R-04-39

Forsmark site investigation

Mapping of unconsolidated Quaternary deposits 2002-2003

Map description

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Geological Survey of Sweden (SGU)

June 2004

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Summary

Swedish Nuclear Fuel and Waste Management Ltd (SKB AB) performs site investigations for localisation of a deep repository for high level radioactive waste. The site investigations are performed at two sites, Forsmark and Oskarshamn. This report presents a map of the Quaternary deposits in the Forsmark area. The knowledge of the composition of Quaternary deposits is of crucial importance for the understanding of the hydrological, chemical and biological processes taking place in the uppermost part of the geosphere.

The aim of this report is to describe the aerial distribution of the uppermost unconsolidated deposits and, where possible, the stratigraphical distribution and thickness of Quaternary deposits covering the bedrock. The map includes all identified bedrock exposures and Quaternary deposits, which exceed 100 m^2. The map was produced for presentation in the scale 1:10 000. The investigated area is 7x6 km.

The investigated area is situated in north-eastern Uppland at the Baltic Sea coast. The landscape is a relatively flat peneplain, which dips gently towards the east. The area is characterised by a large number of, often small, wetlands and lakes. The whole area is situated below the highest coastline. The present land upheaval is 6 mm/year. Most of the area has been raised above the sea during the last 1000 years implying that processes such as chemical weathering and peat formation have affected the area during a relatively short period of time. The till and glacial clay are rich in $CaCO_3$ which emanates from Palaeozoic limestone occurring at the Bothnian Sea floor north of the area. It can be assumed, but not concluded, that the Quaternary deposits have been formed entirely during and after the last ice age.

There are numerous bedrock exposures in the area and altogether 5% of the area comprises bedrock. The frequency of exposed bedrock varies, however, throughout the investigated area, and some areas are poor in bedrock exposures.

An ice moving from the north (350°–360°) has formed most glacial striae. At some sites there are striae formed, by older ice movements, from north-west and almost west (300°).

Glacial till is the most common Quaternary deposit, constituting 75% of the investigated area. The till was subdivided into three main domains: I) sandy till with a normal frequency of superficial boulders, II) clayey till with a low to normal frequency of superficial boulders, III) sandy till with a high frequency of often large superficial boulders. Most of the sandy till is covered by forest, whereas the clayey till is used as arable land and for pasture.

There is a glaciofluvial esker with a north-south direction, the Börstilsåsen esker, which follows the coast in the eastern part of the investigated area. The northernmost part of the esker is linked towards north-west.

In the most exposed positions, till and glaciofluvial deposits have been affected by erosion from waves and streams. Since most of the investigated area has been more or less exposed towards the sea, the areas constituting of fine grained water laid sediments are restricted. However, the major parts of the wetlands consist of glacial clay, sand or gyttja clay. The south-western part of the investigated area is situated at the highest altitude above the present sea level. The wetlands in that area have been above the sea for a period long enough for a peat layer to form.

Stratigraphical investigations have shown that the bedrock surface is more undulating than the rather flat ground surface topography suggests. The total depth of Quaternary deposits is probably highest in the areas consisting of clayey till.

Sammanfattning

Svensk kärnbränslehantering AB (SKB AB) genomför undersökningar på två platser, Forsmark och Oskarshamn, för att lokalisera ett djupförvar för högradioaktivt avfall. Denna rapport presenterar en karta över de kvartära avlagringarna i Forsmarksområdet. Kännedomen om de kvartära avlagringarna är av avgörande betydelse för de hydrologiska, kemiska och biologiska processer som sker i de övre delarna av geosfären.

Syftet med denna rapport är att beskriva den areella fördelningen av de på berggrunden liggande lösa avlagringarna. På utvalda platser beskrivs den stratigrafiska fördelningen och den totala mäktigheten av de kvartära avlagringarna. Kartan visar alla identifierade hällar, samt kvartära avlagringar vars yta överstiger 100 m^2. Kartan är anpassad för att presenteras i skalan 1:10 000. Det undersökta områdets yta är 7x6 km.

Det undersökta området ligger i nordöstra Uppland vid Östersjöns kust. Landskapet är präglat av ett relativt flackt peneplan som lutar svagt mot öster. Området karakteriseras av ett stort antal små våtmarker och sjöar. Hela området ligger under den högsta kustlinjen. För närvarande är landhöjningen 6 mm/år. Området har till största delen höjts över havets yta under de senaste 1000 åren, vilket betyder att processer som kemisk vittring och torvackumulation har påverkat området under en relativt kort tid. Moränen och den glaciala leran innehåller rikligt med $CaCO_3$ som kommer från de paleozoiska kalkstenar, vilka förekommer på botten av havet norr om det undersökta området. Samtliga kvartära avlagringarna i det undersökta området har troligtvis avsatts under och efter tiden för den senaste istiden.

Sammanlagt ca 5 % av det undersökta området består av hällmark. Frekvensen av hällar varierar emellertid, och i vissa delområden finns endast ett fåtal hällar.

De flesta glacialräfflorna har bildats av en is som har rört sig från norr (350°–360°). På några lokaler finns räfflor som bildats av en äldre isrörelse från nordväst och nästan väst (300°).

Morän är den vanligaste kvartära avlagringen och täcker ca 75 % av det undersökta området. Moränen har delats in i tre huvudsakliga domäner: I) sandig morän med en normal frekvens av ytligt liggande block, II) lerig morän med en låg till normal frekvens av ytligt liggande block, III) sandig morän med en hög frekvens av ytliga, ofta stora block. Den sandiga moränen utgörs till största delen av skogsmark, medan den leriga moränen i stor utsträckning används som åkermark och för bete.

Det finns en glacifluvial ås med en nord-sydlig sträckning, Börstilsåsen. Denna ås stryker längst kusten i den östra delen av det undersökta området och böjer längst i norr av mot nordväst.

I de mest utsatta lägena har isälvsavlagringarna och moränen påverkats av vågor och strömmar. Eftersom de största delarna av det undersökta området har varit mer eller mindre exponerat mot havet finns det endast mindre ytor med finkorniga, vattenavsatta sediment. De flesta våtmarkerna underlagras dock av glacial lera och/eller gyttjelera. Den sydvästra delen av det undersökta området ligger på den högsta höjden över havsytan. Våtmarkerna i detta område har varit över havsytan tillräckligt länge för att ett torvlager ska ha hunnit bildats.

Stratigrafiska undersökningar har visat att bergytan är mer kuperad än vad den relativt flacka markytan indikerar. Den totala mäktigheten av de kvartära avlagringarna är troligtvis högst i de områden som täcks av lerig morän.

Contents

1 Introduction

SKB performs site investigations for localisation of a deep repository for high level radioactive waste. The site investigations are performed at two sites; Forsmark and Oskarshamn. This report presents a map (that can be presented in the scale 1:10 000), which shows the distribution of unconsolidated Quaternary deposits and exposed bedrock in the Forsmark area. The report also presents some of the field data gained during 2003. Field data acquired during 2002 were reported in two P-reports (P-03-11 and P-03-14). The mapping was performed according to the Activity Plan AP PF 400-02-12, Version 1.0. The methods used are described in SKB MD 131.001, Version 1.0. The Activity Plan and Method description are SKB internal controlling documents.

2 Objective and scope

In this report a map of Quaternary deposits is presented. The aim is to describe the distribution of the uppermost unconsolidated deposits and, where possibly, the stratigraphical distribution and thickness of Quaternary deposits overlain the bedrock. The map includes all identified bedrock exposures and all Quaternary deposits which exceed 100 m^2. The map was produced for presentation in the scale 1:10 000. The investigated area is 7x6 km (Figure 2-1). The fieldwork started in mid August 2002 and was finished in August 2003.

The investigation includes collection of data such as till fabric and the direction of glacial striae, which both are indicative of the direction of glacial movement. The results from the till fabric will be presented during the spring 2004 in a separate P-report /17/.

Certain samples were analysed for grain size distribution, $CaCO_3$ content and mineralogy. The results from these analyses will be reported in two separate P-reports during the spring 2004 /17, 7/. These reports will also include analyses of samples and stratigraphical information achieved from drilling and excavation performed within other activities.

The information concerning Quaternary deposits will be used for hydrogeological modelling and to reconstruct the Late Quaternary development of the area.

The Quaternary deposits of the area have earlier been mapped by the Geological Survey of Sweden. The oldest maps are showing the distribution of bedrock and Quaternary deposits /2, 19/. These old maps have been made with methods, which have a low accuracy of geographical positioning. A more recent mapping was made in the nineteen eighties and shows the distribution of Quaternary deposits /11, 12/. These recent maps (SGU Ser. Ae, scale 1:50 000) do, however, omit most deposits with extensions less than 50x50 m.

Figure 2-1. *The Quaternary deposits within the black square were mapped. All sites mentioned in the text are shown on the map.*

3 Equipment

3.1 Description of equipment

The uppermost deposits were investigated using a spade and a hand driven probe (Figure 3-1 A and B). GPS and aerial photos (geographically corrected IR photos taken from a height of 2 300 m, scale 1:5 000) were used for orientation. A mirror compass was used to measure the directions of the glacial striae. Most photos were taken with a digital camera.

All field data have been digitally stored in a database in accordance with the SKB method description.

Figure 3-1 a. *The equipment used during mapping.*

***Figure 3-1 b**. Sample taken with the hand driven probe.*

4 Execution

The methods used are described in detail in SKB MD 131.001. Almost the same classification of Quaternary deposits was used as during SGU's earlier investigations in the area /12/. The nomenclature used in this investigation has, however, changed slightly since the earlier SGU investigations in the Östhammar area. For an up to date nomenclature the readers are referred to SKB MD 131.001 or to more recent SGU investigations /18/. Before the fieldwork started, aerial infrared photos, taken from a height of 2 300 m, were interpreted by using a computer. Areas with exposed bedrock were marked. This information was checked during the fieldwork. In addition, information concerning bedrock exposures from the detailed bedrock investigations has been taken into consideration.

Different Quaternary deposits were marked directly on the aerial photos in the field. All Quaternary deposits, which can be delimited from other deposits, and have an area larger than 100 m^2, were marked on the map as surfaces. The map (Figure 5-1) shows the distribution of Quaternary deposits at a depth of 50 cm. Surface layers thinner than 50 cm have also been marked on the map (e.g. peat overlaying other deposits). A large number of different thin surface layers (<50 cm) are used in the map presented here. These thin layers, except thin peat layers, are not presented on the earlier SGU maps from the area /11, 12/.

The field map was redrawn on a plastic film and digitized. All surfaces were given codes representing the different Quaternary deposits.

The stratigraphical distribution of Quaternary deposits was investigated by drilling and machine dug excavation. The results from the excavations, performed during August 2003, will be presented in a separate P-report during the spring 2004 /17/. Hedenström and others will report stratigraphical results from drilling carried out within the hydrogeological program, during the winter and spring 2003 /7/.

There were certain difficulties in interpreting the Quaternary geology during the fieldwork:

- In some areas it was difficult to distinguish primary till boulders and stones from material re-deposited by waves or sea ice. At some locations glacial clay was found below stones and small boulders, which shows that the coastal processes can redeposit coarse material. Some of these, often small, stone covered clay deposits might have been omitted since they are difficult to distinguish from till.
- A thin layer, or small patches, of glacial clay often overlay the till. In some areas it was therefore difficult to distinguish clayey till from sandy till with a thin layer of clay.
- In some areas it was difficult to distinguish clayey till from sandy till. The clayey till has generally a lower superficial boulder frequency compared with the sandy till. At many sites, the superficial boulder frequency was used to make a distinction between the two till types.
- The superficial boulder frequency of the till varies throughout the area. It is sometimes difficult to define surfaces with a certain boulder frequency. Many areas are characterised by hills, a few metres across, with a high superficial boulder frequency. The areas in-between the hills are often characterised by a much lower boulder frequency. The map (Figure 5-2) shows the dominating boulder frequency within each till area. Small surfaces with a diverging character can, however, occur within each area.

4.1 Preparations

The GPS was controlled at a point with a known position (6699539 N, 1631321 E). This control defined a precision better than ±5 m. However, experiences from the fieldwork showed that the precision of the GPS during some circumstances was below ±10 m.

4.2 Data handling

The coordinates of observation points for stratigraphical data, direction of glacial striae, photos etc were recorded with GPS. All observation points were given id-numbers (e.g. PFM-, SFM- or HFM-numbers), together with the observation date. The geological information connected to the id-numbers was stored in SGU's database (Jorddagboken version 5.4.3). All points and dates were later stored in SICADA. Data from the SGU database were exported to Excel files, which were delivered on a CD to SKB.

The drawings of exposed bedrock and Quaternary deposits on the field maps (aerial photos) were scanned and transformed into a database. This information was delivered to SKB, field note no: Forsmark 153, in Arc View shape on a CD-ROM.

The deliverables to SKB for the mapping of unconsolidated Quaternary deposits during 2003 (field note no: Forsmark 153) and 2002 (field note no: Forsmark 39) includes:

- Map of Quaternary deposits and bedrock exposures (Arc View).
- Stratigraphy of Quaternary deposits (SICADA) field note nos Forsmark 39 and 153.
- Direction of glacial striae (SICADA) field note nos Forsmark 39 and 153.
- Point observations from surface mapping (SICADA) field note nos Forsmark 39 and 153.
- Digital photos (File archive).

4.3 Nonconformities

This investigation was carried out in compliance with the Activity Plan AP PF 400-02-12. The methods used are described in SKB MD 131.001. All identified Quaternary deposit with an area larger than 10x10 m are shown on the map in accordance with the activity plan. The map shows, however, all identified bedrock exposures, which include outcrops smaller than 10x10 m. That information was needed by the detailed bedrock investigations. All other parts of this study were performed in accordance with the activity plan.

5 Results and discussion

5.1 Introduction

In this report the map of Quaternary deposits was divided into three maps (Figure 5-1; Figure 5-2; Figure 5-3) in order to exhibit as much information as possible. The maps give an overview of the surface distribution of the Quaternary deposits in the Forsmark candidate area with surroundings. In order to display all details in the map, four selected sub-areas are highlighted (Figure 5-4; Figure 5-5; Figure 5-6; Figure 5-7). The new maps confirm to a large extent the earlier maps from the area /11, 12/. However, this investigation gives more information regarding the distribution of water-laid sediments and peat (see Chapter 5.9). Numerous, earlier unknown, localities with small exposures of bedrock have been found. The striae show a somewhat different pattern from what was observed during the former mapping /11, 12/.

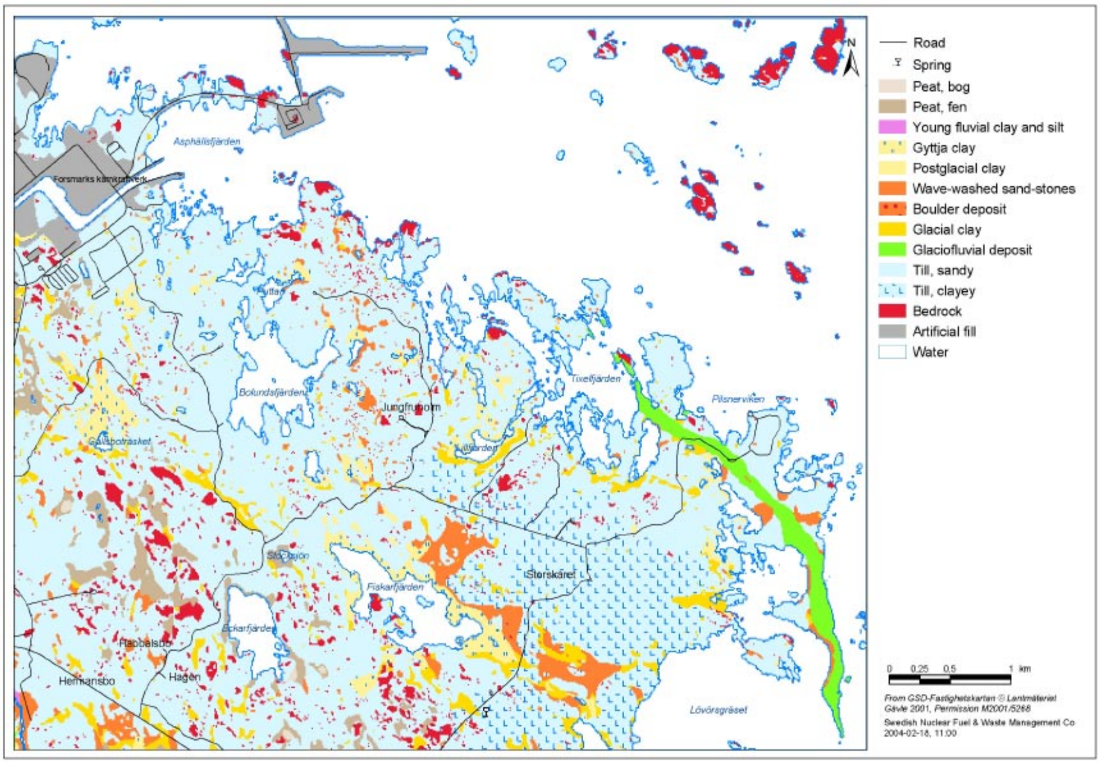

Figure 5-1. The superficial distribution of Quaternary deposits and bedrock exposures in the Forsmark area. The map does not expose all the different types of Quaternary deposits that were defined during the investigation.

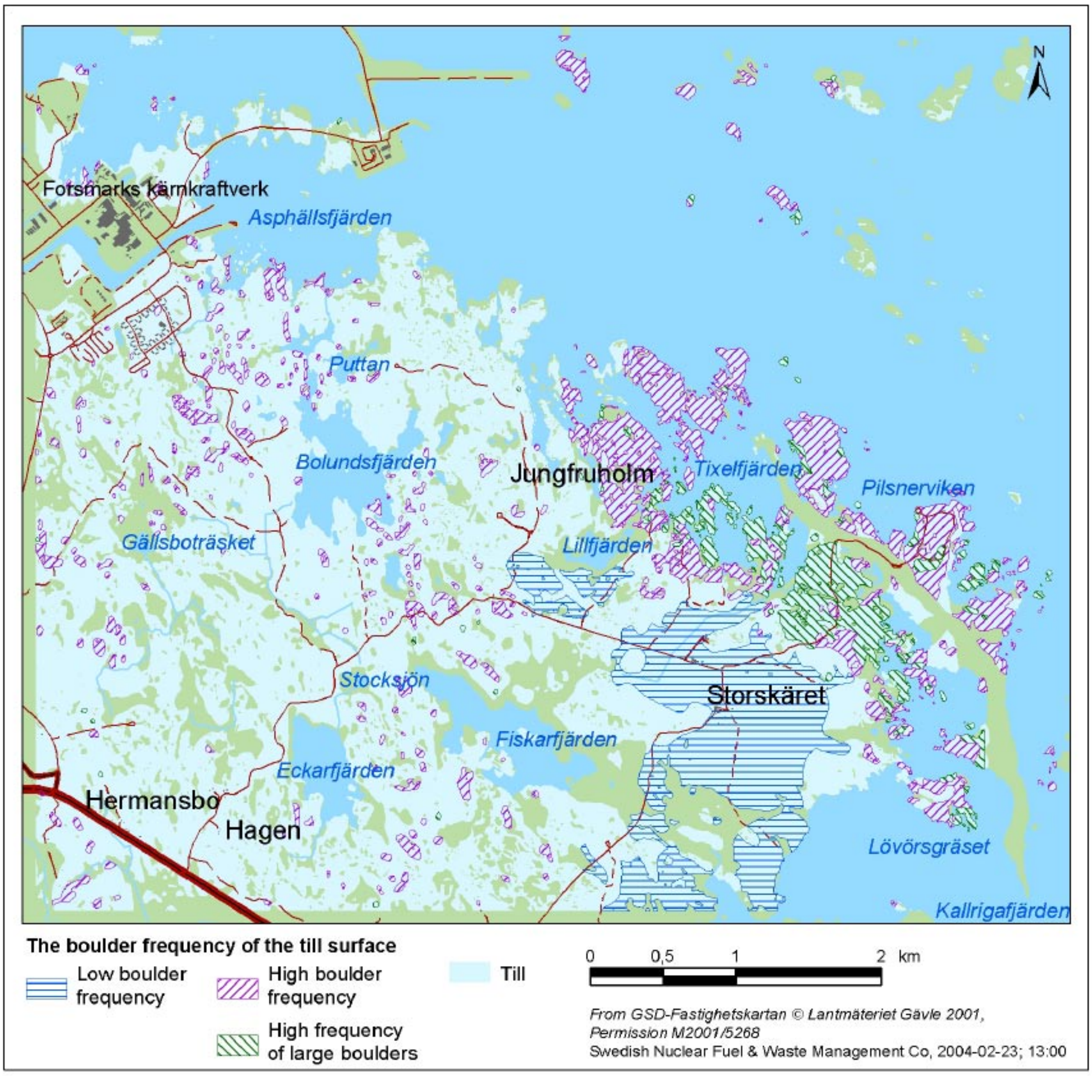

Figure 5-2. *The distribution of till and the boulder frequency of the till surface. Areas consisting of exposed bedrock or Quaternary deposits other than till are marked with green. All till with a normal superficial boulder frequency is shown as till without any superimposed screen.*

Figure 5-3. *All known sites with gravel pits, moraine ridges and beach ridges.*

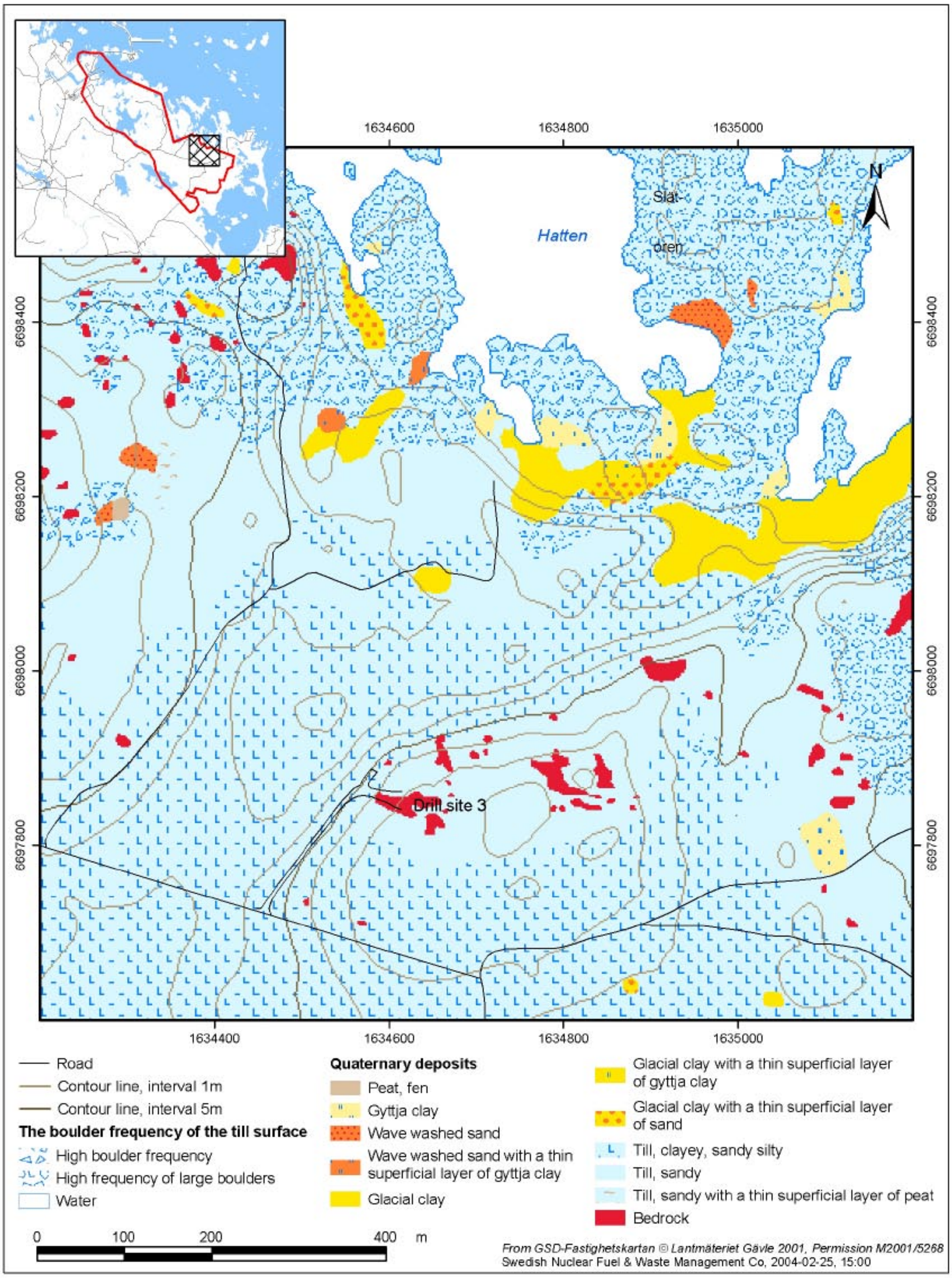

Figure 5-4. *All different Quaternary deposits identified in the area north of Storskäret (till area II). The clayey till has generally a low and the sandy till a normal frequency of superficial boulders respectively.*

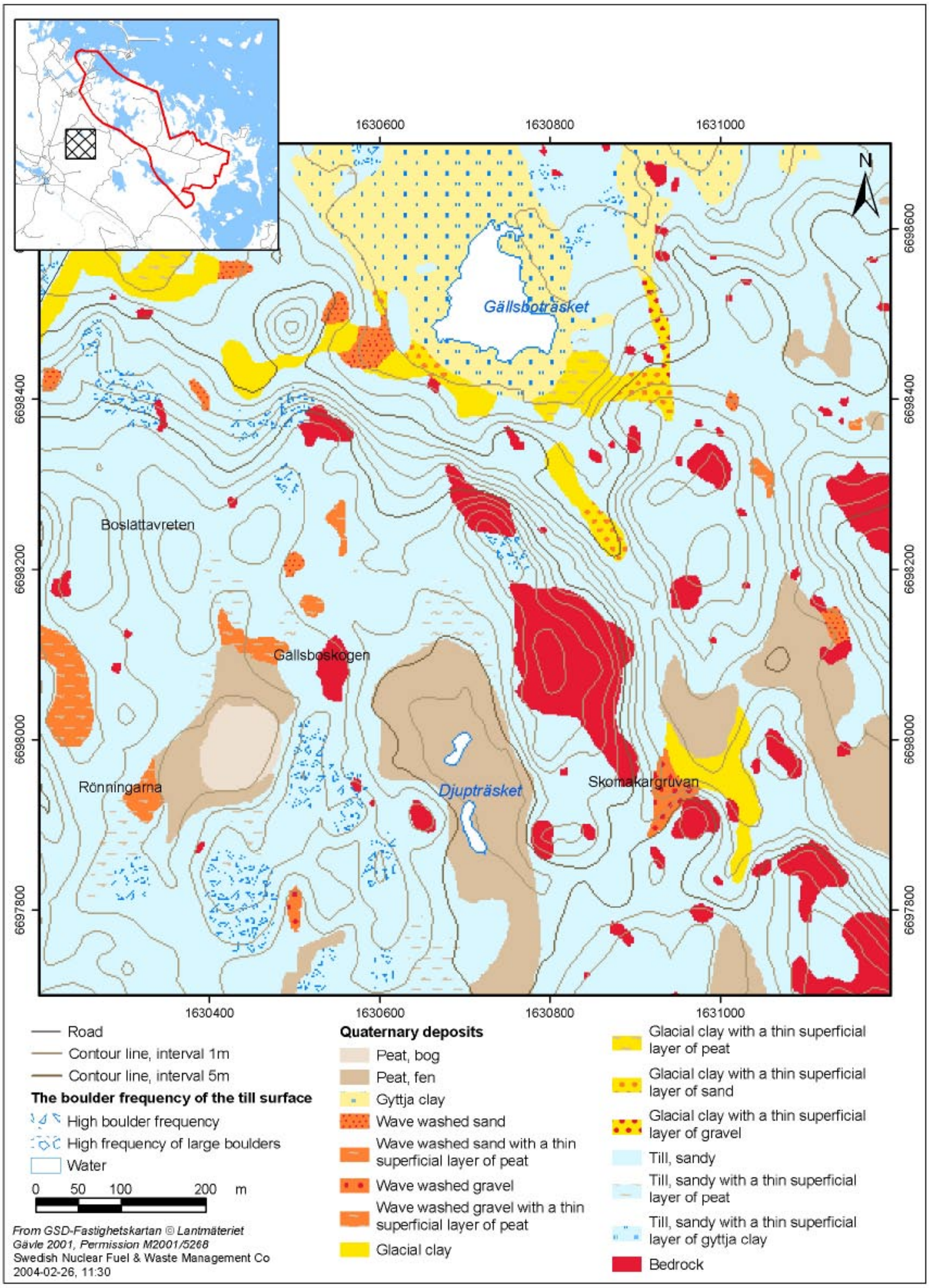

***Figure 5-5.** All different Quaternary deposits identified in the area south Gällsboträsket (till area I). The southern part of the area is situated at a higher altitude and the wetlands consequently have developed a peat layer.*

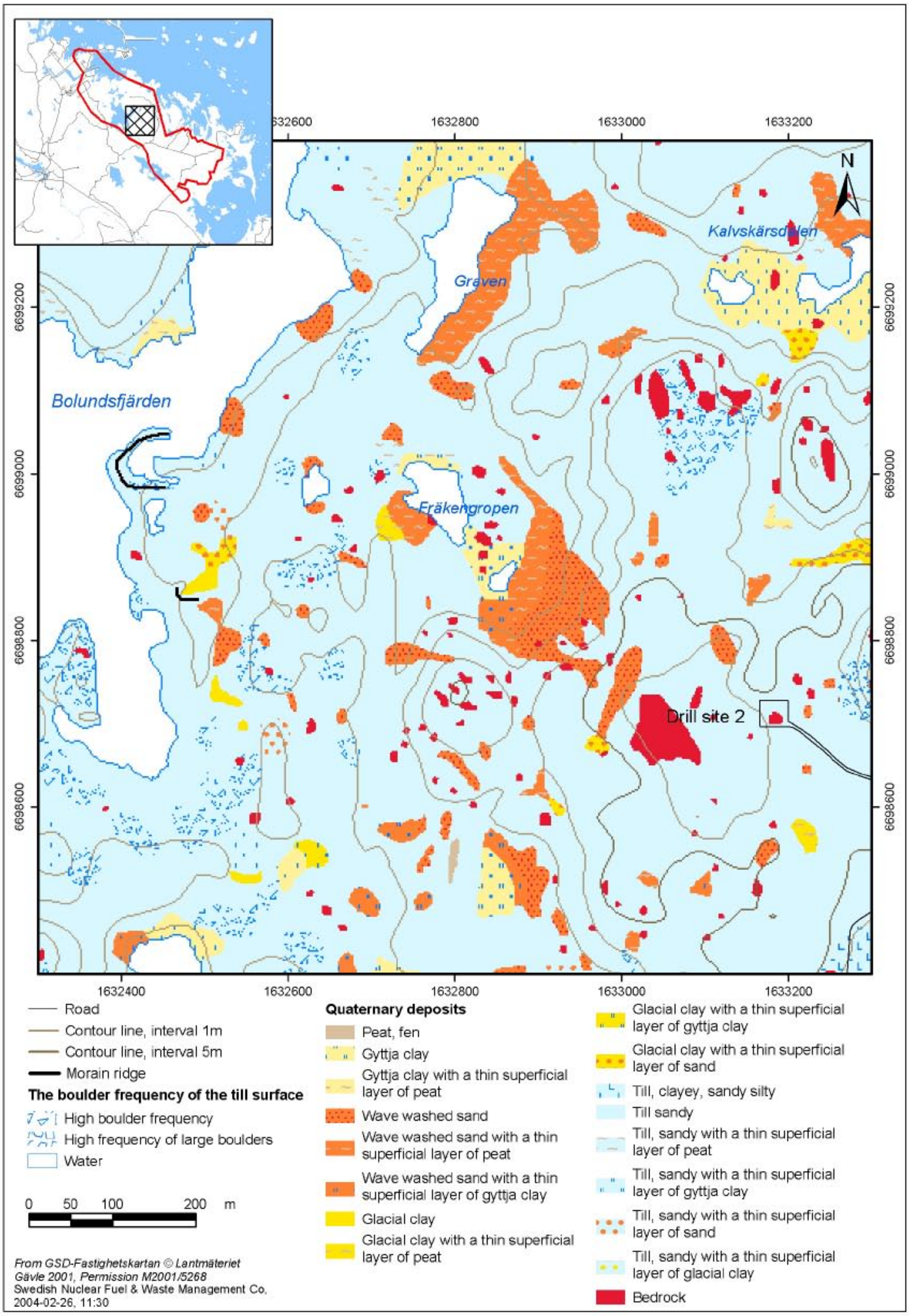

Figure 5-6. *All different Quaternary deposits identified in the area east of Lake Bolundsfjärden (till area I). Sandy till with a high frequency of wetlands characterised by different types of water laid sediments, dominates this area. The distribution of Quaternary deposits in this sub-area is typical for large parts of the entire investigated area.*

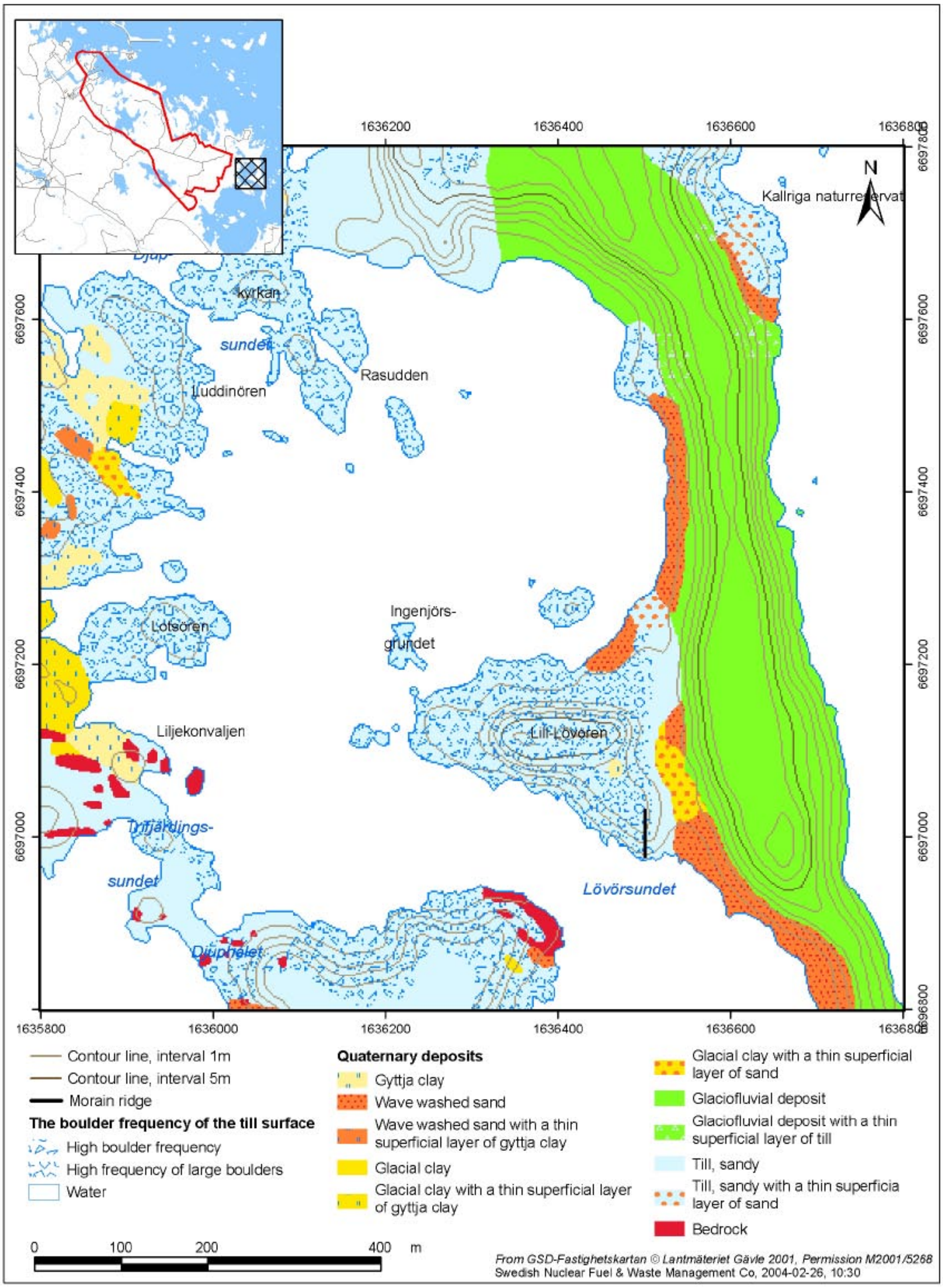

Figure 5-7. *All different Quaternary deposits identified in the northern part of Kallrigafjärden (till area III). The islands in the area are composed of till with a high frequency of often large boulders.*

To get an overview of the Quaternary deposits in the entire Östhammar region, the readers are referred to the earlier SGU investigations in the area (SGU Ser. Ae, scale 1:50 000) /11, 12/. Several publications provide an overview of the processes causing the formation of Quaternary deposits /3/.

The investigated area (Figure 5-1) is flat, and glacial till is the most common Quaternary deposit. The proportional distribution of different Quaternary deposits on land is summarised in Table 5-1. A peneplain, which is dipping gently towards the north-east, characterises the bedrock morphology. The investigated area is situated below the highest shoreline. The highest altitudes (c 20 m a s l) are found in the south-western corner of the area. About 500 BC the first small islands reached above sea level (see Chapter 5.8). At present, the land upheaval is 6 mm/year and most of the present land area has been raised above the sea during the last 1000 years. The area is rich in lakes and wetlands. In the easternmost part of the area there is a small esker (the Börstilsåsen esker) with, in the southern part, a north-south direction, which north of Långören changes to north-west/south-east. Glacial clay, gyttja clay, sand and peat occur frequently as the superficial Quaternary deposits on many small (less than 50x50 m) surfaces. These small deposits are frequent, but cover only a small part of the total area under investigation (Table 5-1). The till and glacial clay are rich in $CaCO_3$ /16, 17, 6, 7/ emanating from Palaeozoic limestone, which occurs at the Bothnian Sea floor north of the area. At several localities $CaCO_3$ occurs from the ground surface and downwards. Since the area has been land during only a short period, too little time has passed for the weathering processes to dissolve the $CaCO_3$ from the uppermost soil. A study from northern Uppland showed that the depth of the carbonate-free zone increases at higher altitudes /8/. It has been concluded that most soils in the Forsmark area are immature since the area has been uplifted for a relatively short period of time /10/.

The area around the nuclear power plant is dominated by artificial filling material consisting mainly of blast bedrock but also containing reworked Quaternary deposits.

Table 5-1. The proportional distribution of Quaternary deposits extracted from the map presented in this report (Figure 5-1).

Quaternary deposit	Coverage %
Peat	2.81
Gyttja clay	3.75
Clay	4.03
Wave washed sand and gravel	3.95
Glaciofluvial sediment	1.72
Till, clayey	11.3
Till, sandy with a medium boulder frequency	52.3
Till, sandy with a high boulder frequency	8.40
Till, sandy with a high frequency of large boulder	2.86
Total area covered by till	*74.86*
Artificial filling material	4.05
Bedrock exposures	4.84

5.2 Glacial striae and exposed bedrock

The Quaternary glaciers moved over the landscape and rock fragments in the ice abraded exposed bedrock surfaces on which glacial striae were formed. These striae reflect the direction of glacial movements (Figure 5-8). Glaciers also polished the bedrock surface to a large extent. Many rock outcrops are “Roches moutonnées” (Figure 5-9 a, b) with a smooth abraded northern side and a rough, steep, plucking side leaning against south. An ice moving from the north (350°–360°) has formed most glacial striae (Figure 5-8). However, at some sites, striae formed by older ice movements, from north-west and almost west (300°) are encountered. Striae are also found on some large boulders, but these were not measured because the boulders have been moved from their original position. The striae with a westerly direction were not reported from the earlier mapping in the area /11, 12/. According to Persson /14/ the striae from north were formed near the ice front during the latest deglaciation. The striae from north-west were formed earlier at a certain distance from the ice front /14/. The results presented here imply that the direction of ice movement successively changed from an almost westerly direction towards a northerly direction.

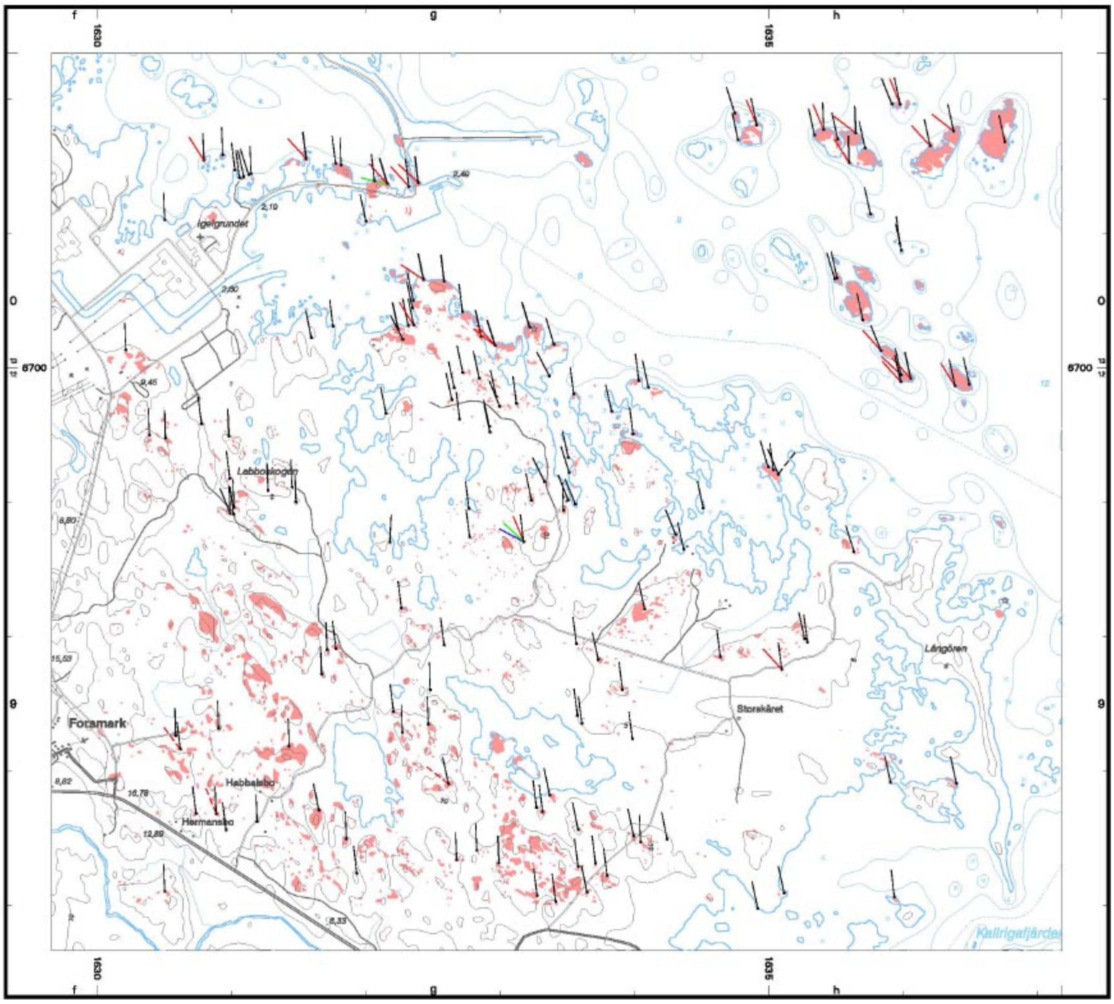

Figure 5-8. The direction of glacial striae measured on bedrock outcrops (shown in light red) in the Forsmark area. On some outcrops more than one striae direction, representing different directions of ice movements was measured. The youngest direction is then marked with a black line and the older directions with coloured lines. The red line represents the youngest direction the green line the second youngest and the blue line the oldest direction. Uncertain striae measurements are marked with dotted lines.

It is not possible to make any conclusions regarding the exact timing of the striae formation. There is nothing in this investigation that contradicts the suggestion that all striae were formed shortly before the latest deglaciation /14/. It is likely that the last ice movement before the deglaciation was from the north. The striae from north-west may, however, be considerably older. The striae will be discussed together with the results from till fabric analysis in another P-report /17/.

Altogether 5% of the area constitute exposed bedrock (Table 5-1). However, the frequency of exposed bedrock varies in different parts of the investigated area (Figure 5-1). Certain areas, e.g. around Storskäret, have a low frequency of exposed bedrock. On the other hand, in the south-western half of the investigation area there are several band-like areas with a NW-SE direction, which have a high frequency of exposed bedrock, as well as other band-like areas with the same orientation characterised by a low frequency of exposed bedrock.

The frequency of exposed bedrock is often high on capes and hills, which are exposed towards the north (Figure 5-9 b and c; Klubbudden and Mikelsbådan). Since the latest ice flow was from the north the glacial erosion was probably relatively high in these positions.

Drilling and stratigraphical investigations in the area have shown that the bedrock surface is more undulating than indicated by the rather flat ground surface topography. One example of that is the results from drilling close to the deep borehole KFM01A, see Figure 2-1, which showed that up to 12 m of till, covers the bedrock. Exposed bedrock is encountered only a few tenths of metres from the drilling site /16/. Forthcoming investigations will provide more information about the topography of the bedrock surface.

Figure 5-9 a. *A good example of a "Roche moutonné" with a smooth abraded northern side and a rough, steep, plucking side leaning towards south. An ice moving from north-north-west (350°) formed the striae on the outcrop. The site is situated at Mikelsbådan south of Asphällsfjärden (PFM002754).*

Figure 5-9 b. *Striae formed by an ice moving from north (355°). Site PFM002759 at Klubbudden.*

Figure 5-9 c. *A 100x300 m large bedrock exposure at Mikelsbådan (PFM 002753).*

5.3 Glacial till

The glacial till is the oldest known Quaternary deposits in the area and was deposited directly by the Quaternary glaciers. It can be assumed, but not concluded, that most of the till was deposited during the latest ice age and rests directly upon the bedrock. The till is poorly sorted with respect to grain size and comprises all grain sizes from large boulders to clay.

All known till in the area contains $CaCO_3$, which indicates that the till material was transported from the north, where limestone is present at the Bothnian Sea floor. Analyses of till fabric have, however, shown that most of the till in the area has been deposited by an ice moving from north-west /17/. An ice moving from the north has affected the uppermost till, which probably was formed synchronously with the youngest glacial striae (see Chapter 7.2). There is one till fabric observation, which suggest that an old till in the area that has been deposited by an ice moving from the north. It is therefore assumed that the $CaCO_3$ rich till in the Forsmark area was first deposited from the north and later re-deposited by an ice moving from north-west /17/.

Three areas with different types of till can be distinguished (Figure 5-10). The stratigraphical distribution between the different till units has not been completely understood /15/. Forthcoming interpretations of geophysical and stratigraphical investigations will hopefully give conclusive information. The three till areas are discussed below:

I, The first till area is characterised by sandy till with a normal frequency of superficial boulders (Figure 5-5; Figure 5-6; Figure 5-11 a and b). Sandy till is the most common Quaternary deposit in the area at the mapping depth (50 cm). This till type dominates in the northern, western and central parts of the investigated area. There are several areas with a high frequency of surface boulders north-west and south-east of Lake Bolundsfjärden within this area (Figure 5-2). Small areas with a high frequency of surface boulders do, however, occur all over this area, especially on the southern side of outcropping bedrock. The topography is gently undulating with numerous exposed bedrock areas at the highest altitudes. However, certain areas are almost devoid of bedrock exposures. Such an area follows the western side of Bolundsfjärden and continues on the eastern side of Lake Fiskarfjärden (Figure 5-1). It is possible that the total depth of Quaternary deposits, probably till, is high in such areas.

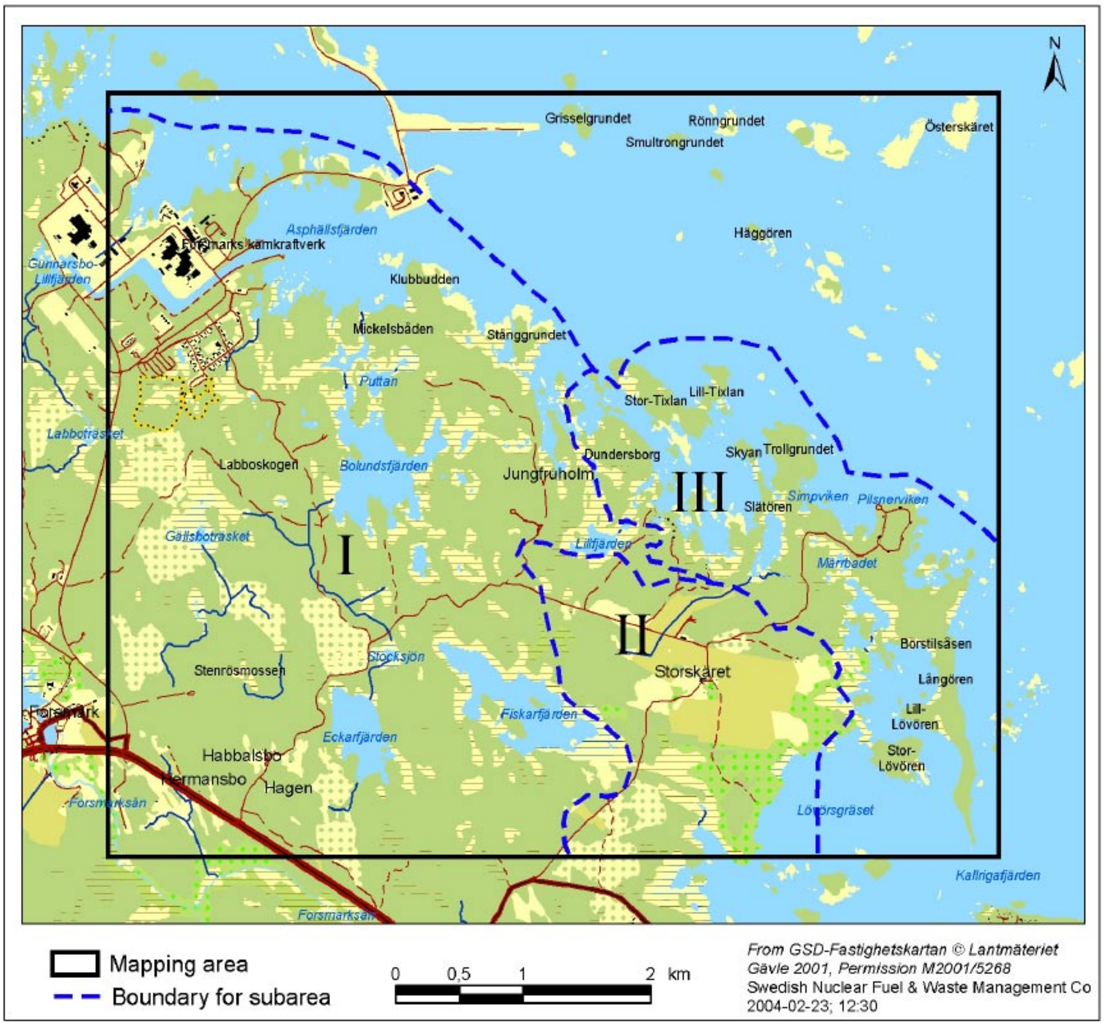

Figure 5-10. *The superficial distribution of the three till types identified within the area of investigation.*

At some sites, low (c 1 m high) ridges of till were found (Figure 5-11 c; Figure 5-3) around Lake Bolundsfjärden and Gällsboträsket. These ridges often have a north – south direction. Till ridges occur also around Lake Bolundsfjärden, although here shaped as half circles forming lagoons along the shores (Figure 5-1). The processes causing the formation of these ridges are not known.

At several localities sandy-silty till and, at a few localities, gravelly till were found at mapping depth. These sporadic occurrences of till types other than sandy are not shown on the map. It is possible that deeper lying till strata have a higher silt content than the uppermost till. This is supported by the results from an earlier report, where it was demonstrated that many drilling samples from till area I consist of sandy silty till /16/. Furthermore, Agrell and Björnbom /1/ observed a silty till underlying a sandy till during the construction of reactor 3 in Forsmark.

The thickness of the till in the area is often less than five metres, but as much as twelve metres of till has been observed close to KFM01A /16/. Three analyses of till fabric have been carried out in this area. The results indicate ice movements from north, north-west and north-east /16/. These results will be discussed together with the results from the till fabric measurements performed during the fieldwork 2004 /17/.

Figure 5-11 a. *Glacial till with a partly normal and a partly high superficial boulder frequency, north of Gällsboträsket (PFM002782).*

Figure 5-11 b. *Sandy till with an originally normal superficial boulder frequency, south of Hermansbo. Most boulders have been picked out from the uppermost soil and were used for constructing the wall. Today the area is used for pasture.*

Figure 5-11 c. *Boulder rich till ridge, with a north-south direction, close to Gällsboträsket (PFM002935). The ridge is approximately 100 m long and 15–20 m wide. The superficial boulder frequency is highest at the northern part of the ridge.*

II, The second till type area is dominated by clayey till and occurs around Storskäret and south of Lake Fiskarfjärden. Around Storskäret this till is used as arable land (Figure 5-4; Figure 5-12 a). The clayey till often has a low superficial boulder frequency, especially around Storskäret. Stones in heaps, around the fields, are rounded and are of equal size. There is a low frequency of outcropping bedrock in the areas covered by clayey till with a low superficial boulder frequency. Areas of clayey till with a normal superficial boulder frequency (Figure 5-12 b) have a somewhat higher frequency of bedrock outcrops. The topography is to a large extent almost flat and could easily be misinterpreted as an area consisting of water laid sediments. This till area is not clearly distinguished from the sandy till area. Patches of clayey till occur within the area generally characterised by sandy till and vice versa. Certain samples from this area have a clay content exceeding 15% and are classified as boulder clay /7, 16, 17/.

The stratigraphical relationship between the clayey till respectively the sand and silt dominated till has been investigated in several studies. Results from drillings indicate that the clayey till is underlain by a silty till /7, 9/. Results from other drillings in till area II showed, however, that the clayey till sometimes rests directly upon the bedrock surface /16/. Stratigraphical studies in machine dug trenches showed that lumps of clayey till occur within the sand and silt dominated till /17/. It is therefore possible that there is a lack of a general stratigraphical relationship between the two till types.

Clayey till covers large areas in north-east Uppland. There is a band of clayey till from northern Gräsö down to the Norrtälje area /14/. Earlier mapping shows that the clayey till in average is thicker than the sandy and silty till /11/. The low frequency of exposed bedrock and the results from the drilling in till area II /9, 16/, support the concept of a generally thicker till in till area II compared to till area I.

Figure 5-12 a. *Clayey till with a low superficial boulder frequency close to Storskäret (PFM002767).*

***Figure 5-12 b**. Clayey till with a normal superficial boulder frequency, east of Storskäret. Many of the boulders have been picked out from the uppermost soil layer and were used for constructing the wall. Today the area is used for pasture (PFM002902).*

III, The third till type occurs in the easternmost part of the area, around the Börstilsåsen esker. This till area is characterised by a high frequency of superficial, often large boulders (Figure 5-7; Figure 5-13 a, b and c) and a low frequency of outcropping bedrock. The matrix in this till type is sandy. There are plenty of boulder-rich hills and islands within this area. The hills do not have any significant geographical direction and are probably built up by till. Some of these hills are more or less completely covered by boulders. The surfaces between the hills are often characterised by water laid sediments, such as sand and/or glacial clay. The large amount of large boulders indicates a relatively short distance of transport. At several sites there are a lot of joints in the exposed bedrock, which sometimes makes it difficult to distinguish the till from bedrock outcrops.

The area is situated within a nature reserve and it has therefore not been possible to carry out any drilling or excavation in the till of this area, i.e. no studies, which may reveal the total thickness of this till type have been performed. It is therefore not known if the high boulder frequency is a merely shallow phenomenon or if it continues downwards.

Till area III is part of a zone of till with a high superficial boulder frequency, which can be followed to Östhammar, c 15 km south-east of the investigation area. Investigations of a similar boulder rich till zone, c 50 km south of the investigation area /13 /, have shown that most boulders are situated close to the ground surface. Persson /13/ suggested that the superficial boulders in that zone have been transported a short distance from the original bedrock position and were deposited shortly before the latest deglaciation. It is likely that the boulders in till zone III have a similar genesis and distribution as in the area further south /13/.

Surfaces completely covered by boulders were found at the islands Dundersborg, Lill-Tixlan and Stor-Tixlan (Figure 5-13 d). These boulder surfaces are situated close to bedrock exposures on the south-western slope of the islands. The genesis of the boulder surfaces is so far unknown. One possibility is that the boulder fields consist of glacial till that has been transported a few metres from the original bedrock position.

Figure 5-13 a. *Glacial till with a high frequency of large superficial boulders at Slätören (PFM002949).*

Figure 5-13 b. *Glacial till with a high frequency of large boulders, south of Märrbadet. The boulders are piled on top of each other and there is no matrix in the uppermost till (PFM004127).*

Figure 5-13 c. *Glacial till with a high frequency of large superficial boulders, south of Märrbadet. The boulders are piled on top of each other and there is no matrix in the uppermost till (PFM004128).*

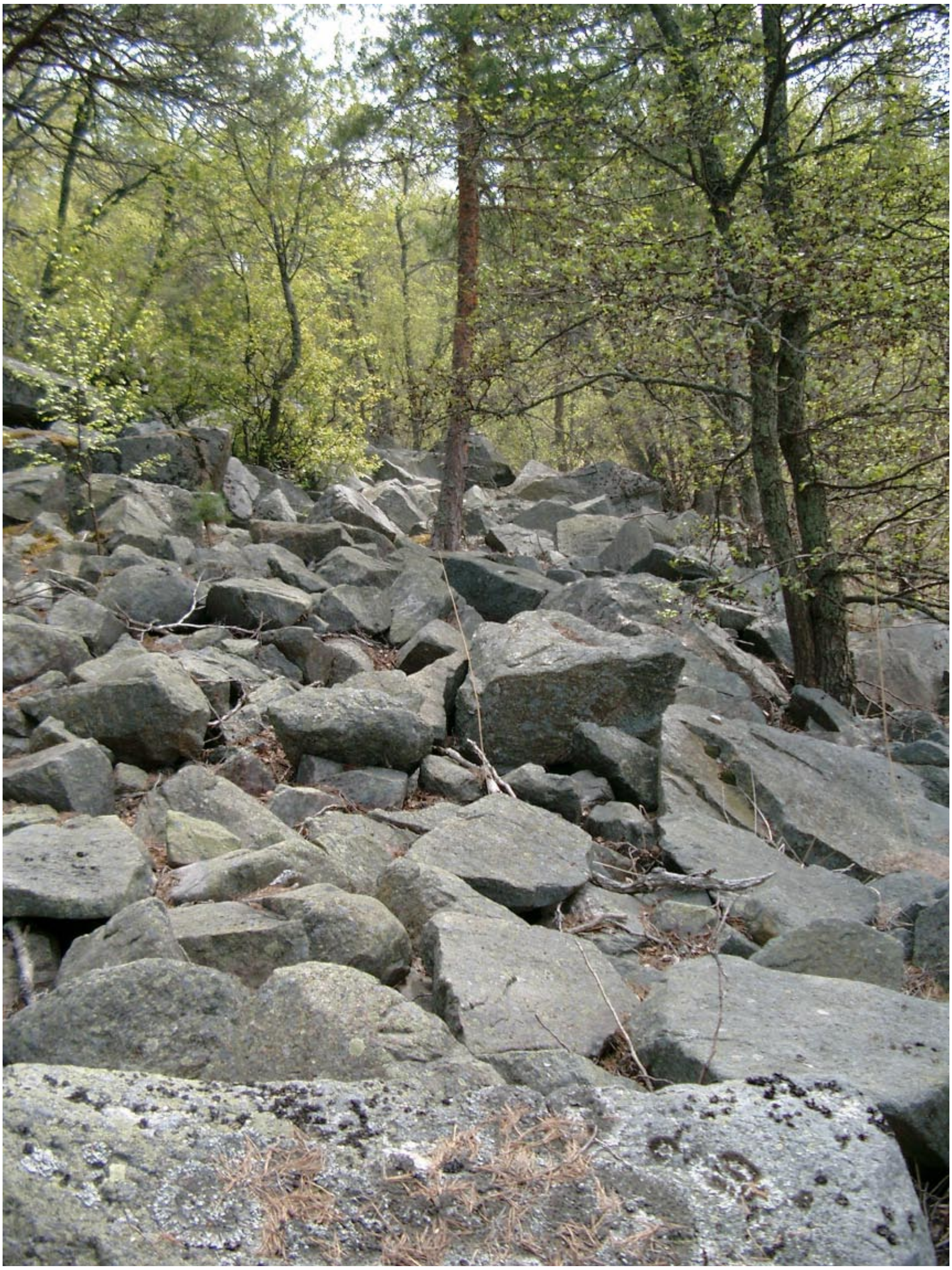

Figure 5-13 d. *Boulder surface on the western slope of Dundersborg (PFM002907).*

5.4 Glaciofluvial deposits

During the deglaciation, the melt water from the ice deposited large amounts of sand, gravel and stones, which often formed eskers. These deposits are referred to as glaciofluvial deposits and are better sorted with respect to grain size compared to the glacial till. The eskers were formed in tunnels in the ice sheet, often close to the receding ice front. The eskers in Uppland generally have a north-south direction and were formed successively as the ice retreated towards the north.

Directly after the deglaciation, the water depth in the area was c180–190 m deeper than the present water level /3/. The melt water from the receding ice contained large amounts of suspended silt and clay, which were deposited in the deepest depressions. In Uppland these deposits are often referred to as glacial clay and are further discussed in Chapter 5.6.

Glaciofluvial eskers were found in the south-eastern and south-western parts of the investigated area. The largest glaciofluvial deposit, the Börstilsåsen esker, (Figure 5-14 a and b) is situated in the south-eastern part of the area. This esker has a north-south direction and is the largest esker in the Östhammar region. It is, however, small compared to several of the large eskers found further west, around Lake Mälaren. In the investigated area the esker has a flat crest and reaches 5–6 m above the present sea level. The esker can be followed from Harg, about 30 km south of the investigation area /11/. Within the investigated area, the cape Långören is the southernmost part of the Börstilsåsen esker. Långören is a tongue of land, which is almost completely built up by glaciofluvial material. The effects of wave erosion are obvious along the eastern shores of Långören, where plenty of shingle is present. Till boulders can be observed at several sites along the esker. This is probably till, which has dropped from the roof of the ice tunnel during the deposition of the esker. At Långören the esker is making a change of direction and continues in a north-west direction to Slätören.

Slätören is the Börstilsåsen esker's northernmost extension on the mainland. The esker has, however, a continuation further north-west on the islands Skyan, Lill-Tixlan and Stor-Tixlan. The possible continuation of the Börstilsåsen esker on the sea floor towards north-west is so far unknown. However, shingle fields on the islands of Grisselgrundet and Häggören north of the Börstilsåsen esker may indicate that these islands represent the continuation of the esker (Figure 2-1). It is possible that these fields were formed after wave washing of glaciofluvial material, which is supported by the fact that the fields have a much lower boulder frequency compared to the surrounding till.

A small esker parallel to the Börstilsåsen esker is present north of the bay Simpviken south of Trollgrundet.

Drilling at the crest of the Börstilsåsen esker showed almost 7 m of glaciofluvial sediments on top of the bedrock (Figure 5-14 b).

Finally, also another esker, smaller than the Börstilsåsen esker, was found in the south-western corner of the mapped area. This esker is shown on the earlier SGU map /11/, but not as far north as in the area investigated here.

***Figure 5-14 a.** The glaciofluvial esker Börstilsåsen at Slätören (PFM002956). The island Skyan, in the background, is partly built up by glaciofluvial material.*

***Figure 5-14 b.** The crest of the glaciofluvial esker Börstilsåsen, north of Märrbadet. The photo was taken in November, 2003, during drilling (SFM0060).*

5.5 Effects of wave washing

The land started to rise when the pressure from the inland ice sheet diminished and the water depth decreased subsequently. As the water depth decreased, waves and streams eroded and reworked some of the previously deposited Quaternary deposits. In that way some of the glacial clay was re-deposited as postglacial clay.

Streams and waves also reworked the glaciofluvial deposits and till as the water depth successively decreased. In wave exposed positions, the finest grains have therefore often been washed out from the uppermost parts of the till.

The material eroded from the till, e.g. sand and gravel, was later deposited at more sheltered positions. Such deposits of sand and gravel often cover the glacial clay and are further discussed in Chapter 5.6.

At places, which were exposed to wave erosion, clay and silt fractions have been washed out from the uppermost decimetres of the till. Areas where the till was eroded by waves were not delimited during this fieldwork. At some sites, which have been exposed to extreme wave washing, the uppermost till consist of a stone layer, so called shingle (Figure 5-15 a). Such enrichments of stones can also be seen at several places along the present shore at Klubbudden, Stånggrundet and on several of the islands (Figure 5-15 b). In most cases the shingle layers are thinner than 0.5 m and are consequently mapped as till. At some localities shown on the map, thicker layers of shingle were found.

Uplifted shorelines were observed at several sites, some of which are shown on the map (Figure 5-3). One of the most evident effects of wave washing can be seen at the crest of the Börstilsåsen esker (Figure 5-15 c), where a raised shingle shoreline is present.

Figure 5-15 a. *Shingle on the south-eastern side of the island Österskäret (PFM004809).*

Figure 5-15 b. *Boulder rich till exposed to wave washing. The picture is taken from the island Rönngrundet towards the island Smultrongrundet (PFM002966).*

Figure 5-15 c. *A shingle field at the crest of the glaciofluvial esker Börstilsåsen, east of Märrbadet (PFM004122).*

5.6 Fine grained water laid sediments

After the deglaciation glacial clay and, later, postglacial clay was deposited in depressions in the terrain. As the water depth decreased, also sand and gravel, eroded from the till and glaciofluvial deposits, was deposited in these sheltered positions.

Postglacial clay, which was and still is deposited at the deepest parts of sheltered bays, often contains organic material, which emanates from algae and other vegetation in the neighbourhood. The organic material is referred to as gyttja, and the sediments containing gyttja are called clay gyttja, gyttja clay or gyttja depending on their content of organic material (clay gyttja < gyttja clay < gyttja).

The areas covered by clay sediments, are in the investigated area small compared to many other parts of Uppland. This is probably due to that the Forsmark area is rather flat with few major depressions (e.g. valleys) that have been sheltered from the erosional forces of the sea waves.

A general stratigraphy can be established for the water laid sediments in the Forsmark area. The same stratigraphy was identified in all lakes during the investigation of lake sediments /Table 5-2; /5, 6/. Sand or gravel often overlay the oldest sediment, the varved glacial clay. The sand and gravel originates from older deposits (e.g. till or glaciofluvial deposits) that have been eroded by waves or sea floor currents. Gyttja clay and gyttja are the uppermost and youngest sediments deposited in the lakes and along the coast. Postglacial clay overlies the glacial clay but is rare in the area. The largest deposits are found south-east of Lake Fiskarfjärden. As mentioned above, the area is flat and has been exposed to the erosional forces of the sea waves. This explains the low occurrence of postglacial clay and the many locations with sand and gravel.

Small pockets of glacial clay are found all over the area. A few decimetres or centimetres of glacial clay is often found in the uppermost till, between boulders and stones. These thin and irregular covers of glacial clay have most probably a reducing effect on the capacity of water infiltration.

Most areas with water laid sediments are found in, or in association with wetlands (Figure 5-16 a). Numerous areas with water laid sediments occur in a band-like sub-area, which runs through Lake Fiskarfjärden and Gällsboträsket. The largest continuous area with water laid sediments is found around Lake Fiskarfjärden, where large areas are composed of sand and gyttja clay. The largest wetlands have a diameter of more than 500 m (e.g. Gällsboträsket, Figure 5-16 b). There are, however, hundreds of wetlands, which are less than 100 m across (Figure 5-16 c). The deposits on these small areas are often not shown on the earlier map of Quaternary deposits /11, 12/. The unconsolidated deposits of the wetlands are of varying genesis. Clay gyttja and glacial clay are the most common deposits in the wetlands. The glacial clay is often overlain by 20–40 cm of sand and gravel. In many wetlands these sand and gravel deposits are thicker than 50 cm (the mapping depth). Many of the areas shown as sand or gravel are most probably underlain by glacial clay. Gyttja clay is found in positions sheltered from wave erosion along the shores of the lakes and sea. The gyttja clay is often thinner than 1 m and is often underlain by till, glacial clay and sand (see Table 5-2). Gyttja clay is more common at low places (e.g. around Fiskarfjärden) than at higher places, were the gyttja clay is overlain by peat. Gyttja was found at one site close to the nuclear power plant. The gyttja was probably deposited in a lake, which was drained when the power plant was constructed. Some wetlands consist of a flat till surface e.g. large parts of the shores around Lake Bolundsfjärden (Figure 5-16 d). Sand, gravel and glacial clay also occur at sites that are not wetlands, e.g. the sand deposits north of Fiskarfjärden.

Many of the small wetlands are submerged by shallow water during the spring and early summer. These seasonal water tables do not always represent the groundwater table. In many cases the water remains for a long period in the wetlands due to the occurrences of clay layers that hinders the rain and melt water from infiltrating.

Fluvial water laid sediments (clay and silt) were found in one area close to the small river Forsmarksån. These deposits were formed during periods, when the water table in the river was high, covering the surrounding flat areas.

Figure 5-16 a. *An open marshy field constituting glacial clay and surrounded by predominantly till north of Fiskarfjärden (PFM004175).*

Figure 5-16 b. *Gyttja clay is the dominating Quaternary deposit in the fen Gällsboträsket. (PFM002727).*

Figure 5-16 c. *A small wetland in Labboskogen with a stratigraphy typical for the area. (PFM002724). The uppermost 2 dm consist of fen peat which is underlain by sand and glacial clay.*

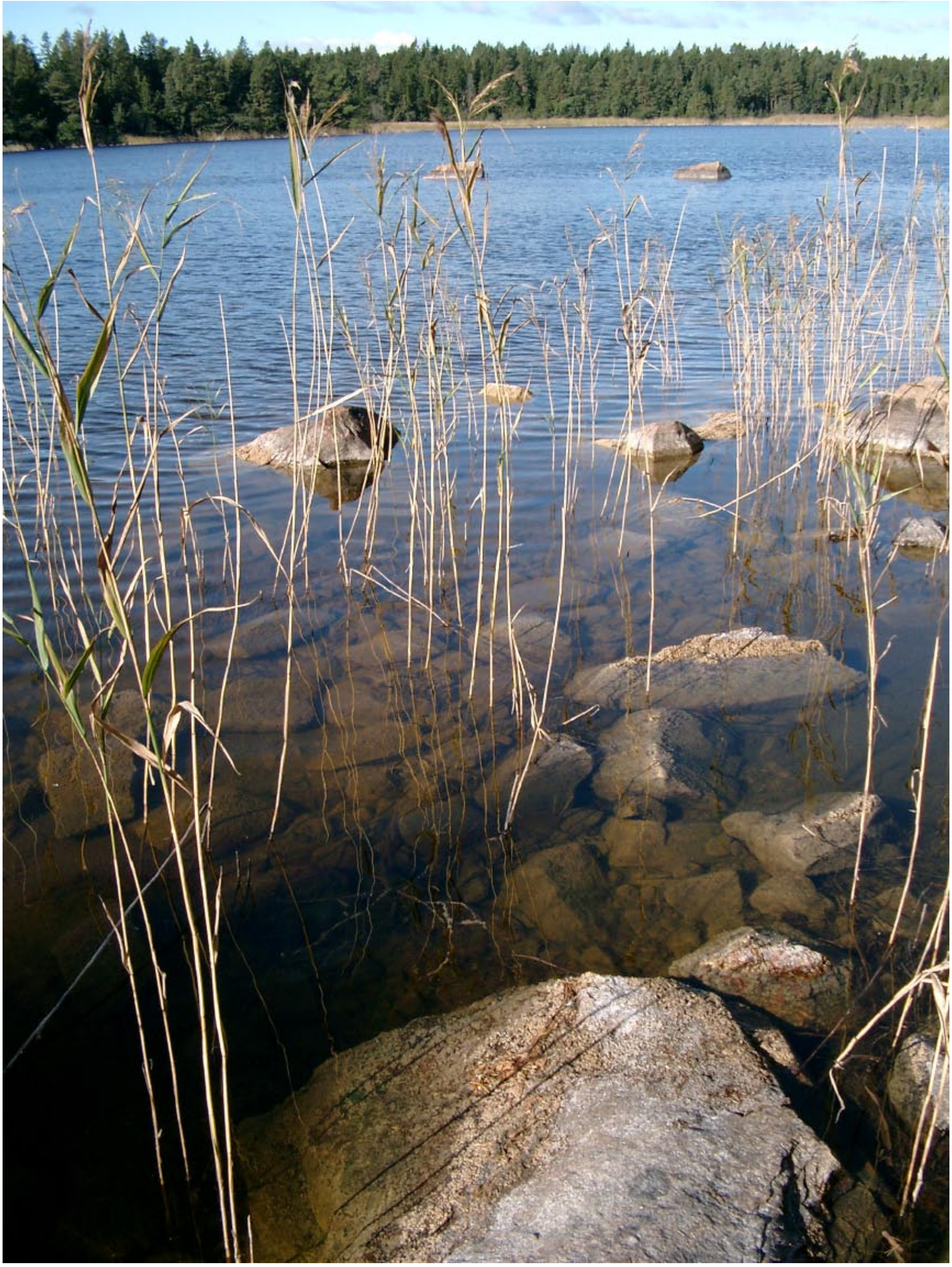

Figure 5-16 d. *Glacial till dominates the shores around Lake Bolundsfjärden. Till boulders can be seen far out in the shallow lake (PFM002731).*

Table 5-2. General stratigraphy of water laid sediments in the Forsmark area, modified from Hedenström 2003 /5/.

Environment	Lithology
Freshwater lake	Gyttja
Postglacial Baltic basin	Gyttja clay/clay gyttja
Shallow coast	Sand, gravel
Postglacial Baltic basin	Postglacial clay
Late glacial Baltic basin	Glacial clay

5.7 Peat

Peat consists of dead vegetation remnants, which are preserved in areas (often mires) where wet conditions prohibit break-down of organic material. The peat mires are divided into two types: bogs and fens. A coherent cover of *Sphagnum*-species characterises the bogs. In the investigated area, only a few wetlands were identified as bogs.

Most wetlands consisting of peat in the investigated area, are situated south-west of a NE – SE sub-area, which runs through the Lake Fiskarfjärden and the northern part of the Gällsboträsket (Figure 5-17 a and b). This peat-rich area has been situated above the sea level for the longest period, and there has been time enough for a peat layer to develop. North-east of this zone, less extensive peat areas were identified than is shown on the earlier maps of Quaternary deposits /11, 12/. In this area, the sea most recently covered most of the present lakes and wetlands (Figure 5-21), entailing that the time to form a distinguished peat layer has been too short. Large parts of the present lakes and wetlands, however, will be covered by peat in the future, like today at higher altitudes a few kilometres south-west of the area mapped in this study /11/.

The total thickness of the peat is often less than one metre. Results from a stratigraphical investigation of the wetlands with peat will be presented in a separate P-report /4/. Gyttja clay was discovered only in a few wetlands in the south-western, peat-rich part of the mapped area. In this area the gyttja clay and glacial clay are overlaid by peat. In many cases the peat is formed directly on top of the glacial till (Figure 5-17 c), e.g. along the shores of Lake Bolundsfjärden where, the till in many places is covered by a thin peat layer.

Figure 5-17 a. *Fen with a peat cover, east of Gällsboträsket, (PFM002728).*

Figure 5-17 b. *One of the largest peat fens in the area, Stenrösmossen (PFM004758). At the central part of the fen, the vegetation indicates nutrient poor conditions. The marginal parts of the fen have a richer vegetation.*

Figure 5-17 c. *Fen with a thin layer of peat, which has developed directly on glacial till, north of Lake Eckarfjärden (PFM002763).*

5.8 The effects of shoreline displacement

The evolution of the investigated area during the past 2500 years is summarised in five figures (Figure 5-18; Figure 5-19; Figure 5-20; Figure 5-21; Figure 5-22). The distribution of Quaternary deposits has certainly changed during that time (e.g. peat formation and deposition of sediments). It must therefore be kept in mind that the five maps do not give a complete and fully correct picture of the distribution of Quaternary deposits at each time sequence. Furthermore, the erosion by waves and streams has probably changed both the topography and distribution of Quaternary deposits at some places. It is likely that the crest of the Börstilsåsen esker has been considerably lowered by the action of waves. Both the topography and geology have been changed during the construction of the power plant, in the north-western corner of the investigated area. The evolution shown in the five maps is therefore not completely correct in that sub-area.

The oldest land areas, which are found in the south-western part of the investigation area, had started to emerge above the sea level about 550 BC (Figure 5-18). In the eastern part of the investigation area, the Börstilsåsen esker and part of the area with exposed bedrock had started to emerge above the sea level c 450 AD (Figure 5-19). The shores of these first land areas were probably subjected to considerable erosion by wave actions. Five hundred years ago (1450 AD), most of the present wetlands in the eastern part of the area were still covered by the sea (Figure 5-21). Many of these present wetlands were then favourable environments for deposition of fine grained water laid sediments. Both the areas around Storskäret, composed of clayey till, and the Börstilsåsen esker were islands at that time (Figure 5-21). Most sand areas are situated in the former straits, which separated these islands. It is possible that stream and wave action deposited the sand during this stage. As late as 1700 AD, many of the areas were gyttja clay is found were sheltered bays (Figure 5-22), which were favourable for the deposition of these sediments. Some of the wetlands in the south-western corner are more than 1000 years old (Figure 5-20), and have been emerged above the sea level long enough for a coherent peat layer to form. Lake Bolundsfjärden and Lake Fiskarfjärden were bays connected with the sea as late as during the 18-th century. These lakes are still more or less in the same level as the Baltic Sea.

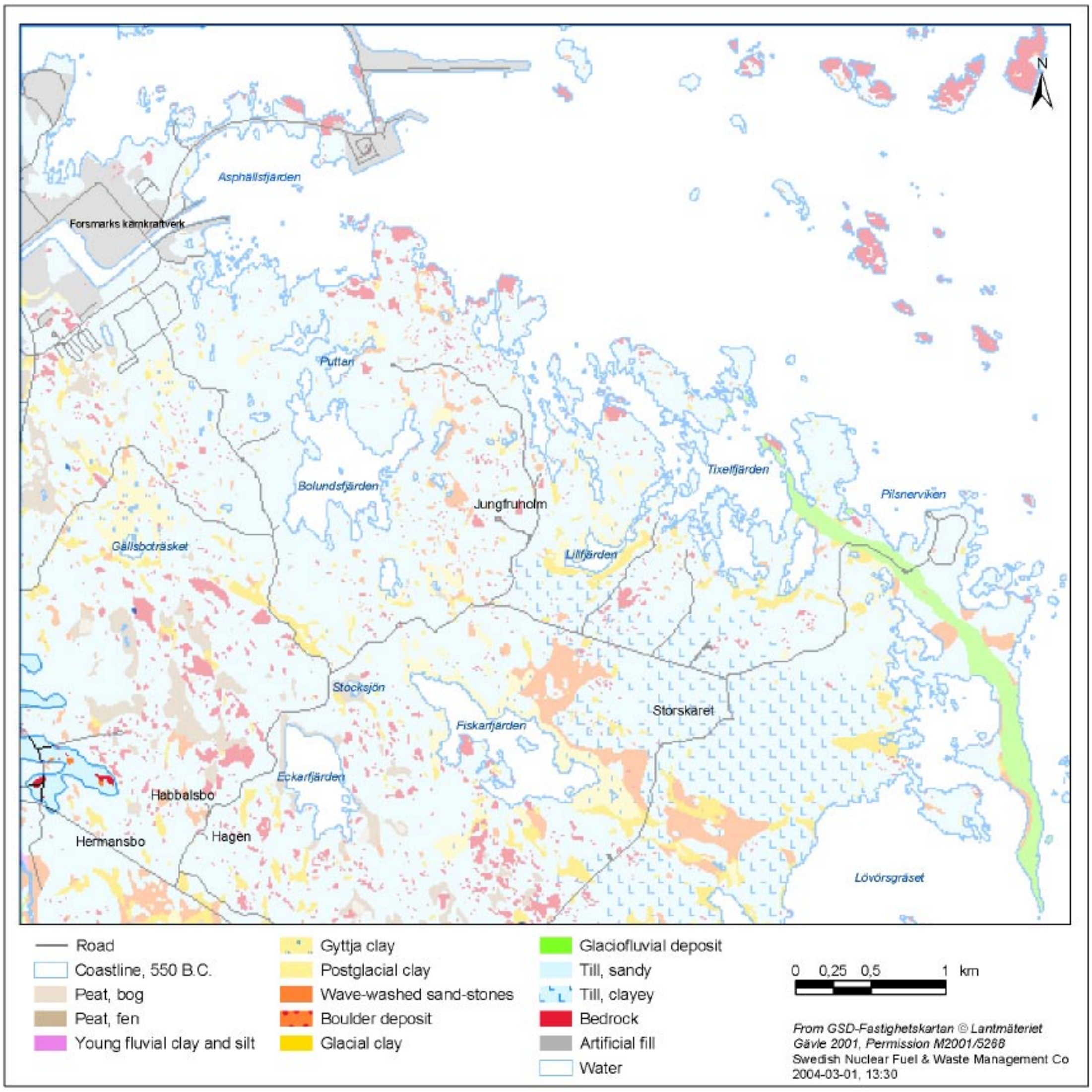

Figure 5-18. *The land-sea distribution 550 BC. The water depth was about 17.5 m above the present sea level. Areas covered with water, which at present are land, are shown in pale colours, left side of the map.*

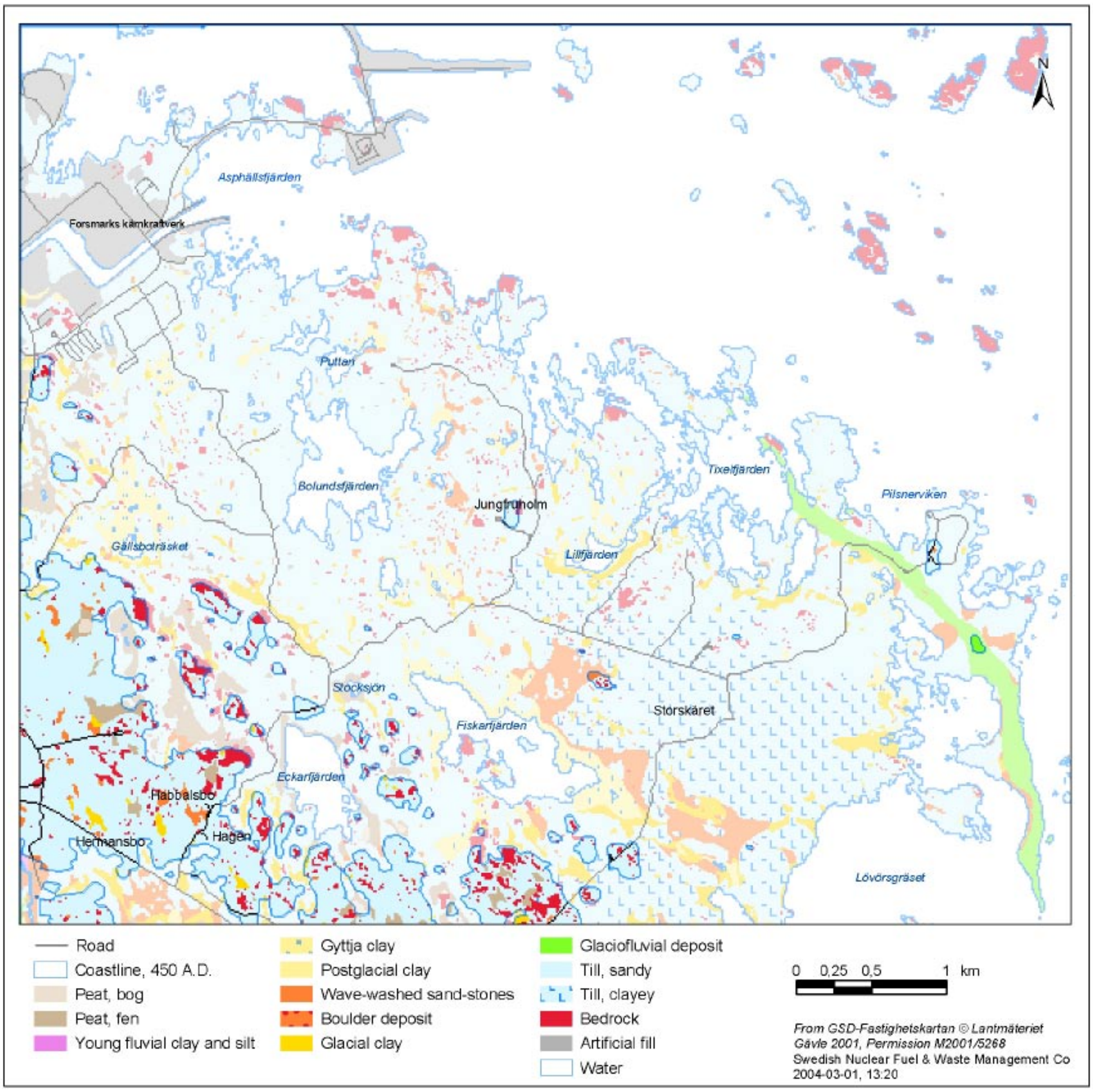

Figure 5-19. *The land-sea distribution 450 AD. The water depth was about 10 m above the present sea level. Areas covered with water, which at present are land, are shown in pale colours.*

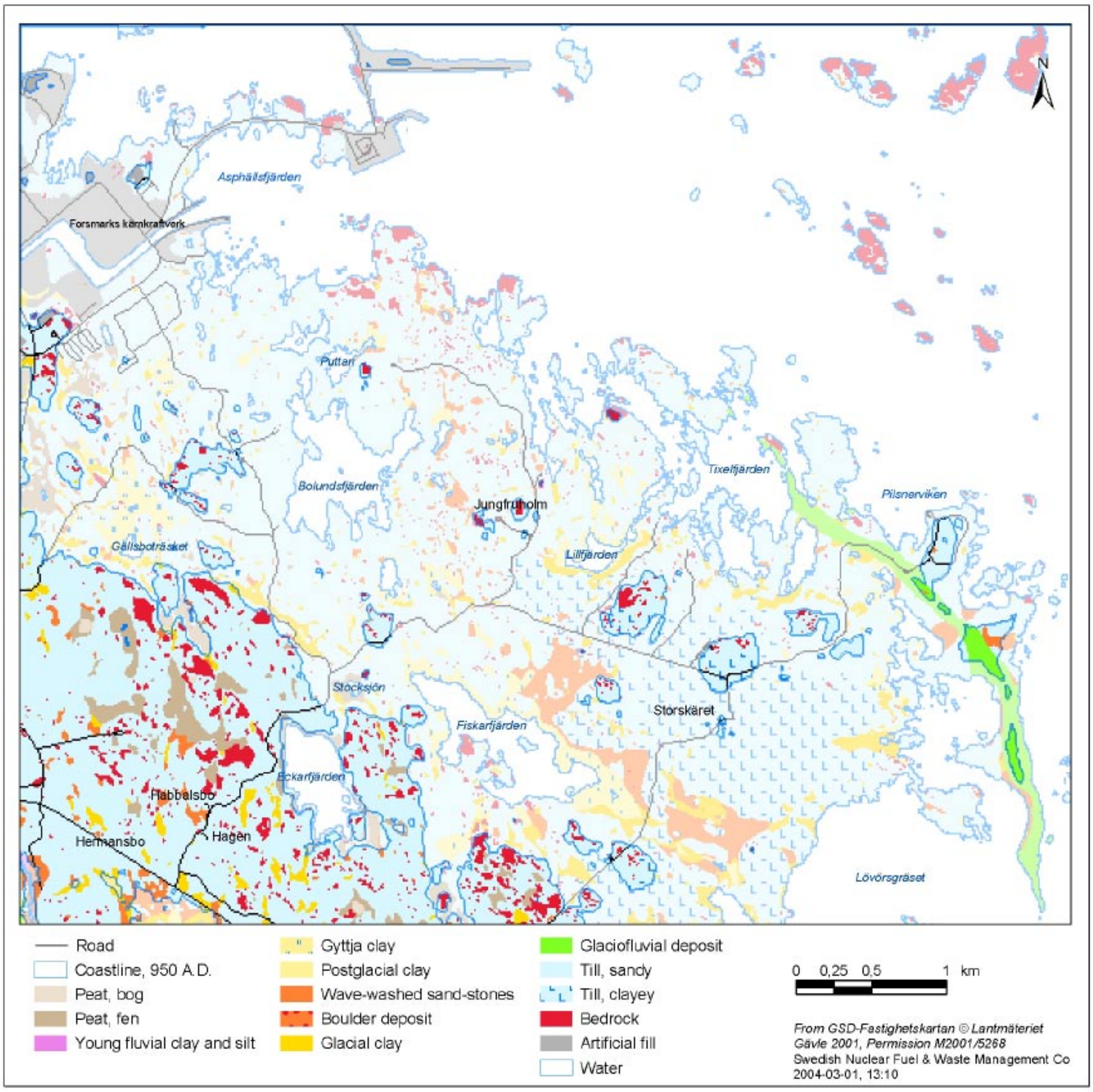

Figure 5-20. *The land-sea distribution 950 AD. The water depth was about 6.5 m above the present sea level. Areas covered with water, which at present are land, are shown in pale colours.*

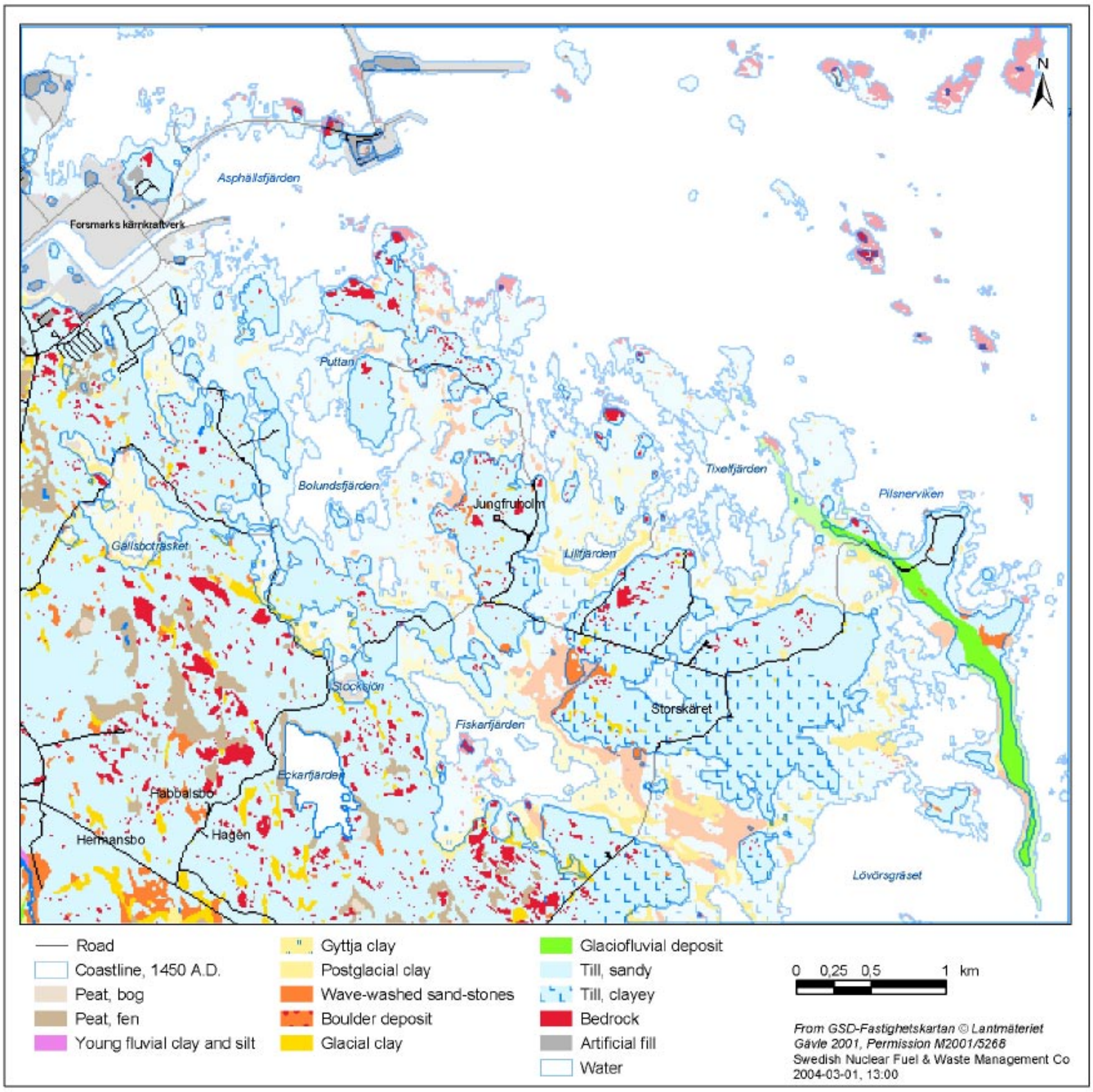

Figure 5-21. *The land-sea distribution 1450 AD. The water depth was about 3 m above the present sea level. Areas covered with water, which at present are land, are shown in pale colours.*

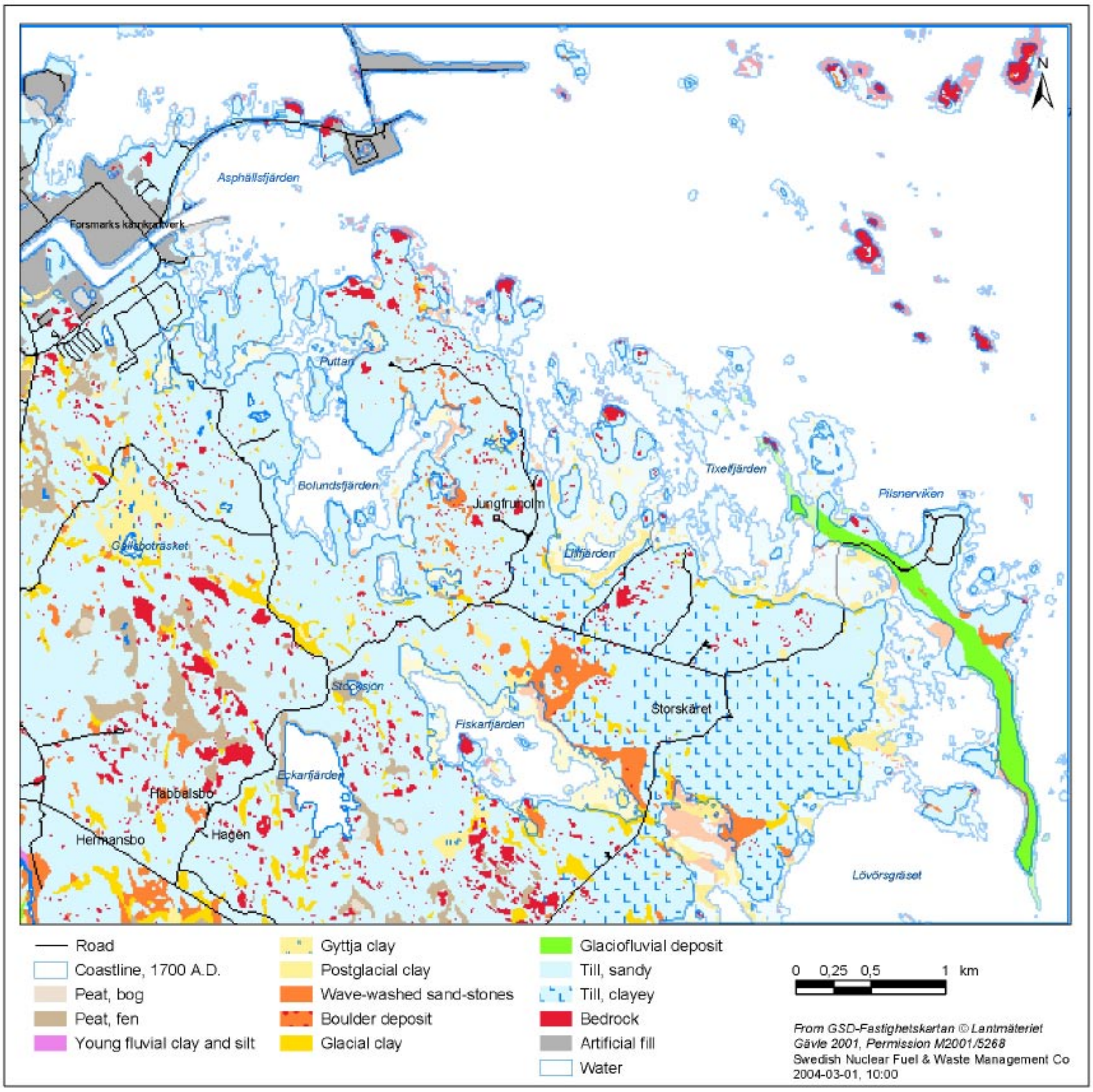

Figure 5-22. *The land-sea distribution 1700 AD. The water depth was about 1.5 m above the present sea level. Areas covered with water, which at present are land, are shown in pale colours.*

5.9 Comparison with the earlier SGU map

The map presented here and the maps produced by SGU /11, 12/ give the same general view of the investigated area. There are, however, some differences between the two maps. The proportional distribution of Quaternary deposits in the investigated area according to the SGU map /11, 12/ (Table 5-3), can be compared with the results from the present investigation (Table 5-1). This comparison shows that the areas constituting exposed bedrock and peat are considerably larger in the former SGU map.

A closer comparison between the two maps shows that many of the small areas of exposed bedrock are much too large on the former SGU map. These minor bedrock areas have probably been enlarged to make it possible to show them in the scale 1:50 000.

Most wetland areas were mapped as peat on the old map. The new map reveals, however, that many of these wetlands constitute deposits other than peat, especially close to the present sea level. The wetlands close to the sea are often composed of gyttja clay. Another comparison between the two maps demonstrates that much larger areas were consequently mapped as gyttja clay in the later investigation.

In the forest areas there are many dry (not wetland) surfaces with water laid sediments. Many of these "dry land" deposits are not shown on the former maps of Quaternary deposits.

Table 5-3. The proportional distribution of Quaternary deposits in the investigated are extracted from the SGU maps /11, 12 /.

Quaternary deposit	Coverage %
Peat	6.98
Gyttja sediments	0.7
Clay	2.36
Postglacial sand and gravel	2.63
Glaciofluvial sediment	1.82
Till, clayey	11.46
Till, sandy	59.75
Total area covered by till	*71.21*
Artificial filling material	2.94
Precambrian bedrock	11.36

5.10 Summary

The most important conclusions from the mapping of Quaternary deposits in the Forsmark area are listed below:

- The area is dominated by glacial till (75%), which can be separated in three main domains: I) sandy till with a normal frequency of superficial boulders, II) clayey till with a low to normal frequency of superficial boulders, III) sandy till with a high frequency of often large, superficial boulders.
- Most of the area is characterised by a high frequency of, often small, wetlands. In the south-western part of the area, a peat layer often terminates the stratigraphical sequence of the wetlands. The major parts of the wetlands in the area have a stratigraphicaphy of glacial clay, sand or gyttja clay.
- Most of the area has been raised above the sea during the last 1000 years, entailing that processes such as chemical weathering and peat formation have affected the area during a relatively short period of time. That is reflected in 1) a high frequency of shallow lakes and ponds, 2) the absence of peat in many wetlands, 3) a high content of $CaCO_3$ in the uppermost soil layer.
- The old map /11, 12/ and the map presented here give the same general view of the investigated area. The new map shows, however, that the total areas of peat and exposed bedrock are exaggerated on the earlier map, whereas too small areas were mapped as gyttja clay.

6 References

/1/ **Agrell H, Björnbom S, 1978.** Blå morän vid Forsmarks kärnkraftverk. SGU centralarkiv F8 ID: C3 ME: paper (in Swedish).

/2/ **Blomberg A, 1886.** Kartbladet Öregrund. Geological Survey of Sweden, Aa 101 (in Swedish).

/3/ **Fredén C (ed), 2002.** Berg och jord. Sveriges nationalatlas. Tredje upplagan. 208 s (in Swedish).

/4/ **Fredriksson D, 2004.** Forsmark site investigation. Peatland investigation Forsmark. Svensk Kärnbränslehantering AB.

/5/ **Hedenström A, 2003.** Forsmark site investigation. Investigation of marine and lacustrine sediments in lakes. Field data 2003. P-03-24. Svensk Kärnbränslehantering AB.

/6/ **Hedenström A, 2004.** Forsmark site investigation. Investigation of marine and lacustrine sediments in lakes. Stratigraphical and analytical data (in progress). P-04-86. Svensk Kärnbränslehantering AB.

/7/ **Hedenström A, Sohlenius G, Albrecht J, 2004.** Forsmark site investigation Stratigraphical and analytical data from auger drillings and pits. P-04-111. Svensk Kärnbränslehantering AB.

/8/ **Ingmar T, Moreborg K, 1976.** The leaching and original cont1ent of calcium carbonate in till in northern Uppland, Sweden. Geologiska Föreningen i Stockholm Förhandlingar. 98, 120–132.

/9/ **Johansson P-O, 2003.** Drilling and sampling in soil. Installation of groundwater monitoring wells and surface water level gauges. Forsmark site investigation. P-03-64. Svensk Kärnbränslehantering AB.

/10/ **Lundin L, Lode E, Stendahl J, Melkerud P A, Björkvald L, Thorstensson A, 2004.** Soils and site types in the Forsmark area. R-04-08. Svensk Kärnbränslehantering AB.

/11/ **Persson Ch, 1985.** Description and map to the Quaternary map Östhammar NO. Geological Survey of Sweden, Ae 73. (in Swedish with English summary).

/12/ **Persson Ch, 1986.** Description and map to the Quaternary map Österlövsta SO/ Grundkallen SV. Geological Survey of Sweden, Ae 76. (in Swedish with English summary).

/13/ **Persson Ch, 1988.** Description and map to the Quaternary map Östhammar SO. Geological Survey of Sweden, Ae 90. (in Swedish with English summary).

/14/ **Persson Ch, 1992.** The latest ice recession and till deposits in northern Uppland, eastern central Sweden. SGU Ca 81, 217–224.

/15/ **Sohlenius G, Rudmark L, Hedenström A, 2003.** Forsmark, Mapping of unconsolidated Quaternary deposits. Field data 2002. P-03-11, Svensk Kärnbränslehantering AB.

/16/ **Sohlenius G, Rudmark L. 2003.** Forsmark site investigation. Mapping of unconsolidated Quaternary deposits. Stratigraphical and analytical data. P-03-14. Svensk Kärnbränslehantering AB.

/17/ **Sundh M, Hedenström A, Sohlenius G.** Forsmark site investigation. Stratigraphical investigation of till in machine-cut trenches. P-04-34. Svensk Kärnbränslehantering AB.

/18/ **Svantesson S-I, 1999.** Description to the map Västervik SO/Loftahammar SV. Geological Survey of Sweden, Ae 124 (in Swedish with English summary).

/19/ **Svenonius F, 1887.** Kartbladet Forsmark och Björn. Geological Survey of Sweden Aa 98 & 99 (in Swedish).