l).*

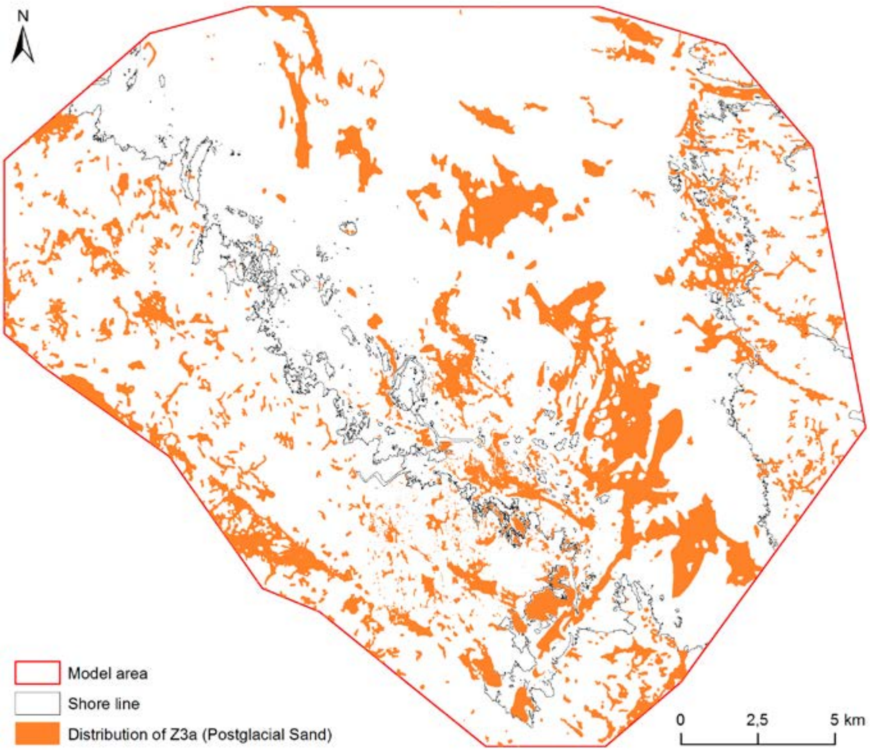

Figure A1-5. *Distribution of postglacial sand (Z3a).*

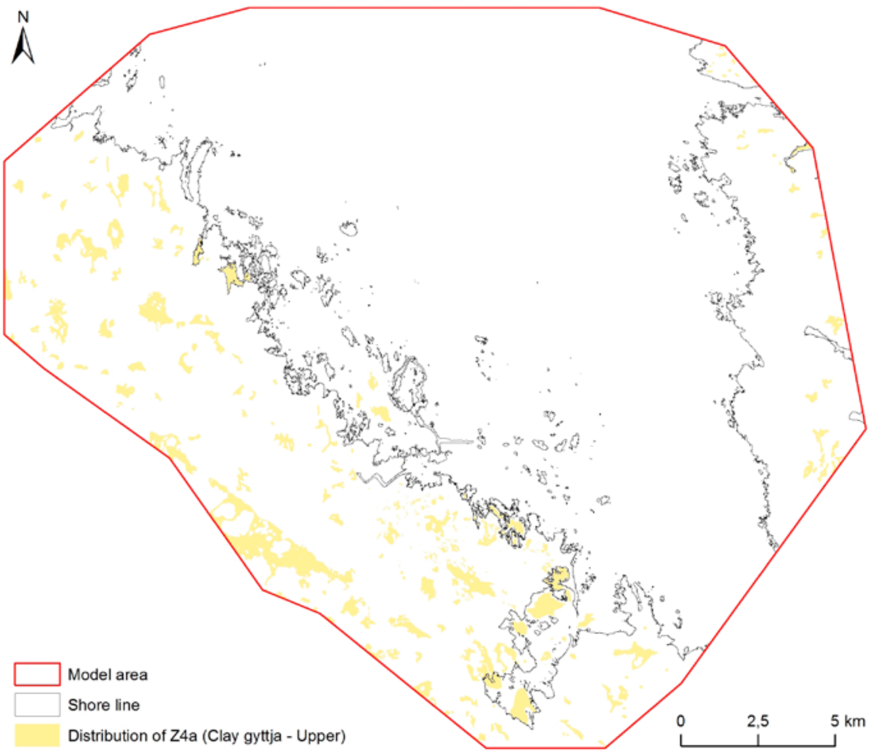

Figure A1-6. *Distribution of clay gyttja in terrestrial areas, shallow bays and in lakes (Z4a).*

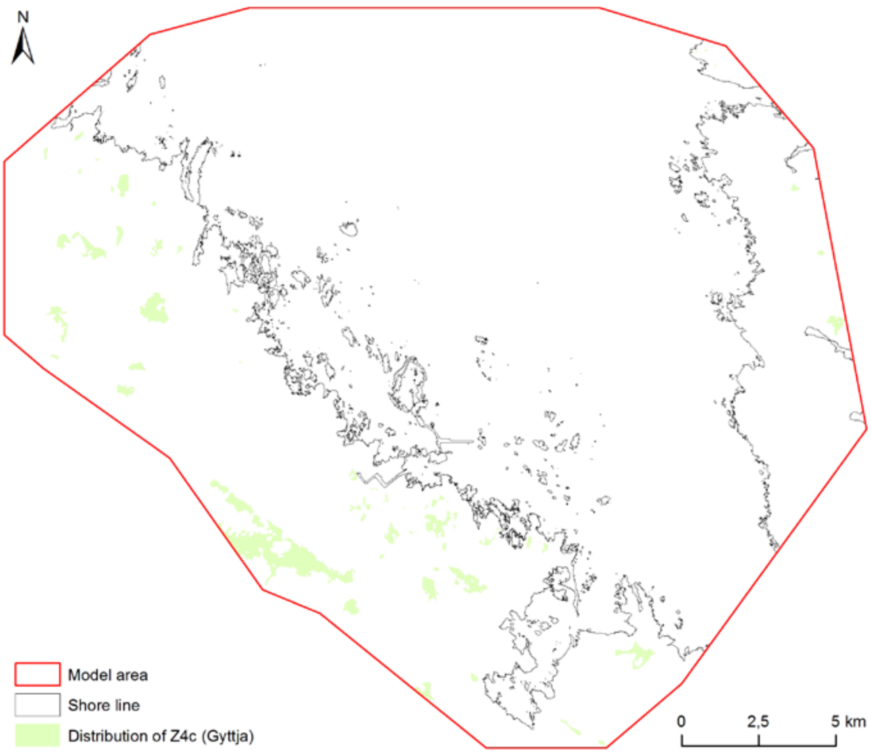

Figure A1-7. *Distribution of gyttja (Z4c).*

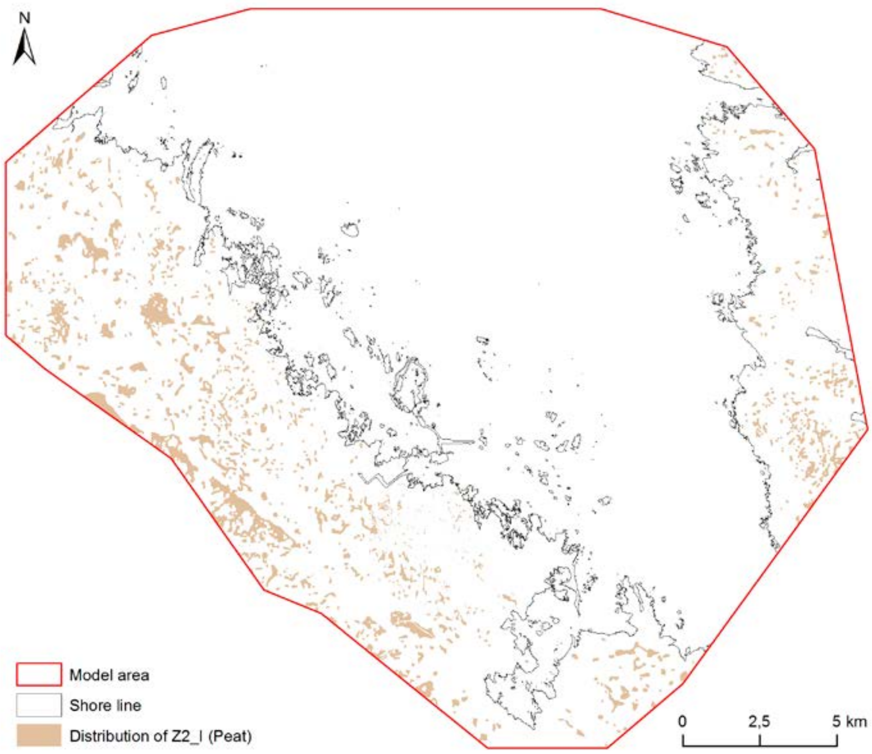

Figure A1-8. *Distribution of peat (Z2_I).*

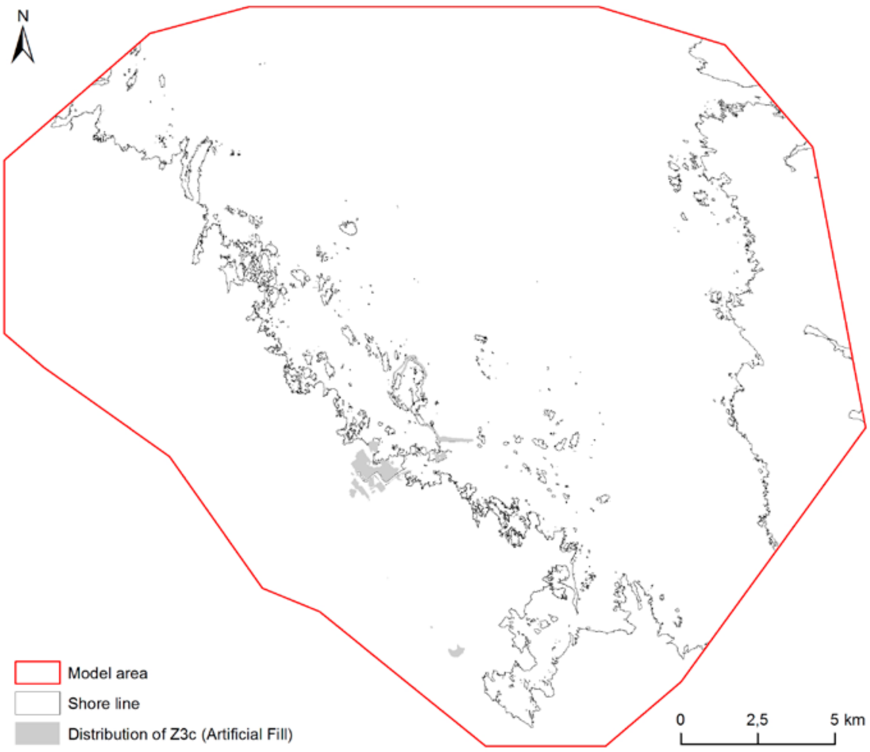

Figure A1-9. *Distribution of artificial fill (Z3c).*

Appendix 2

The following post-processing steps were made for the for the peat layer (Z2_I):

1. Merging of sub-model areas using Mosaic to New Raster tool in ArcGIS.
   a. Processing extent: Union of inputs.
   b. Snap to raster: z2_i_ext (rasterized spatial distribution of z2_i).
   c. Cell size: 20
   d. Number of bands: 1
   e. Bit depth: 32 bit float.
   f. Area mask: model_area_large_2016-12-14.shp
2. Check to see that the extent of the merged raster layer covered the whole model area (1400, 1203), if not using Raster Calculator.
   a. z2_i_th * 1
   b. Processing Extent: z2_i_ext
3. Convert NoData pixel values to 0 and decrease thickness in areas of thinner peat using algorithm in Raster Calculator.
   a. Con((“z2_i_th” > 0.4) & ((IsNull(“fivemgrid”)) | (~IsNull(“z2_i_tunn”))),0.4,”z2_i_th”)
   b. Con(IsNull(“z2_i_ext”),0,”z2_i_th”)
4. Apply a Low Pass Filter to the layer using Raster Calculator.
   a. Con(~IsNull(“z2_i_ext”),Filter(“z2_i_th”,”LOW”,”DATA”),”z2_i_th”)
5. Check for null pixels and fill with interpolated value.
   a. Con(Isnull(“z2_i_th”),Filter(“z2_i_th”,”LOW”,”DATA”),”z2_i_th”)

The following post-processing steps were made for the for the till layer (Z5_I):

1. Extract all bedrock outcrops smaller than 1 000 m^2.
2. Apply a 20 m radial buffer to these outcrops.
3. Rasterize the buffered outcrops à “z5hallbuff”.
4. Merging of sub-model areas using Mosaic to New Raster tool in ArcGIS.
   a. Processing extent: Union of inputs.
   b. Snap to raster: z5_i_ext (rasterized spatial distribution of z5_i)
   c. Cell size: 20
   d. Number of bands: 1
   e. Bit depth: 32 bit float.
   f. Area mask: model_area_large_2016-12-14.shp
5. Check to see that the extent of the merged raster layer covered the whole model area (1400, 1203), if not using Raster Calculator.
   a. z5_i_th * 1
   b. Processing Extent: z5_i_ext
6. Set the thickness of the Till to 0 where the layer is not present and where the buffered smaller bedrock outcrops are present.
   a. Con((IsNull(“z5_i_ext”) | (~IsNull(“z5hall20buff”))),0,”z5_i_th”)
7. Apply a Low Pass Filter to the layer using Raster Calculator:
   a. Con(~IsNull(“z2_i_ext”),Filter(“z2_i_th”,”LOW”,”DATA”),”z2_i_th”)
8. Check for null pixels and fill with interpolated value.
   a. Con(Isnull(“z2_i_th”),Filter(“z2_i_th”,”LOW”,”DATA”),”z2_i_th”)

The following post-processing steps were made for the for the artificial fill (Z3c):

1. Merging of sub-model areas using Mosaic to New Raster tool in ArcGIS.
   a. Processing extent: Union of inputs.
   b. Snap to raster: z3c_ext (rasterized spatial distribution of z3c).
   c. Cell size: 20
   d. Number of bands: 1
   e. Bit depth: 32 bit float.
   f. Area mask: model_area_large_2016-12-14.shp
2. Check to see that the extent of the merged raster layer covered the whole model area (1400, 1203), if not using Raster Calculator.
   a. z3c_th * 1
   b. Processing Extent: z3c_ext.
3. Check for null pixels and fill with interpolated value.
   a. Con(Isnull("z2_i_th"),Filter("z2_i_th","LOW","DATA"),"z2_i_th")

The following post-processing steps were made for the for clay gyttja (Z4a and Z4a_I), glacial clay (Z4b), gyttja (Z4c), postglacial sand/gravel (Z3a) and glaciofluvial material (Z3b):

1. Merging of sub-model areas using Mosaic to New Raster tool in ArcGIS.
   a. Processing extent: Union of inputs.
   b. Snap to raster: [layer]_ext (rasterized spatial distribution of [layer]).
   c. Cell size: 20
   d. Number of bands: 1
   e. Bit depth: 32 bit float.
   f. Area mask: model_area_large_2016-12-14.shp
2. Check to see that the extent of the merged raster layer covered the whole model area (1400, 1203), if not using Raster Calculator.
   a. [layer]_th * 1
   b. Processing Extent: [layer]_ext.
3. Convert NoData pixel values to 0.
   a. Con(IsNull("[layer]_ext"),0,"[layer]_th")
4. Apply a low pass filter to the layer.
   a. Con(~IsNull("[layer]_ext"),Filter("[layer]_th","LOW","DATA")," [layer]_th")
5. Check for null pixels and fill with interpolated value.
   a. Con(Isnull("[layer]_th"),Filter("[layer]_th","LOW","DATA"),"[layer]_th")

The steps listed above resulted in 9 raster layers showing regolith thicknesses in the entire model area. However, projection of the raster was in RT 90 2.5 gon V RHB70. Raster Calculator in ArcGIS was used to produce bottom and top raster layers in SWEREF 99 and RH 2000. The following raster were produced:

[layer]_b = bottom of [layer], continuous over entire model area.

[layer]_th = thickness of [layer], continuous over entire model area, 0 where the layer is not present.

dem = digital elevation model in SWEREF 99 18 00.

These equations were used to produce raster showing the lower elevation of each Z-layer:

z3c_b = dem – z3c_th

z2_i_b = z3c_b – z2_i_th

z4c_b = z2_i_b – z4c_th

z4a_b = z4c_b – z4a_th

z3a_b = z4a_b – z3a_th

z4a_i_b = z3a_b – z4a_i_th

z4b_b = z4a_i_b – z4b_th

z3b_b = z4b_b – z3b_th

z5_i_b = z3b_b – z5_i_th

All layers were connected to the DEM in all steps to ensure correct pixel locations.

Appendix 3

This appendix presents examples of sections interpreted in SubsurfaceViewer that show the vertical distribution of the regolith layers used for modelling. The locations of the selected sections are shown in Figure A3-1 and the sections in Figures A3-2 to A3-9. The colours of the regolith types are explained in Figure 3-1 (the regolith map). The interpretations are based on data obtained from stratigraphical field observations and geophysical interpretations. The locations of these observations are shown in the profiles. The triangles in the sections shows the crossing of another section. Note that the scale on the y-axis is 20 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.

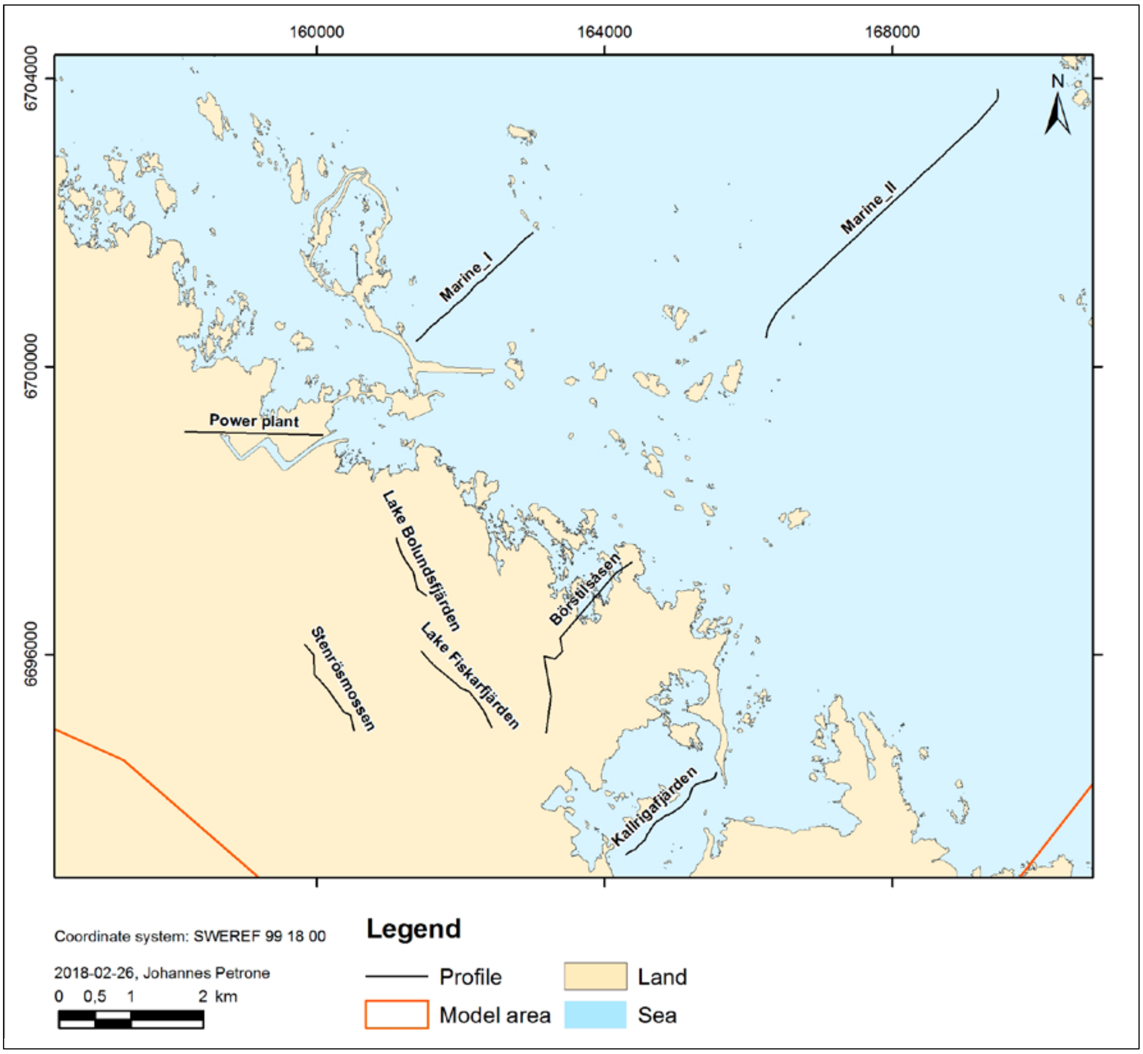

Figure A3-1. *Map showing the location of the eight sections.*

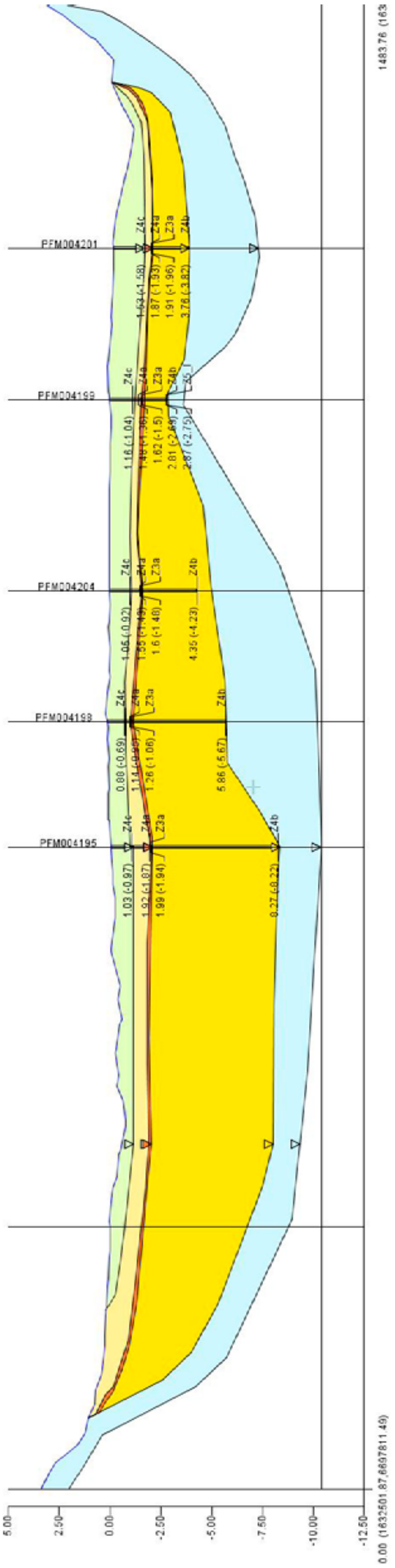

Figure A3-2. *Section "Lake Fiskarfjärden" (Figure A3-1).*

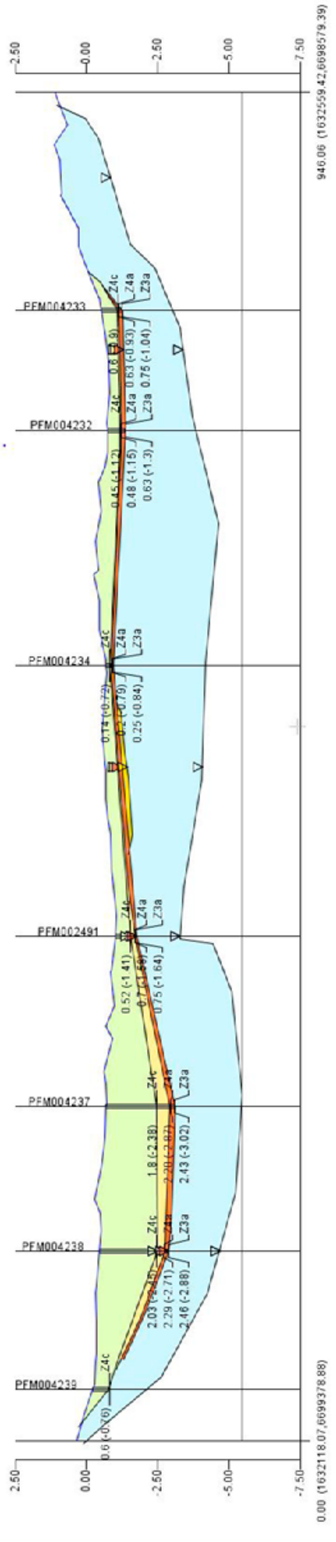

Figure A3-3. Section "Lake Bolundsfjärden" (Figure A3-1).

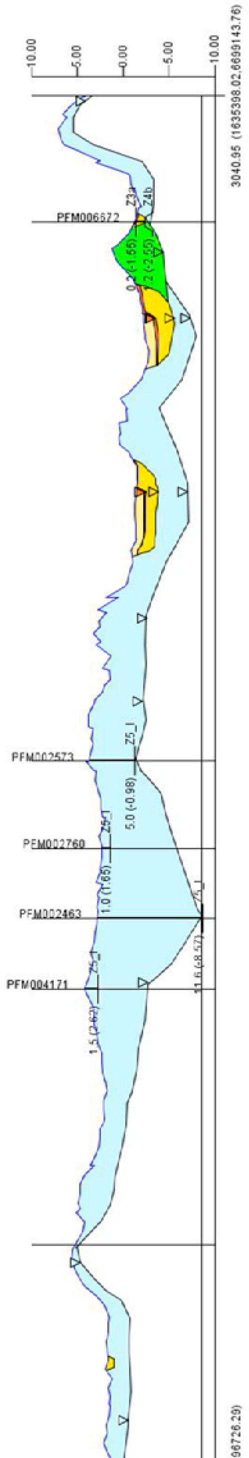

Figure A3-4. *Section "Börstilsåsen" (Figure A3-1) through parts of the terrestrial area, including the glaciofluvial esker Börstilsåsen.*

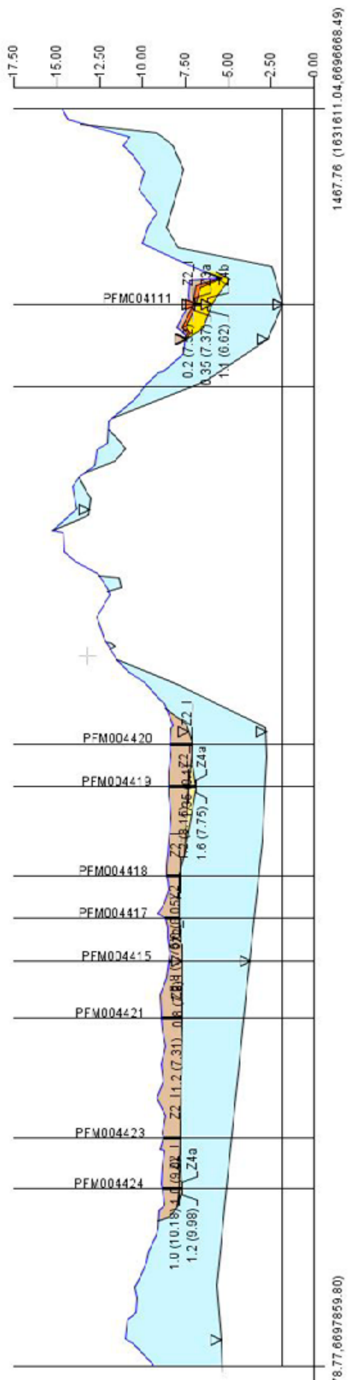

Figure A3-5. *Section "Stenrösmossen" (Figure A3-1) through the peat covered wetland Stenrösmossen.*

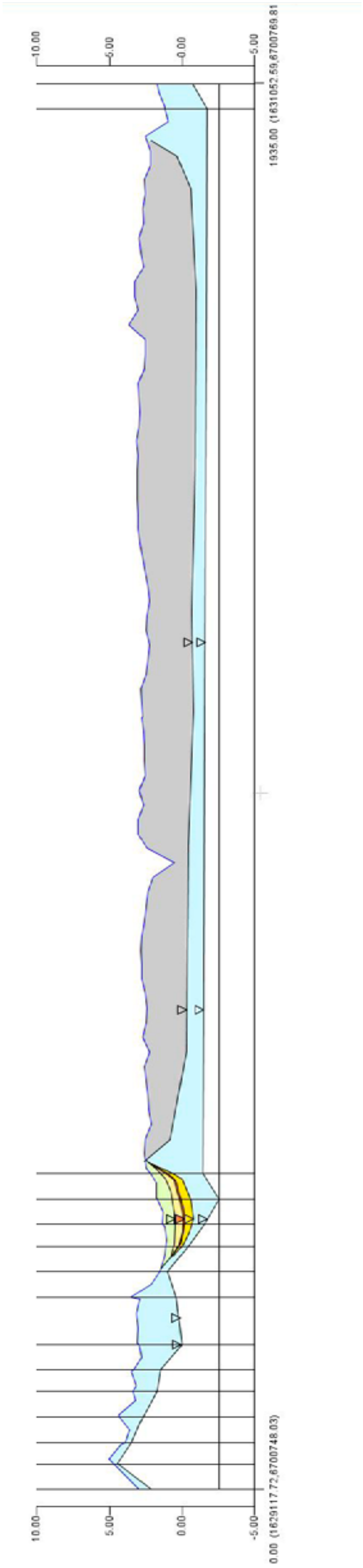

Figure A3-6. *Section "Power plant" (Figure A3-1) through the area with artificial fill surrounding the nuclear power plant.*

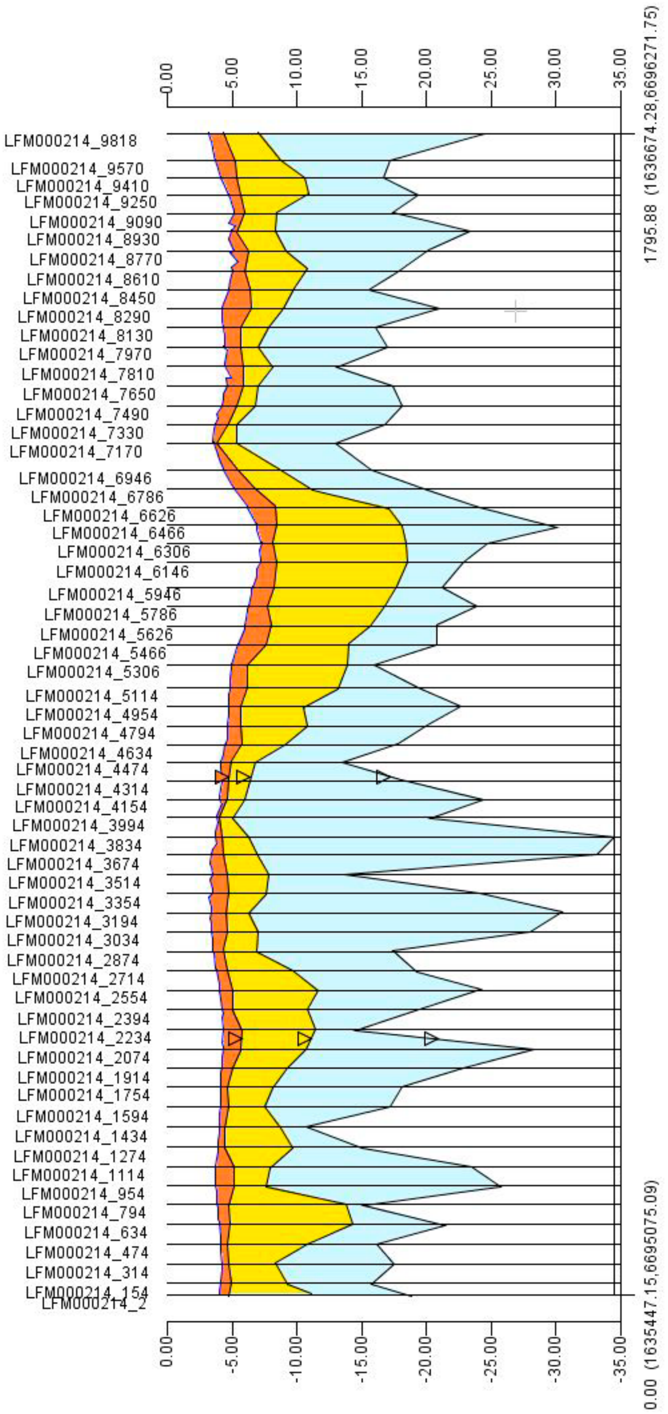

Figure A3-7. *Section "Kallrigafjärden" (Figure A3-1) through the Kallrigafjärden bay in the southern part of the model area.*

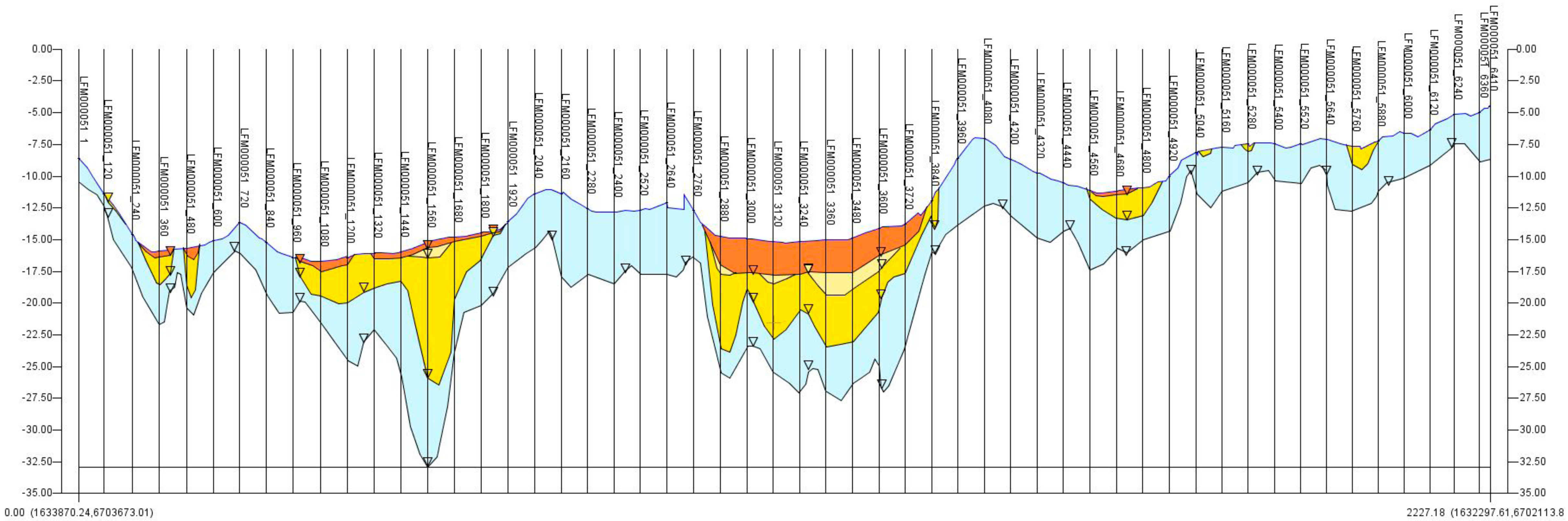

Figure A3-8. *Section "Marine_I" (Figure A3-1) through parts of the marine area just north of the SFR pier.*

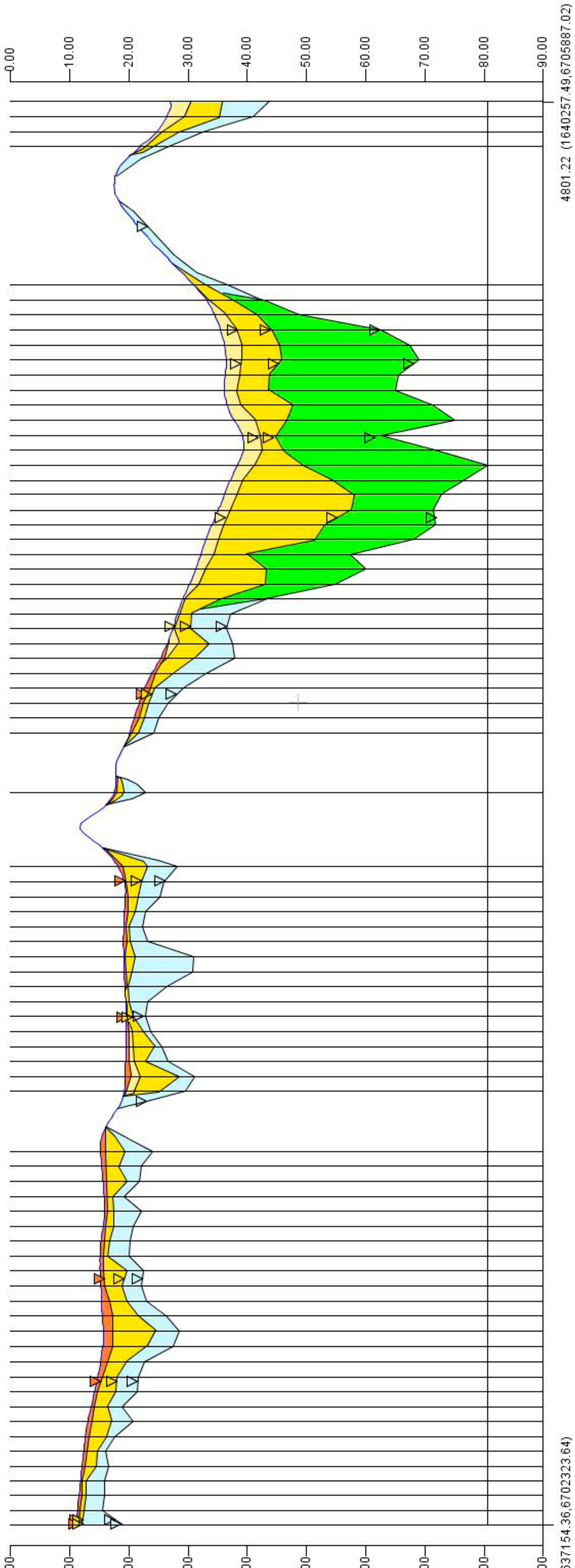

Figure A3-9. *Section "Marine_II" (Figure A3-1) through the central parts of Öregrundsgrepen.*