R-05-51

Forsmark site investigation

Searching for evidence of late- or postglacial faulting in the Forsmark region

Results from 2002–2004

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Geological Survey of Sweden (SGU)

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Keywords: AP PF 400-02-13, AP PF 400-03-20, AP PF 400-04-103, Late- or postglacial faulting, Earthquake, Quaternary deposits, Seismically induced liquefaction, Sliding, Bedrock fracturing and quarrying.

Summary

The study was designed to determine whether any major late- or postglacial faulting occurred in the proposed repository area at Forsmark or in its vicinity. “Major faulting” in this context is defined as dislocations in the order of several metres along faults several kilometres long. Faults of such dimensions may, if conditions are favourable, be detected by means of interpreting aerial photographs. Furthermore, they would have generated high magnitude earthquakes that could produce characteristic distortions in waterlogged sandy or silty sediments.

Interpretation of aerial photographs was carried out in a relatively large area (Figure 1-1) in northeast Uppland, with the purpose of looking for morphologically conspicuous lineaments, i.e. late- or postglacial fault candidates. A number of fairly prominent but short escarpments and crevasses were noted, but when later field-checked these candidates for young fault movement proved to be more or less strongly glacially eroded, i.e. formed prior to the last deglaciation.

In order to search for seismically induced distortions, all gravel and sand pits being worked in the investigation area were visited and some fifty machine-dug trenches were excavated, mainly in sandy-silty glaciofluvial deposits along eskers. Contorted and folded sequences of glacial clay were encountered at many of the localities, but the disturbances were generally interpreted as caused by sliding. A seismic origin for the sliding cannot be excluded, but no conclusive evidence of this was found. As no distortions attributable to seismically induced liquefaction were noted in any of the trenches excavated along the Börstil esker, to the southeast of Forsmark, it is concluded that no major (> M 7) earthquakes occurred in the Forsmark area after the disappearance of the last inland ice sheet.

An erosional unconformity accompanied by a laterally persistent layer of coarse-grained sediments was found in most of the investigated trenches and it is concluded that strong currents were responsible for significant erosion of the bed of the ancient sea. Together with sliding, this erosion resulted in extensive redistribution of sediments and in a substantial levelling of the terrain.

The discovery of apparently freshly fractured bedrock within the candidate area at Forsmark raised the question of the origin and significance of the features. The spatial and temporal relationships between this fracturing, still more intensely disrupted bedrock exposures and an extreme abundance of glacially transported boulders in the vicinities suggest that a phase of greatly intensified fracturing and quarrying occurred during a late stage of deglaciation. Field evidence clearly indicates that in parts of the investigation area the surficial bedrock, previously protruding bedrock knobs included, were disrupted and transformed into sheets of boulders.

Sammanfattning

Undersökningens syfte var att försöka fastställa om större sen- eller postglaciala förkastningsrörelser har ägt rum inom eller i närheten av det föreslagna förvarsområdet i Forsmark. Med "större förkastningsrörelser" avses i detta sammanhang flera meters förskjutningar utmed flera kilometer långa förkastningar. Förkastningsrörelser i den storleksordningen kan i gynnsamma fall upptäckas genom flygbildstolkning. Eftersom större förkastningsrörelser normalt orsakar stora jordbävningar så bör det dessutom vara möjligt att spåra dem genom seismiskt orsakade störningar i vissa typer av jordlager.

Ett större område i nordöstra Uppland (figur 1-1) flygbildstolkades i syfte att spåra morfologiskt framträdande strukturer som skulle kunna tyda på att unga förkastningsrörelser ägt rum. Ett antal tämligen iögonfallande men korta hak eller öppna sprickor noterades, men vid fältkontroller visade sig dessa vara mer eller mindre starkt slipade av inlandsis och därmed äldre än den senaste isavsmältningen.

För att spåra eventuella seismiskt orsakade störningar i jordlagren rekognoserades alla aktiva täkter inom undersökningsområdet. Dessutom grävdes ett femtiotal undersökningsschakt, huvudsakligen i sandig-siltiga isälvssediment utefter åsstråken inom området. Lagerföljder med starkt tillknölad och veckad lera påträffades på många av platserna, men störningarna bedömdes genomgående ha uppkommit genom skredrörelser utefter den forntida havsbottnen. Det kan inte uteslutas att skreden utlösts av jordbävningar, antingen måttligt stora skalv i närområdet eller större men mer avlägsna skalv, men några belägg för att så skulle vara fallet hittades inte. Eftersom några entydigt jordbävningsorsakade störningar inte påträffades i något av de grävda schakten utmed Börstilåsen strax sydost om Forsmark, kan man sluta sig till att åtminstone inga verkligt stora (> M 7) jordbävningar, och därmed sannolikt inte heller stora förkastningsrörelser, ägt rum i Forsmarksområdet efter att den senaste inlandsisen smälte bort.

Spår efter en anmärkningsvärt stark erosion av den forntida havsbottnen, med efterföljande avsättning av grovkorniga sediment, påträffades i flertalet maskingrävda schakt. Sannolikt var det starka bottenströmmar som ledde till att t ex merparten av den ursprungligt avsatta glacialleran eroderades bort.

Upptäckten av synbarligen färska sprickor i berggrunden inom platsundersökningsområdet väckte frågan om vad som orsakat uppsprickningen samt dess eventuella betydelse för förvarsproblematiken. Det rumsliga och sannolikt även tidsmässiga sambandet mellan de färska sprickorna inom platsundersökningsområdet, ännu starkare uppspruckna bergblottningar och extremt blockrika områden, antyder att det finns ett orsakssamband mellan de tre företeelserna. Det mesta tyder på att en mycket intensiv uppsprickning av ytliga delar av berggrunden, samt en kort transport av lösbrutna block, ägde rum under en sen fas av den senaste isavsmältningen, såväl inom delar av undersökningsområdet som annorstädes. Några tecken på att uppsprickningen skulle ha orsakats av tektoniska processer har inte iakttagits, men det kan finnas anledning att försöka finna en förklaring till vilka glaciologiska mekanismer som lett till den omfattande uppsprickningen och lösbrytningen av block. Företeelsen är knappast förenlig med den traditionella uppfattningen om glacialerosion och s k plockning.

Contents

1 Introduction

This document reports the results obtained from *Searching for evidence of late- or postglacial faulting in the Forsmark region*, which is one of the activities performed within the site investigation at Forsmark. The work was carried out in accordance with activity plans AP PF 400-02-13, AP PF 400-03-20 and AP PF 400-04-103 and Method description MD 133.001 (all of them SKB internal controlling documents). The area under investigation is shown in Figure 1-1. Data are stored in the SICADA database and are traceable by the activity plan numbers.

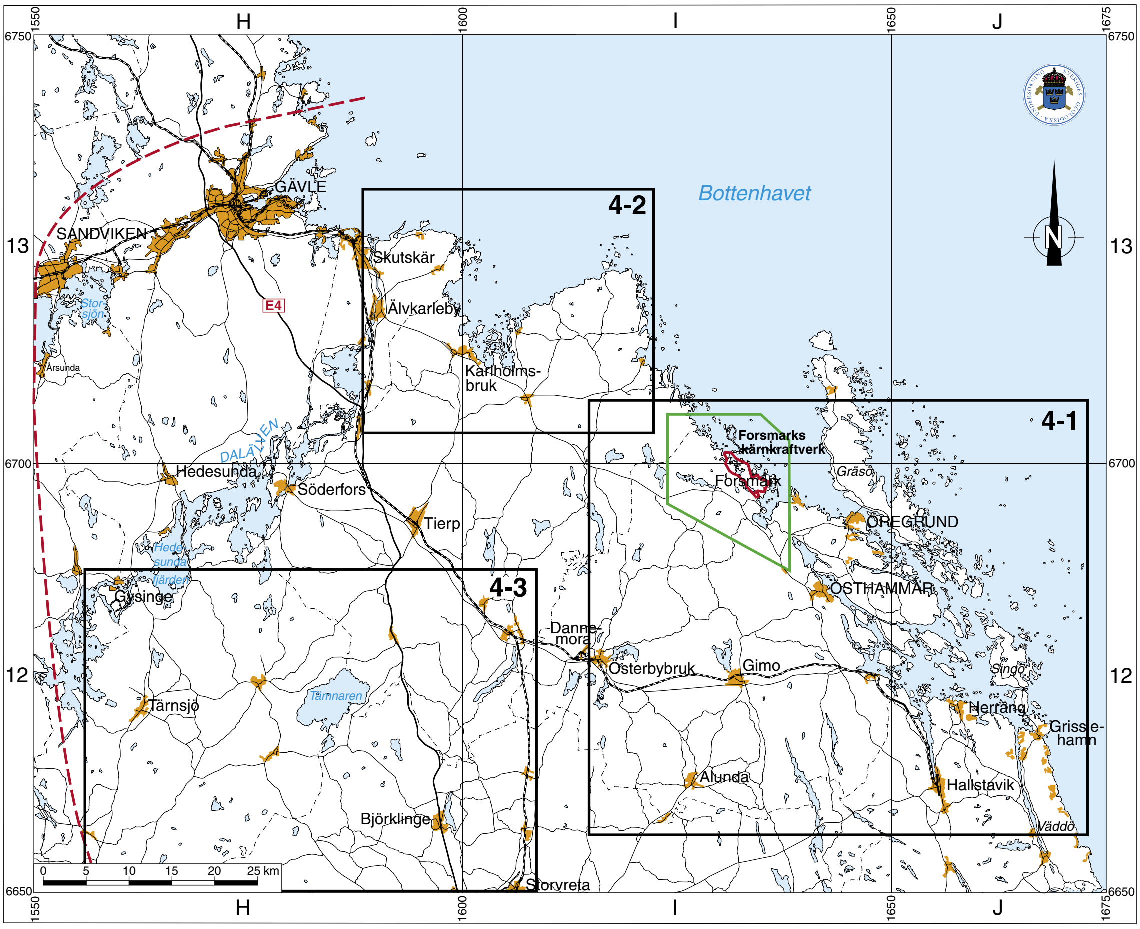


Figure 1-1. Map of investigation area in north-eastern Uppland (mainland areas east of stippled line). Continuous red line marks candidate area for detailed investigations. Green line marks area covered by low-altitude aerial photographs. Areas shown in Figures 4-1, 4-2 and 4-3 are marked with black rectangles.

2 Objective and scope

The study was undertaken to establish whether any major late- or postglacial faulting had occurred in the proposed repository area in Forsmark or in its vicinity. “Major faulting” in this context means dislocations in the order of several metres along faults extending several kilometres. Faults of such dimensions may, if conditions are favourable, be detected by means of aerial photo interpretation. The process of dislocation may have been associated with high magnitude earthquakes that could produce characteristic distortions in waterlogged sandy or silty sediments. Thus, fault movements may be indicated either directly by distinct dislocations manifested in bedrock surface or covering regolith, or indirectly, by seismically derived deformations of certain types of Quaternary sediments. If late- or postglacial fault movement is indicated and assigned to a specific fault or fault zone, the event should as far as possible be dated and fault displacement be quantified. The study was initiated in 2002 and this report includes the results of fieldwork performed in 2002–2004.

3 Equipment

3.1 Description of equipment

Aerial photo interpretation was performed using a Wild Aviopret stereoscope and IR-images on a scale of 1:30,000 within the main part of the investigation area and 1:15,000 within the site investigation area (Figure 3-1A).

Excavators capable of digging trenches to a depth of some 5 m were used for stratigraphic work (Figure 3-1B). Trench wall sections were trimmed manually with shovels, bricklaying trowels, etc, and then documented with sketches and photographs (Figure 4-6).

A hand-held drilling machine (Cobra) combined with a through-flow sampler was used for coring of sediments (Figure 4-7).

GPS (hand-held) was used for positioning.

Figure 3-1. *Aerial photo interpretation (A) and stratigraphical investigations in machine-dug trenches (B) were the most important steps in the investigation.*

4 Execution

The study comprised four main steps in accordance with SKB MD 133.001:

1. a review of geological literature about the area,
2. aerial photo interpretation,
3. field reconnaissance,
4. stratigraphic investigations.

Activities according to 1–3 were carried out mainly in 2002, while during 2003 and 2004 the study was concentrated on stratigraphic work in machine-dug trenches.

4.1 Review of literature

The literature review in 2002 was confined principally to descriptions relating to geological maps in SGU series Aa and Ae. These descriptions were scrutinized for any information indicative of recent faulting or earthquakes. A few other publications relevant to the purpose of the study were glanced through as well.

4.2 Aerial photo interpretation

The entire investigation area (Figure 1-1) was interpreted by means of aerial photographs on a scale of 1:30,000 and the candidate area on a scale of 1:15,000 as well. Anything that might be indicative of recent faulting (principally fresh-looking escarpments) or earthquakes was noted for later checking in the field. All gravel and sand pits were marked on topographical maps for later field checking.

4.3 Field reconnaissance

The stratigraphies in practically all gravel and sand pits being worked in the investigation area, temporary road cuttings, etc were examined for any seismically induced distortions. Most of the fresh-looking escarpments, crevasses, etc, noted during aerial photo interpretation were field-checked and rather extensive surveying of bedrock exposures in the archipelago was undertaken. Findings of apparently fresh fractures at deep drilling site BP5 /Leijon, 2005/ and exploratory trenches LFM00810–11 in the candidate area raised the question of the origin and significance of these features and justified some additional reconnaissance within as well as outside the investigation area.

4.4 Stratigraphical investigations

In 2002 and 2003, activity was concentrated on investigating machine-dug trenches along the Börstil esker southeast of the candidate area at Forsmark (Figure 4-1) while in 2004 the excavation sites were more spread within the investigation area (Figures 4-2, 4-3).

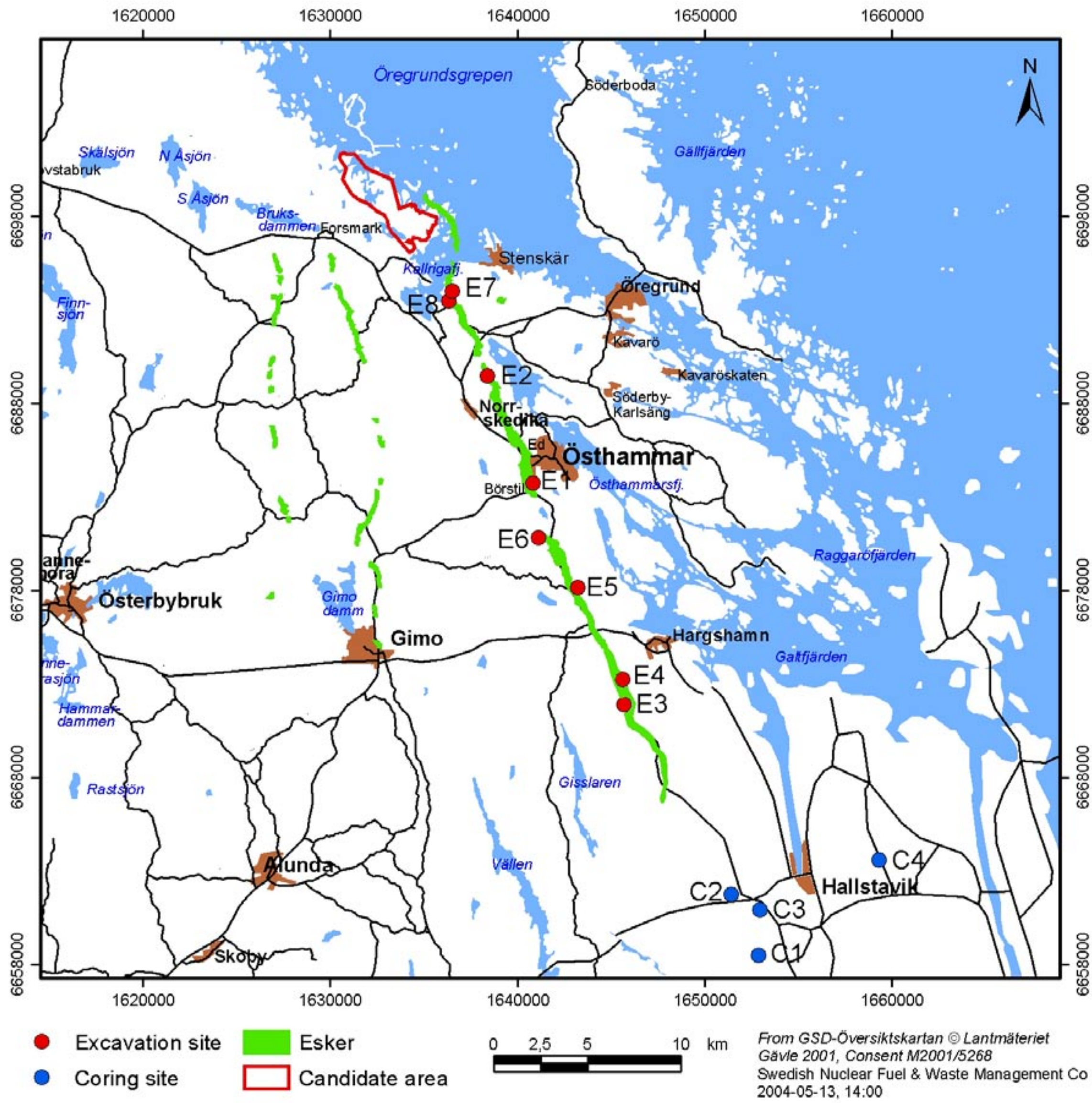


Figure 4-1. *Location and names of excavation (E) and coring (C) sites. E1 Börstil. E2 Lindersvik. E3 Hultet. E4 Kråkmötet. E5 Lädra. E6 Marka. E7 Örnäs. E8 Östansjö. C1 Hammarby. C2 Kristinelund. C3 Söderängen. C4 Kusby.*

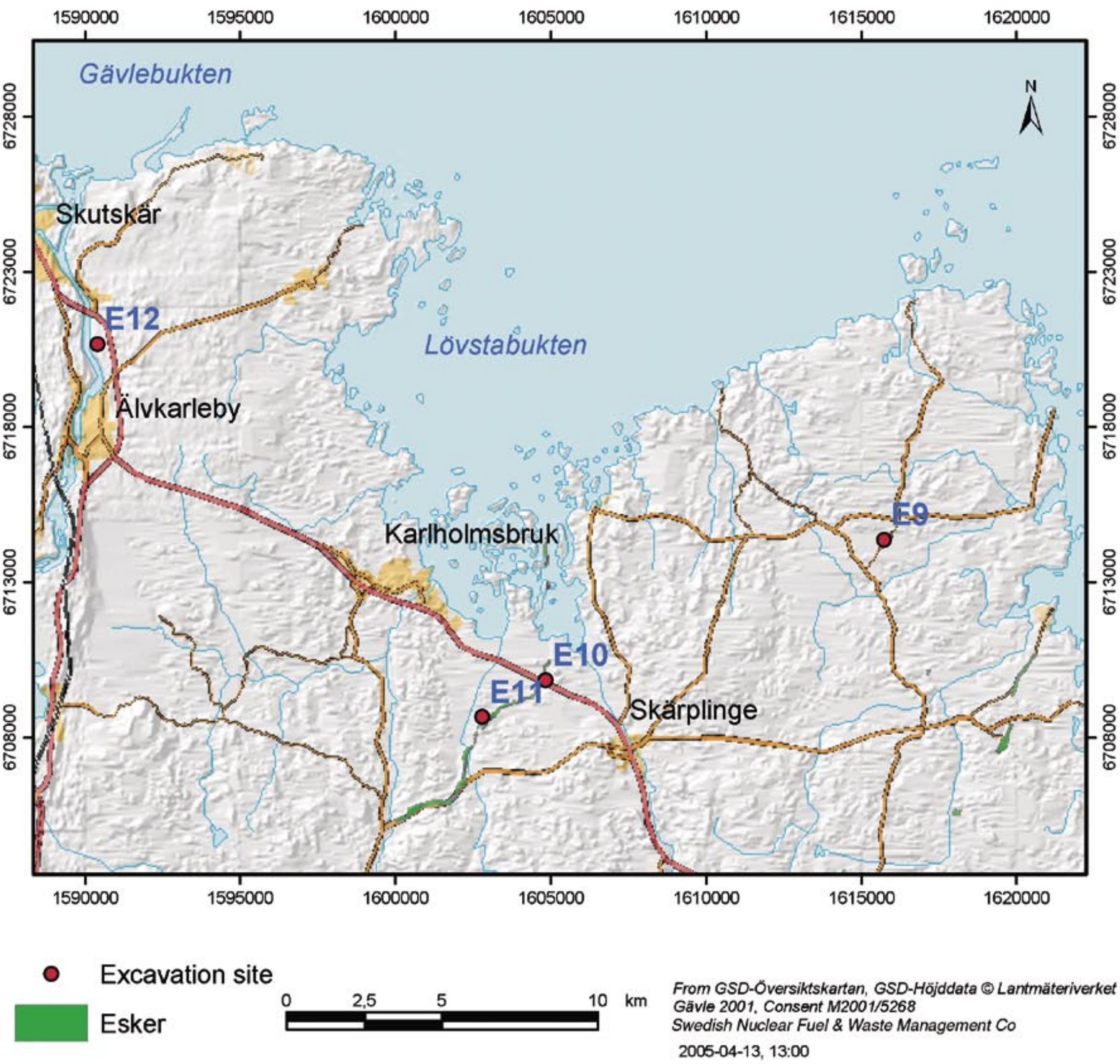


Figure 4-2. *Location and names of excavation sites. E9 Hjälmunge. E10 Skärmarbo. E11 Väläängarna. E12 Älvkarleby.*

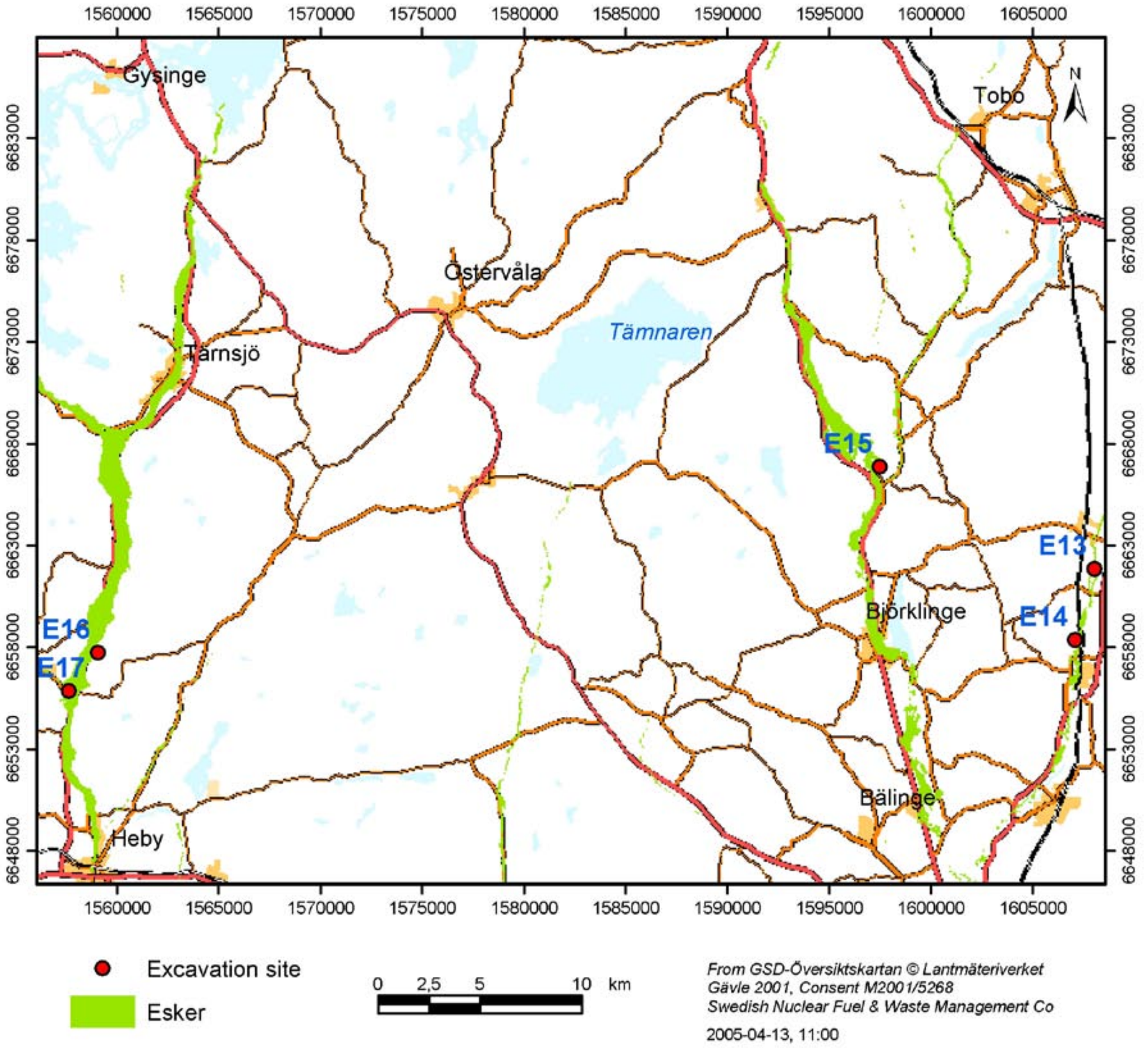


Figure 4-3. *Location and names of excavation sites. E13 Salsta. E14 Brunna. E15 Torkelsbo. E16 Fallet. E17 Runhällen.*

Altogether 48 trenches with an overall length of some 900 m and a number of minor pits were excavated at 18 different sites. The trenches were excavated on the flanks of and perpendicular to eskers with the intention of reaching sandy glaciofluvial deposits or coarse glacial silt, covered ideally by a moderately thick bed of finer grained sediments. However, the sediment stratigraphy varied considerably from one trench to another and it was not always easy to find adequate stratigraphies for investigation (Figure 4-4). All of the trenches were excavated in level or only gently sloping terrain (Figure 4-5) at depths of some 1.5 to 5.0 m. Trench walls were cleaned manually and afterwards documented with sketches and photographs (Figure 4-6). Documentation had to be brief; the time available for excavation, documentation and restoring of cultivated ground averaged 2 days at each site.

In addition to the trenchwall work, complementary stratigraphic investigations were made by coring. Coring of clay beds intercalated by sandy layers was carried out at four sites near Hallstavik (Figure 4-1). The deepest bore hole reached about 9 m, while the others were terminated at a few metres depth after penetrating the sandy layer sought for and the upper part of underlying clay. Coring also provided complementary information about the thickness and character of sediments at excavation sites (Figure 4-7).

Figure 4-4. *How to find adequate stratigraphies for investigation? Due to intense post-sedimentary erosion, the exterior ground surface gives almost no intimation as to what may be found at depth. Although only 3 m apart, these two pits close to the completely flattened Börstil "esker" (situated by the trees just beyond the car) at Lindersvik (E2 in Figure 4-1) display completely different stratigraphies; > 4.5 m of dense, clayey glacial till (foreground) and > 4.5 m of saturated glaciofluvial sand, respectively.*

Figure 4-5. *Typical excavation site in very gently sloping ground along the Börstil esker. Kråkmötet (E4 in Figure 4-1) after opening of a first test pit.*

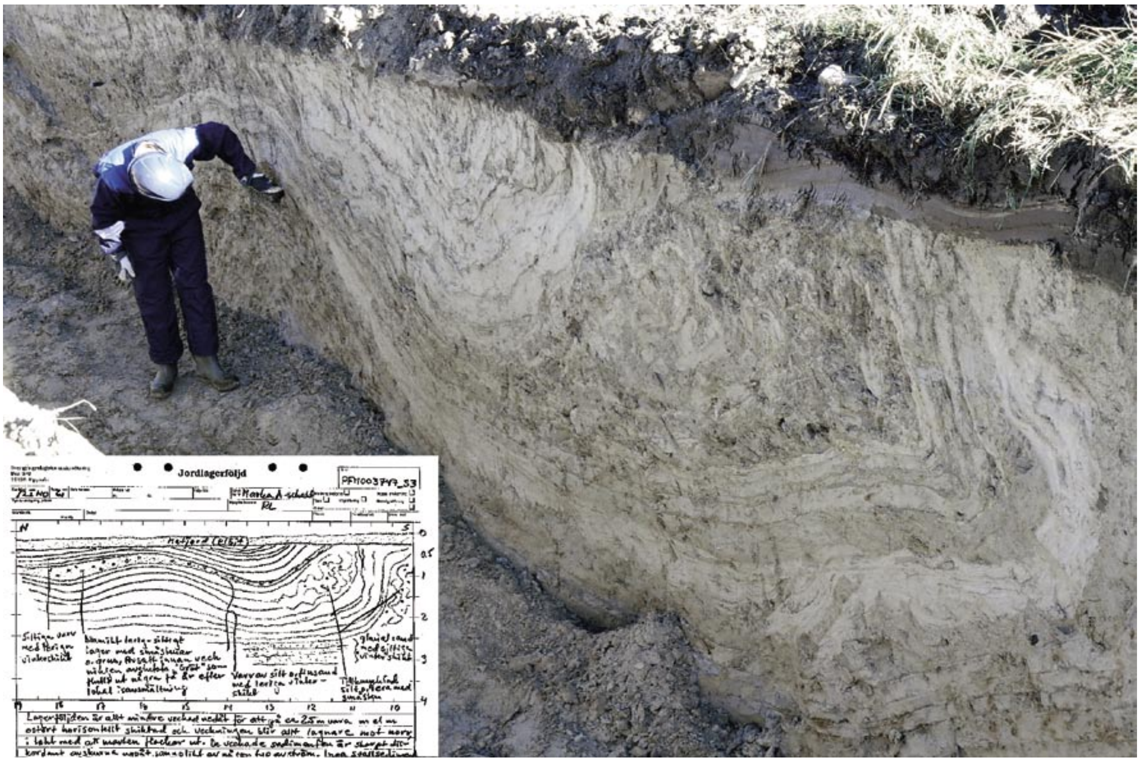


Figure 4-6. *Trench wall sections were cleaned manually with shovels, bricklaying trowels, etc and then documented with photographs and sketches (inset in lower left corner). The photograph shows part of the stratigraphy at Marka (E6 in Figure 4-1). The abruptly cut folds in glacial silt indicate substantial erosion of a formerly thicker sequence.*

Figure 4-7. *Coring provided complementary information about thickness and character of sediments at depths at Torkelsbo (E15 in Figure 4-3).*

4.5 Data handling

The positions of stratigraphic and geological observations, photographs, etc, were determined by GPS or topographical maps. The dates of the observations were noted and all were given PFM numbers. All points and dates were later stored in SICADA. The geological information connected with the PFM numbers was stored in the SGU database (*Jorddagboken,* version 5.4.3). Data from the SGU database were transferred to Excel files.

Delivery to SKB from the investigations carried out during 2002–2004, consisted of:

1. Data files with stratigraphic and other geological information.

SKB_PFM_NEO030429.xls

SKB_PFM_NEO040401.xls

SKB_PFM_NEO_050405.xls

2. Data files with photos and sketches.

PFM003684_A – PFM003735_I (jpg) (33 photos)

Foton_PFM_NEO_040401 (jpg) (69 photos)

Foton_PFM_NEO_050405 (jpg) (69 photos)

PFM003735_S1 – PFM003735_S11 (jpg) (11 sketches)

Skisser_PFM_NEO_040401 (tif) (37 sketches)

Skisser_PFM_NEO_050405 (jpg) (41 sketches)

4.6 Basic principles for analyses and interpretation

In connection with the aerial photo interpretation, any linear escarpment or other type of lineament considered atypical of the general landscape and protruding as an anomalous feature was noted for later field checking. However, as there are many reasons why faults may easily escape detection, the search for evidence of recent faulting cannot rely solely on morphological expressions on the ground surface, but must also consider any secondary effects of faulting. As major fault movements usually generate significant earthquakes, the study was concentrated largely on searching for earthquake-induced deformation of late- or postglacially deposited sediments.

The ultimate interpretation of the stratigraphic information obtained in the machine-dug trenches, i.e. were there any major postglacial earthquakes in the vicinity of Forsmark?, is based mainly on the concept of earthquake-induced liquefaction. When loosely packed, waterlogged frictional sediments are subjected to strong ground shaking they may lose their strength and behave as liquids. As a consequence of liquefaction, the primary sedimentary structures will be destroyed and replaced by a variety of deformational features. Earthquake-induced liquefaction is controlled by a number of variables such as packing and sediment grain size, level of water table, duration of earthquake, amplitude and frequency of shaking and, not at least, distance from earthquake epicentre. It is commonly considered that liquefaction phenomena may develop in highly susceptible sediments at magnitudes as low as M5, but become more common at M6 or greater. A shallow-focus M6 earthquake may cause liquefaction features at a distance of some 20 km from epicentre, a M7 earthquake within some 100 km, while a great M8 earthquake may induce liquefaction as far away as 300 km /e.g. Obermeier, 1996/.

Whereas the presence of liquefaction features may indicate strong paleoearthquakes, an absence of such features (provided that susceptible sediments are widespread) strongly indicates that no major earthquakes have occurred in the vicinity since sediment deposition. The Lansjärv and Burträsk areas in northern Sweden, in geological settings similar to those in northeastern Uppland, may serve as reference areas when the results of the present investigation are evaluated. In both these areas, postglacial faulting induced a great variety of regionally distributed liquefaction phenomena /Lagerbäck, 1990/ (Lagerbäck and Sundh, unpublished).

5 Results

5.1 Review of literature

In the reviewed literature, primarily descriptions relating to the maps of Quaternary Deposits in SGU series Ae and Aa, observations of disturbed late-Quaternary stratigraphies are described from about 10 localities. The types of disturbance described range from faulted deposits in the Börstil esker /Persson, 1985/ to more plastic deformational structures in glacial silt and clay /Ericsson and Lidén, 1988; Grånäs, 1985; Sandegren et al. 1939; Sandegren and Asklund, 1948; Sandegren and Lundegårdh, 1949/. However, the deformations described were generally considered to be of non-seismic origin but caused by glaciotectonics, sliding, or processes related to land upheaval.

/Agrell, 1981; Persson, 1990; Sjöberg, 1994; Mörner, 2003/ described a so-called boulder cave called *Gillberga gryt* in the southwestern section of map sheet 11 J Grisslehamn SV. The authors have differing opinions regarding the nature of the cave formation. Agrell, Sjöberg and Mörner suggest a seismo-tectonic origin of the feature, while Persson favours a glaciotectonic origin. See further 5.3.3.

5.2 Aerial photo interpretation

The entire investigation area (Figure 1-1) was aerial photo interpreted. A number of fairly prominent but short escarpments and crevasses were noted for later field checking but no major, sustained late- or postglacial fault candidates were identified. Nor were any landslide scars noticed but were perhaps not to be expected in the flat, peneplain terrain of northeast Uppland.

5.3 Field reconnaissance

5.3.1 Escarpments

The most prominent of the fresh-looking escarpments and crevasses noted in connection with the aerial photo interpretation were field-checked. However, all these tentative candidates for young fault movement turned out to be more or less strongly glacially abraded, i.e. not late- or postglacial in age.

5.3.2 Sand and gravel pits

Altogether about 40 gravel and sand pits were visited. Of these, 11 displayed sandy-silty deposits regarded as susceptible to seismically induced liquefaction, but no liquefaction phenomena of any significance were notified. Strongly contorted and folded sequences of glacial clay were encountered at several localities, but the deformations were interpreted as a result of sliding. At a few localities, sandy-gravelly beds with a tendency to graded bedding were found to intercalate clay sequences. Sliding of clayey deposits as well as coarse sediment intercalating clay sequences later proved to be common phenomena along the gentle slopes of the eskers in the investigation area (see Section 5.4).

The gravel pit with the fault described by /Persson, 1985/ was visited but found to have been restored and no longer in operation. However, in another gravel pit, situated ca 1 km to the south along the Börstil esker, a more or less vertical fault was encountered. The origin of the fault is uncertain but settling of the sediments is probably the most likely interpretation, though a glaciotectonic origin cannot be ruled out as glacial till was found covering the glaciofluvial deposits. No sections with contorted clay sequences similar to those described by Sandegren (op cit) were encountered.

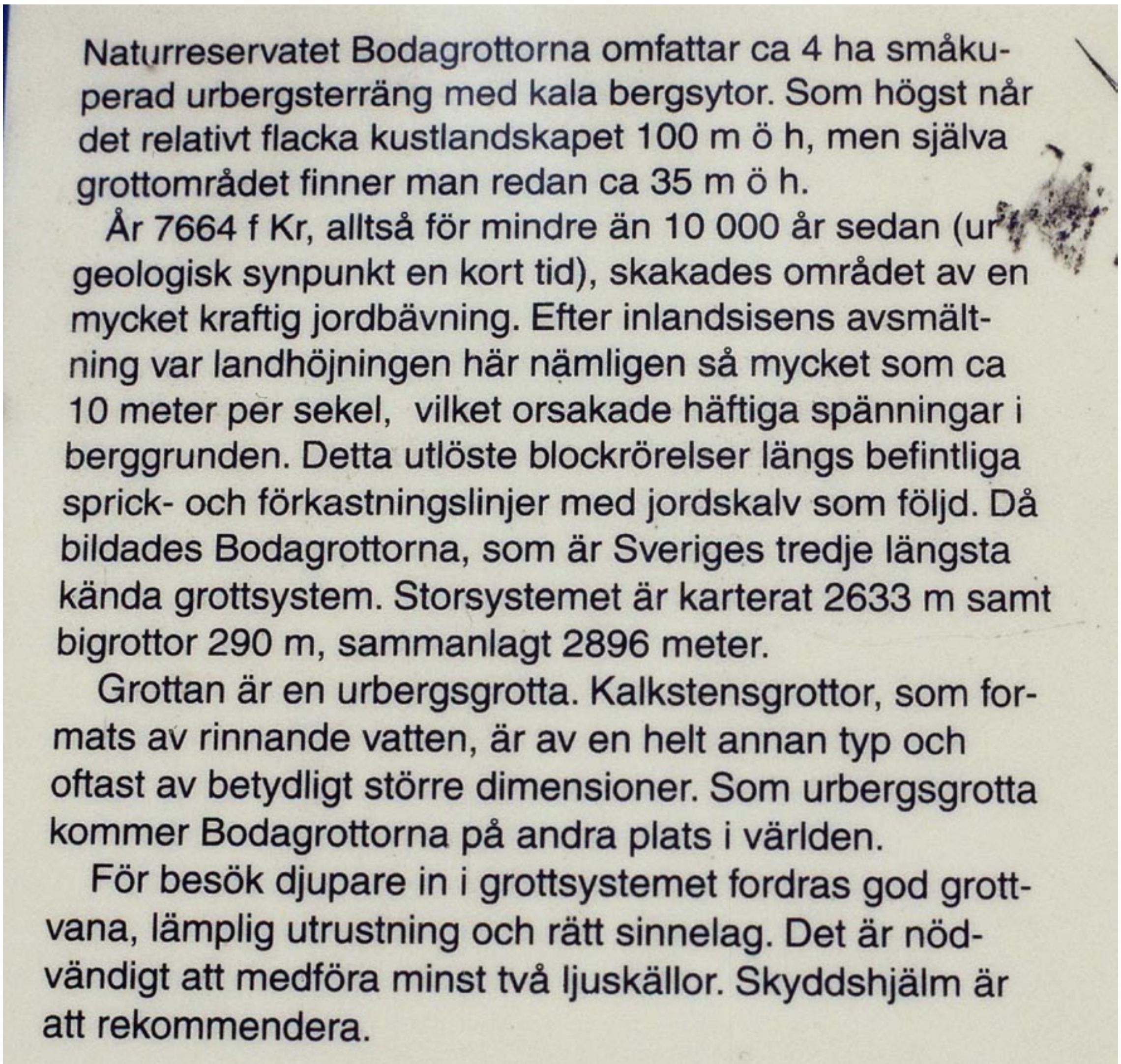
5.3.3 Bedrock fracturing and quarrying

In spite of quite extensive surveying of glacially polished bedrock exposures in the archipelago, no fracturing or dislocations of bedrock surface, tentatively indicating minor postglacial fault movements, were found. However, the occurrence of apparently fresh fractures in the bedrock surface at deep drilling site BP5 (Figure 5-1) and exploratory trenches LFM00810–11 within the candidate area indicated that this experience was not applicable to the investigation area as a whole. As it was considered important to establish whether the fracturing might be related to late- or postglacial tectonics, a thorough investigation programme of deep drilling site BP5 was undertaken, including documentation of the Quaternary deposits and glacial imprints on bedrock /Robertson, 2004; Lokrantz and Albrecht in Leijon, 2005/. The relationships between fractures, glacial striations, fracture infill and glacial sediments indicate that the fracturing occurred during a late stage of local deglaciation (Figure 5-2).

Figure 5-1. *Glacially smoothed and striated bedrock exposure at deep drilling site BP5 in the candidate area at Forsmark. Fresh looking fractures occur almost all over the exposure. The major fracture (foreground), lacking signs of being affected by glacial abrasion, was filled with laminated silty and fine sandy sediments.*

Figure 5-2. *Trench wall at deep drilling site BP5 displaying two different units of glacial deposits. The upper bed consists of a sandy till of typical appearance for the area, while the lower unit is characterized by a rich content of water-lain sand and silt. The sedimentary character of the lower unit, reaching roughly to the summits of surrounding bedrock obstacles, indicates deposition in a basal, water-filled cavity between ice and bedrock. The pollen (reworked) spectra of these sediments /Robertsson, 2004/ proved very similar to those of the silty infill of the major fracture (to the right in picture, cf Figure 5-1), indicating inward transport of sediment-bearing water into the bedrock fracture system. Provided that this interpretation is correct, it implies that the fractures developed prior to deposition of till but, as the fractures were not affected by glacial abrasion, during a late stage of the deglaciation.*

Intensely disrupted bedrock, forming masses of angular blocks with interstitial cavities, so-called "boulder caves", occur sporadically in Sweden. Not least among speleologists it is widely believed that these features have a postglacial seismotectonic origin, but credible evidence for this is generally missing. The concept of a "neotectonic" origin of the features is so generally cherished that it is sometimes proclaimed an official truth (Figure 5-3). *Bodagrottorna*, located near Iggesund in the province of Hälsingland, is the most impressive of the Swedish boulder caves (Figure 5-4). According to /Mörner, 2003/ the bedrock fracturing at Boda reflects a major palaeoseismic event in 9,663 BP according to the applied clay-varve chronology, i.e. well after local deglaciation. The deformation of the bedrock is attributed to the interaction of "shaking, rise and fall of the ground at the passing of seismic waves and methane venting" (Mörner, op cit). However, this imaginative process of massive bedrock disruption is hardly demonstrated elsewhere. Generally, sudden displacement and disruption of bedrock generates earthquakes, rather than the converse.



Naturreservatet Bodagrottorna omfattar ca 4 ha småkuperad urbergsterräng med kala bergsytor. Som högst når det relativt flacka kustlandskapet 100 m ö h, men själva grottområdet finner man redan ca 35 m ö h.

År 7664 f Kr, alltså för mindre än 10 000 år sedan (ur geologisk synpunkt en kort tid), skakades området av en mycket kraftig jordbävning. Efter inlandsisens avsmältning var landhöjningen här nämligen så mycket som ca 10 meter per sekel, vilket orsakade häftiga spänningar i berggrunden. Detta utlöste blockrörelser längs befintliga sprick- och förkastningslinjer med jordskalv som följd. Då bildades Bodagrottorna, som är Sveriges tredje längsta kända grottsystem. Storsystemet är karterat 2633 m samt bigrottor 290 m, sammanlagt 2896 meter.

Grottan är en urbergsgrotta. Kalkstensgrottor, som formats av rinnande vatten, är av en helt annan typ och oftast av betydligt större dimensioner. Som urbergsgrotta kommer Bodagrottorna på andra plats i världen.

För besök djupare in i grottsystemet fordras god grottvana, lämplig utrustning och rätt sinnelag. Det är nödvändigt att medföra minst två ljuskällor. Skyddshjälm är att rekommendera.

Figure 5-3. *Excerpt from a tourist information sign at Bodagrottorna, a so-called boulder-cave near Iggesund, province of Hälsingland. According to the sign, the cave system was created in connection with an earthquake in 7,664 BC, i.e. after deglaciation of the area.*

Figure 5-4. *Heavily disrupted bedrock at Bodagrottorna. An interstitial network of cavities in the mass of angular blocks forms the "boulder caves".*

A short visit to Boda clearly indicated that the mass of angular boulders here was slightly displaced in the ice flow direction and a couple of very large angular boulders were found a hundred metres away from the cave area (Figure 5-5). Further, several of the angular boulders in the main rock mass were stacked in an "imbricated" manner (inclined but not necessarily overlapping), likewise indicating impact of an overriding ice sheet. This pattern, dislocation in ice-flow direction and an "imbricated" appearance of the bedrock blocks, proved to be characteristic of several of the heavily disrupted bedrock occurrences found during reconnaissance (Figure 5-6). As at Boda, a field inspection of *Gillberga gryt*, in the southern part of the investigation area, indicated that angular boulders were transported a short distance to the southeast of the cave area, i.e. in the dominating ice flow direction. Thus, the fracturing probably pre-dates local deglaciation.

Figure 5-5. *One of several very large boulders located a hundred metres south of the main mass of blocks at Bodagrottorna.*

Figure 5-6. *Disrupted bedrock outcrop at Trollberget, some 10 km to the northeast of Uppsala (cf Figure 5-9). The rock fragments appear in an "imbricated" manner, something that was found during reconnaissance to be typical of many of the heavily broken bedrock outcrops. The consistent inclination of the glacially abraded block surfaces is interpreted to reflect impact of ice flow from right to left.*

Jointly for *Bodagrottorna, Gillberga gryt, Trollberget* and other occurrences of intensely fractured bedrock outcrops encountered during reconnaissance, is the association with a significantly increased boulder frequency in the surroundings (Figures 5-7, 5-8, 5-9). All disrupted bedrock outcrops found during reconnaissance proved to be located within or at the margin of areas extremely rich in glacially transported and deposited boulders. Furthermore, a brief look at the maps of Quaternary deposits in the area readily indicates an inverse relationship between the frequency of boulders on the ground surface and the occurrence of bedrock outcrops (Figures 5-7, 5-8, 5-9, 5-10). Glacially smoothed bedrock outcrops, that otherwise are so common in and typical of the region (Figures 5-12A, 5-14), are virtually absent from these areas so extremely rich in boulders. It seems evident that former bedrock knobs, and in some areas probably much of the superficial parts of the bedrock, are disintegrated and transformed into clusters of angular boulders (Figure 5-12B) or spread over the terrain to create fields of angular boulders (Figure 5-13).

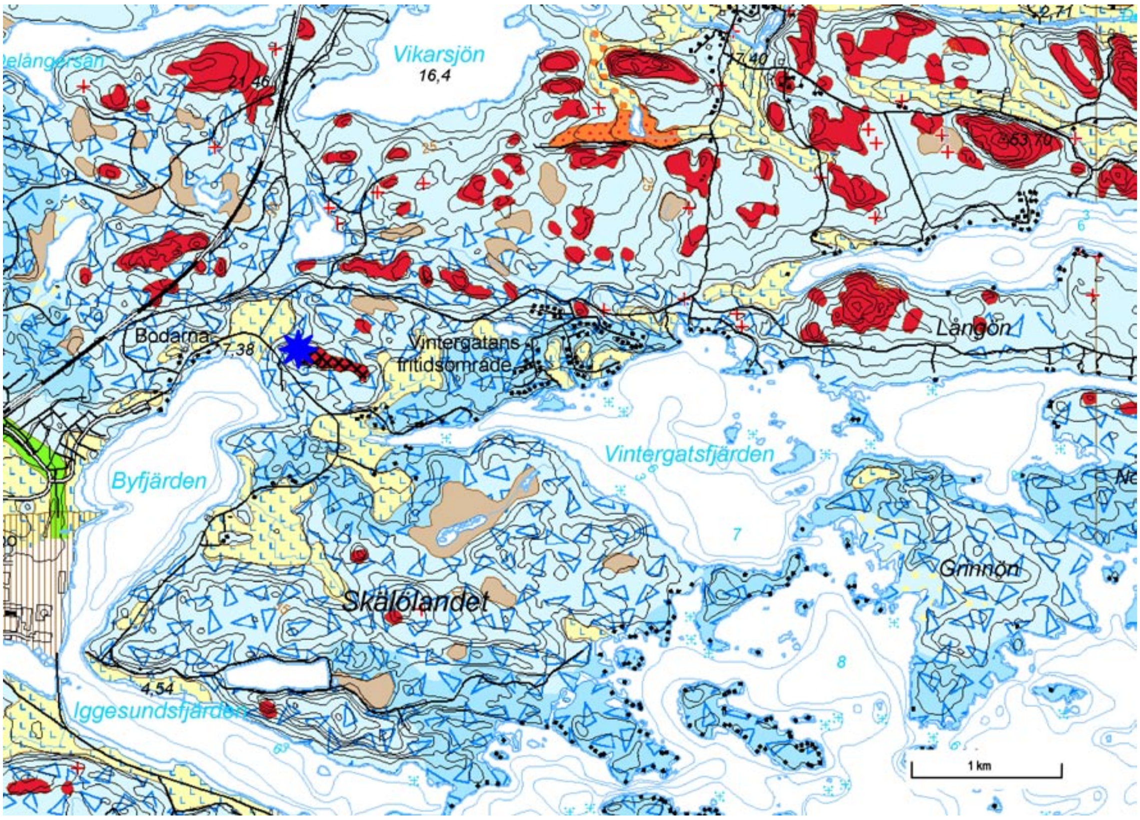


Figure 5-7. *Excerpt from Quaternary map Hudiksvall NV /Svedlund, 2002/. The heavily disrupted bedrock at "Bodagrottorna", marked by blue star, is located in an area of increased boulder frequency and very few outcrops. Outcrops in red, till in blue, peat deposits in brown and clay in yellow. High frequency of boulders is depicted by blue triangles.*

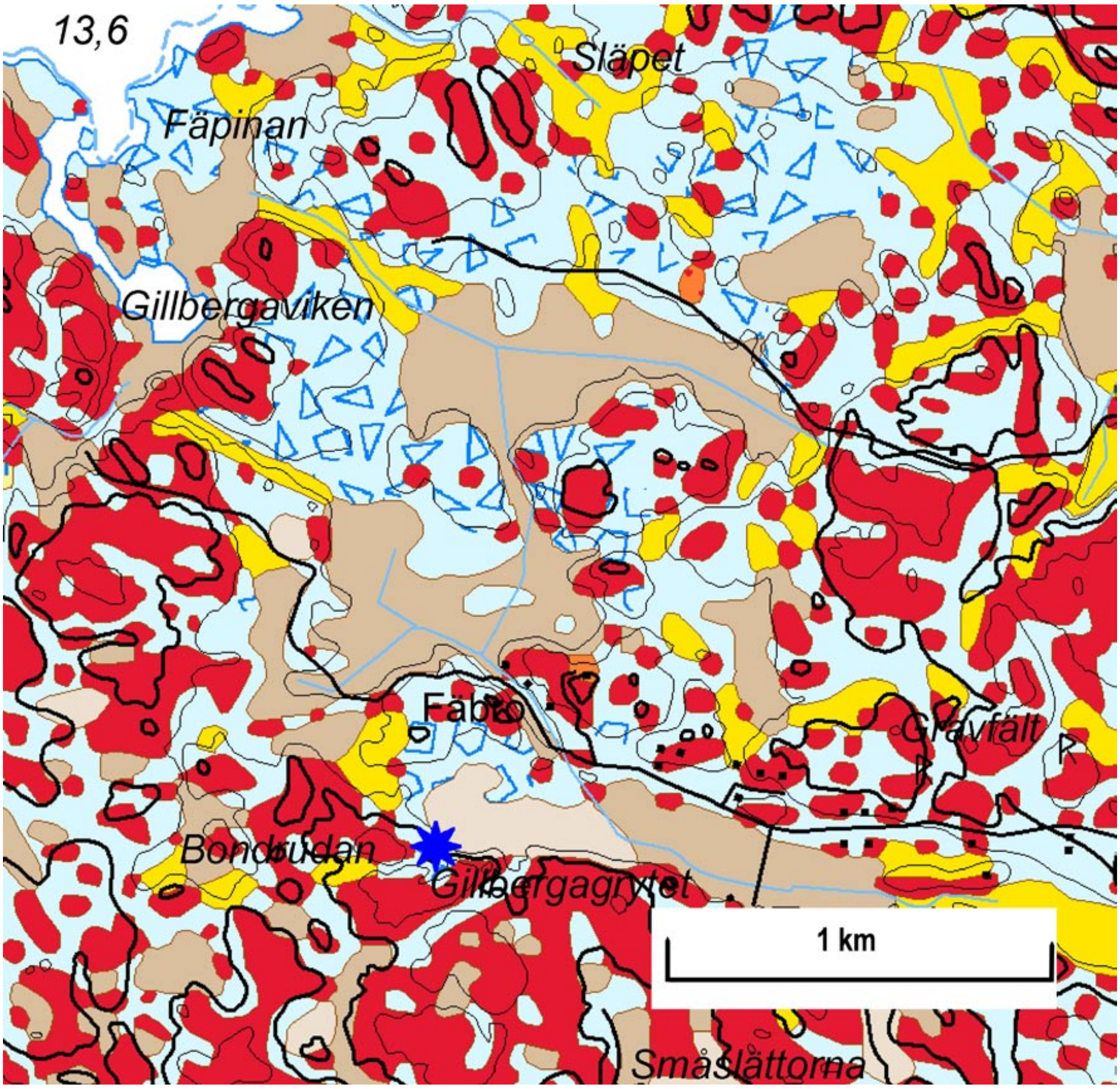


Figure 5-8. *Excerpt from Quaternary map Grisslehamn SV /Persson, 1990/. The disrupted bedrock at Gillberga gryt, marked by blue star, is located at southern margin of an area with increased boulder frequency. Outcrops in red, till in blue, peat deposits in brown and clay in yellow. Blue triangles or pentagons depict high frequency of boulders.*

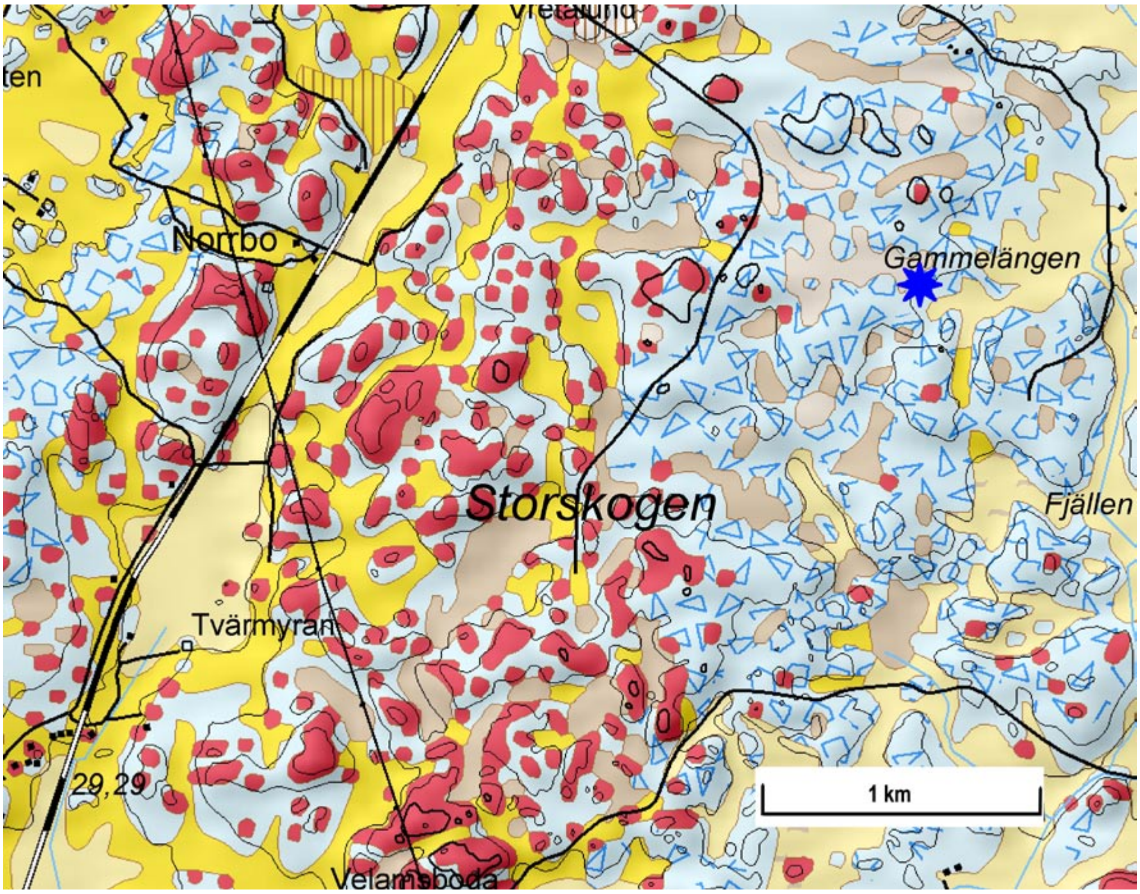


Figure 5-9. *Excerpt from Quaternary map Uppsala NV /Möller, 1993/. Blue star marks disrupted bedrock at "Trollberget" (cf Figure 5-6). Note the deficit of bedrock outcrops within areas of high boulder frequency, when compared with areas of moderate or low boulder frequency. Outcrops in red, till in blue, peat deposits in brown and clay in yellow. Blue triangles or pentagons depict high frequency of boulders.*

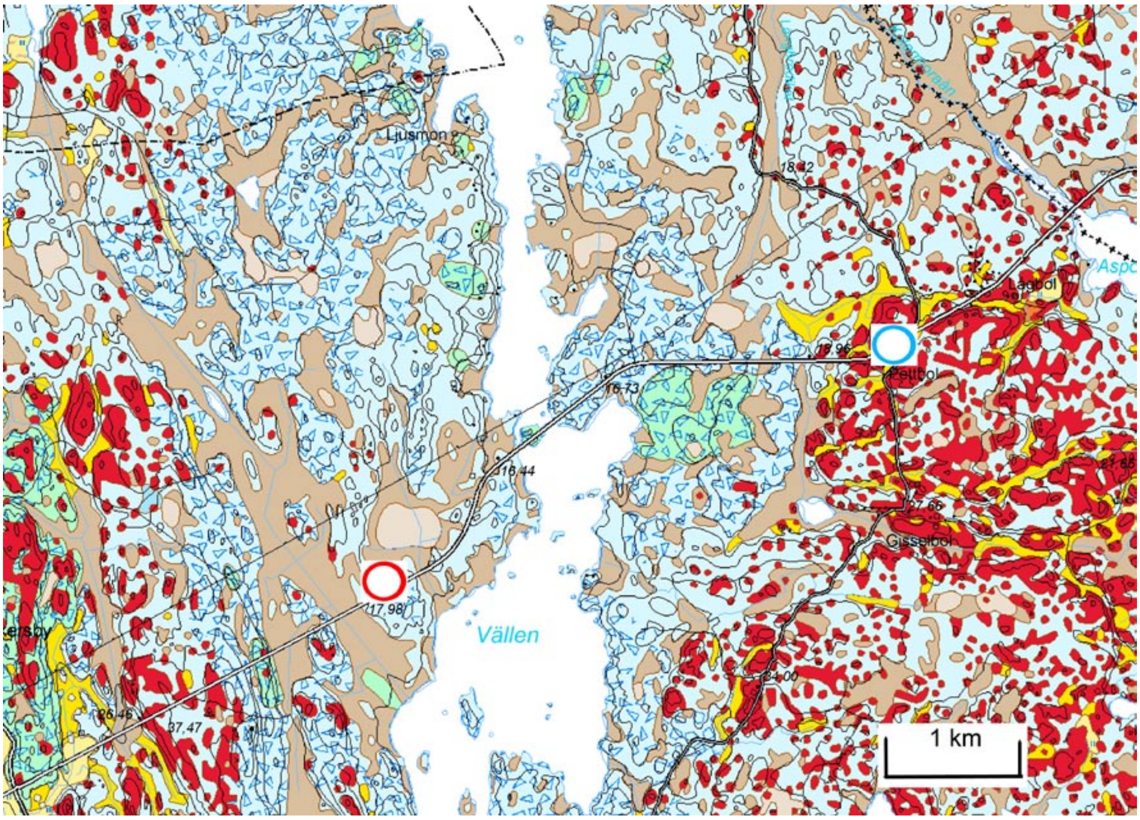


Figure 5-10. *Excerpt from Quaternary map Östhammar SO /Persson, 1988/. The character of the terrain and Quaternary deposits changes abruptly on both sides of Lake Vällen, along the road from Uppsala to Hallstavik. In the area of high boulder frequency surrounding Lake Vällen (Figure 5-13) there is an almost complete absence of bedrock outcrops, while immediately outside, glacially smoothed outcrops are very common (Figure 5-14). Photographs in Figures 5-13 and 5-14 are taken at red and blue circles respectively. The drastically increased boulder frequency appears to be independent of rock type (Figure 5-11). Outcrops in red, till in blue (sandy) or pale green (gravelly), peat deposits in brown and clay in yellow. Blue triangles or pentagons depict high boulder frequency.*

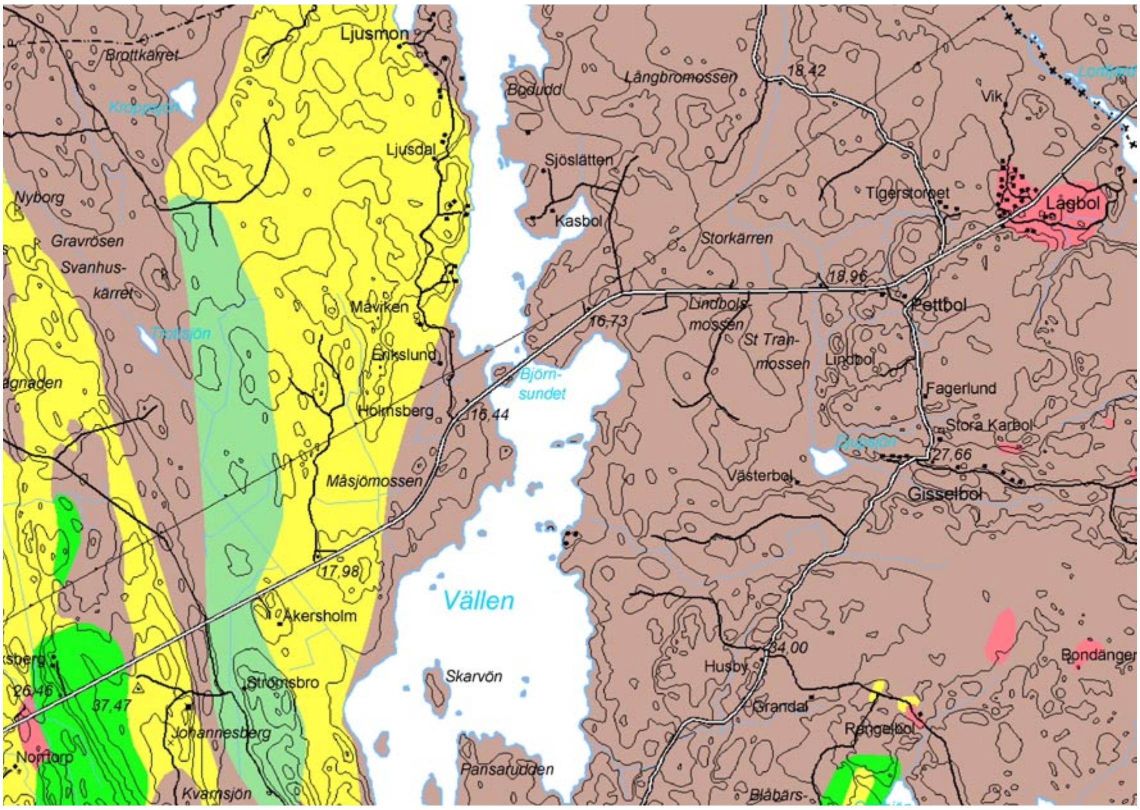


Figure 5-11. *Excerpt from the provisional regional map of bedrock geology Uppsala /Persson and Stålhös, 1991/. The figure shows the same area as Figure 5-10. Brown: granites-granodiorites. Red: young granites. Yellow: metavolcanics. Green: basic plutonites.*

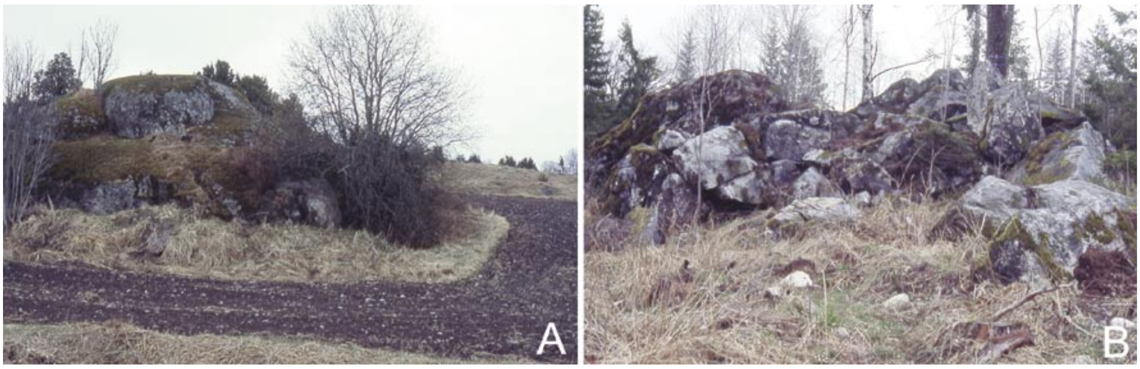


Figure 5-12. *Protruding and glacially smoothed outcrops (A) are typical of most of the investigation area but within or at marginal parts of areas with a significantly increased boulder frequency they are often found to be disrupted and transformed into clusters of bedrock blocks (B).*

***Figure 5-13.** High frequency of superficial angular boulders west of Lake Vällen (cf Figure 5-10). Practically all of the boulders belong to the same rock type and are most probably of local origin.*

***Figure 5-14.** Glacially smoothed bedrock exposure at Pettbol, 2 km east of Lake Vällen (cf Figure 5-10). Only a few boulders occur in the surrounding terrain (the rubble in the foreground is artificial fill along the roadside).*

5.4 Stratigraphical investigations

In 2002 and 2003 the stratigraphical investigations were concentrated to the flanks of the Börstil esker to the southeast of the Forsmark candidate area (Figure 4-1). The results of this study were reported earlier in /Lagerbäck et al. 2004/ and are only briefly summarized here. Deposits of loosely packed sand or coarse silt covered by clayey beds were encountered in almost all of the trenches. Despite favourable conditions, no significant features related to dewatering or liquefaction were noted in any of the trenches (Figure 5-15). The most remarkable observation was the discovery of extensive and repeated sliding down the very gentle slopes of the esker. Evidence of sliding or folding was encountered in almost all of the trenches. Slabs of clayey or silty deposits were found to have detached along planar failures parallel to the bedding and then slid down slopes to cover previously deposited sediments. The slide deposits varied from plates of more or less undisturbed sediments (Figure 5-16) to strongly folded sequences (Figure 5-17) or a chaotic mixture of all kinds of sediments without any primary sedimentary structures preserved (Figure 5-18). In some of the sections there was evidence of at least three episodes of sliding separated by erosional events or by periods of undisturbed sedimentation. No regional north-south divergence along the esker was indicated concerning the character or extent of sliding.

Figure 5-15. *Typical of the stratigraphy along the Börstil esker, this trench section at Östansjö (E8 in Figure 4-1) shows a bed of loosely packed fine sand and coarse silt covered by a bed of clay-laminated silt. The uppermost 0.4 m consists of cultivated topsoil. Extended excavation revealed loosely packed and saturated glaciofluvial sand to a depth of at least 5 m. Although the stratigraphy is considered to be highly susceptible to liquefaction, no deformations related to seismically induced liquefaction were found here or elsewhere along the Börstil esker.*

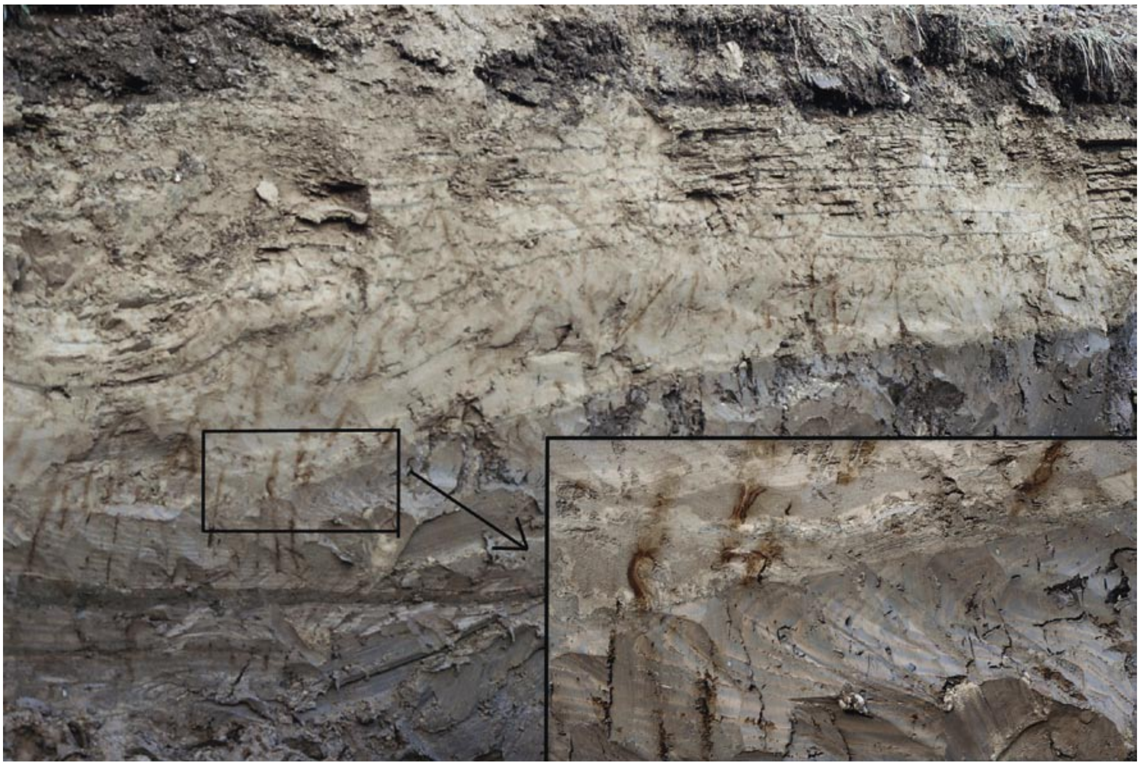


Figure 5-16. *Illusory stratigraphy due to graceful sliding at Örnäs (E7 in Figure 4-1). An almost undeformed slab of thick-varved, sandy silt (light coloured with thin, dark layers of clay) has come to rest on varved glacial clay. The uppermost bed consists of cultivated topsoil rich in pebbles and cobbles. The close-up photo (lower right-hand corner) shows the slip surface with drag folds in the upper parts of the clay.*

Figure 5-17. *Gently folded silt and fine sand at Östansjö (E8 in Figure 4-1).*

Figure 5-18. *Chaotically mixed slide deposits of fine sand, silt and glacial clay at Hultet (E3 in Figure 4-1).*

It was not possible to accurately date the sliding in any of the trenches and, accordingly, we could not establish any synchronism of events between the different sites. The so-called "spot zone", a sequence of thin-varved glacial clay characterized by a rich content of limestone fragments, was included in the slide deposits in several of the investigated trenches. According to /Strömberg, 1989/ this clay was deposited while the receding ice sheet rapidly melted away from the southern part of the Bothnian Sea. Most of the clay involved in the sliding was clearly varved and probably of glacial origin. Thin-varved clay, or clay without any visible varves, occurred in a few sections but unmistakable postglacial clay was not found either in slide deposits or undeformed on top of these. It appeares that sliding occurred on several occasions during the early postglacial period, whereas there was no evidence of this in any later episodes.

Substantial deposits and, consequently, relevant information was found to be missing due to erosion. Erosional unconformities, most likely indicating bottom currents in the ancient sea, occurred between some of the stratigraphic units in several of the sections. Furthermore, in most of the sections the uppermost stratigraphic unit consisted of a thin sandy or gravelly layer, with erosional unconformity with underlying deposits. Also in sections where this layer of coarse-grained sediments was missing, there was good evidence of very intense surficial erosion, as bedding as well as deformational structures were discordantly cut at ground surface (Figure 4-6). This very intense erosion was found to occur not only in places exposed to the waves of the erstwhile sea but also in sheltered places in the terrain, indicating that strong bottom currents (rather than wave-washing) were responsible for the erosion as well as deposition of coarse-grained sediments.

Complementary information about this phase of intense erosion and deposition of coarse-grained and regionally distributed sediments was obtained by coring at four sites around Hallstavik (C 1–4 in Figure 4-1). At all four sites a chiefly sandy layer, 10–100 cm thick, was found to separate typical postglacial gyttja clay from glacial clay. At one of the sites there was coarse sand throughout, at two of them the sediments displayed graded bedding, fining upwards from gravely sand to coarse silt, while at the fourth site the sequence contained not only sand and gravel but also richly shell-bearing sand and a thin layer of clay. The rich content of shells in this sequence indicates that the sedimentation at this site occurred in rather shallow water during a late stage of the Holocene.

In 2004 the stratigraphical investigations were geographically extended to include 29 trenches at nine excavation sites, all but one (E9) situated along the Västland, Vattholma, Uppsala and Enköping eskers (Figures 4-2 and 4-3). One of the previously investigated sites along the Börstil esker (E7 in Figure 4-1) was reinvestigated as well. The overall length of the trenches measured some 340 m. Deposits of loosely packed glaciofluvial sand or coarse silt, covered by clayey beds, were encountered in almost all of the trenches. While the excavation sites along the Börstil esker are situated no more than 5–20 m above the present sea level and, consequently, were entirely waterlogged from the moment of deglaciation until they were raised above the sea fairly recently, some of the sites investigated in 2004 are situated significantly higher (close to 80 m) and, accordingly, were raised above the sea at an earlier stage. However, a present-day high groundwater table in many of these sections means that the deposits remained largely susceptible to liquefaction throughout the Holocene.

Evidence of sliding was encountered in trenches along the Västland esker at Skärmarbo (E10) and Välaängarna (E11), along the Vattholma esker at Salsta (E13) and along the Uppsala esker at Torkelsbo (E15). These slide deposits differed from those encountered along the Börstil esker as they were to a greater degree dominated by clay and less contorted. Underlying sandy-silty sediments were only occasionally involved in the sliding (Figure 5-19).

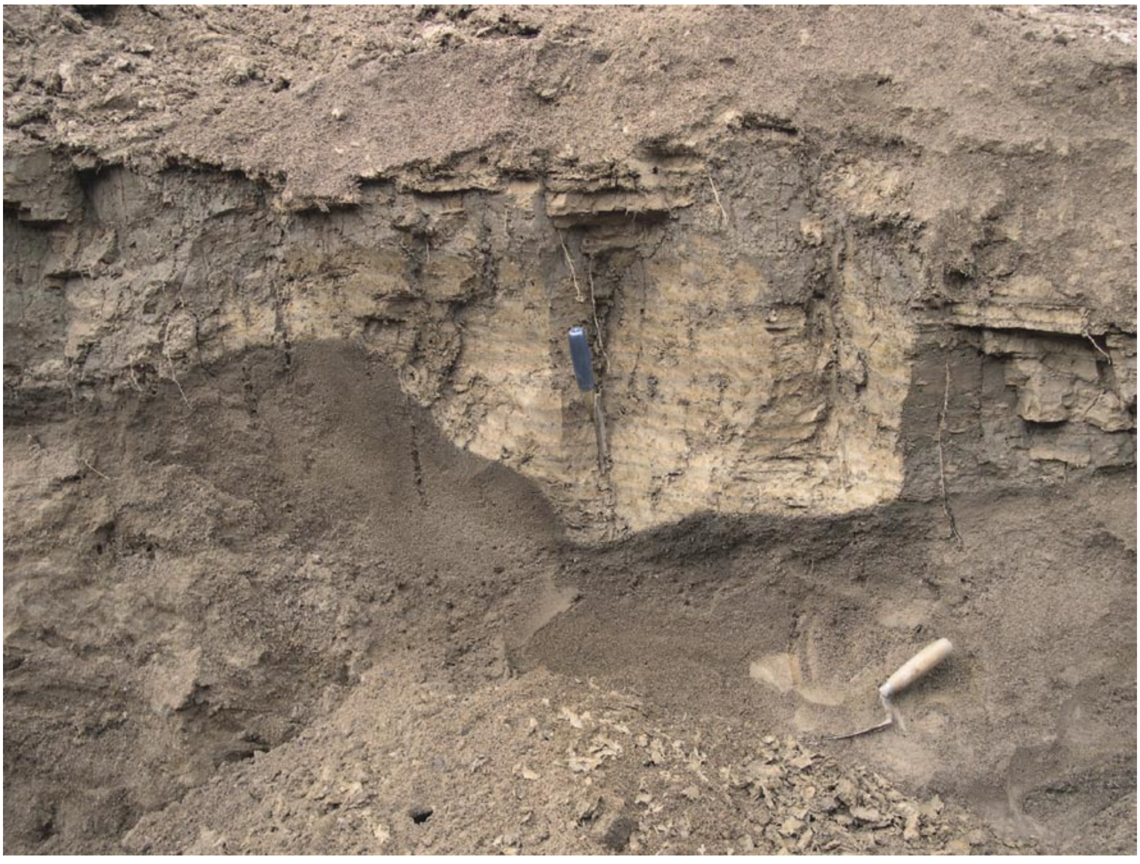


Figure 5-19. *Slide deposits of non-folded glacial clay in uneven contact with underlying sandy sediments at Salsta (E13 in Figure 4-3). The dark-coloured layer along the slide surface beneath the clay is a mixture of sand and clay.*

As in several of the sections along the Börstil esker, the glacial clay was significantly eroded at several sites. On the eastern side of the tiny Västland esker at Skärmarbo (E10), a substantial part of the glacial clay sequence is missing and the remaining thick-varved clay was discordantly cut along a perfectly flat surface (Figure 5-20). On top of this erosional unconformity was a thin layer of gravel, containing occasional cobble-sized clasts, followed by about 1 m of fine, homogeneous and structureless sand reaching to the ground surface (Figure 5-21). The stratigraphy in two trenches excavated on the western side of the esker differed significantly. The glacial clay sequence here was found to be more or less intact and contained thin-varved glacial clay as well as "spotted clay" (Figures 5-22 and 5-23). Clayey slide deposits and a topmost thin layer of gravel covered the clay sequence, but the fairly thick sand bed found on the eastern side of the esker was missing.

Although loosely packed sandy or coarse silty deposits were present at almost all of the investigated sites, significant features possibly related to water escape structures or liquefaction were noticed only at two of them. At Torkelsbo (E15 in Figure 4-3) along the Uppsala esker major water escape structures were encountered in one of the trenches. Sand-filled pipes, emanating from glaciofluvial sand at depths, were cutting through several metres of fine-sandy, silty and clayey deposits and upwards forming a 17 m wide and 3 m thick, funnel-shaped filling of sand near the ground surface (Figures 5-24 and 5-25). The truncated, fine-sandy, silty and clayey deposits were in places chaotically contorted and the injected sand contained lumps of silt and clay.

Figure 5-20. *Straight-lined erosional contact between discordantly cut thick-varved glacial clay and sand on the eastern side of the esker at Skärmarbo (E10 in Figure 4-2).*

Figure 5-21. *A thin layer of gravel, occasionally containing cobble-sized clasts, separates the eroded glacial clay from covering fine sand on the eastern side of the esker at Skärmarbo (cf Figure 5-20)*

Figure 5-22. *A well-preserved sequence of thin-varved glacial clay and "spotted clay" encountered beneath clayey slide deposits on the western side of the esker at Skärmarbo.*

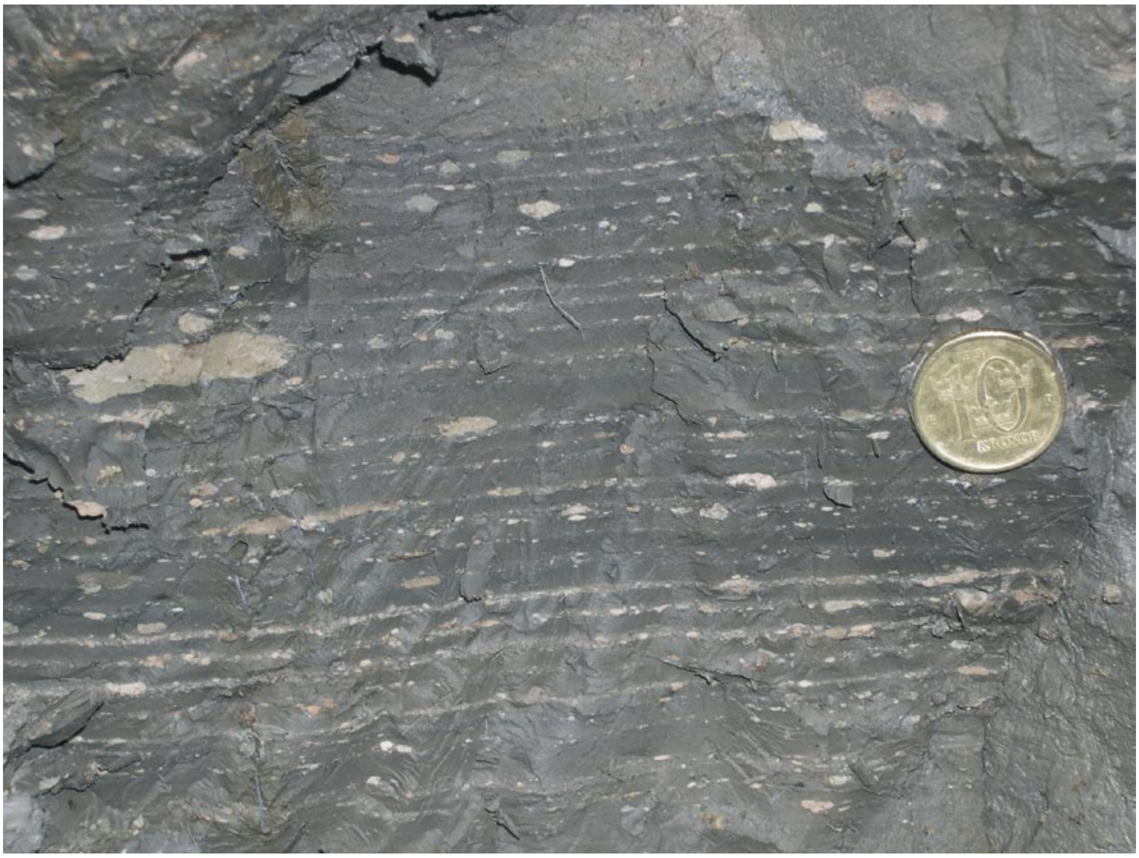


Figure 5-23. *Close-up of the "spotted clay", a dark-coloured thin-varved glacial clay characterized by a rich content of limestone fragments, in a trench at Skärmarbo. These fragments, spots, are concentrated to the surfaces of each clay lamina, giving the clay a banded or striped appearance.*

Figure 5-24. *Water-escape structures in the form of sand-filled pipes cutting through several metres of fine-sandy and silty deposits in a trench at Torkelsbo (E15 in Figure 4-3). The virtually vertical sand-filled tubes, as seen on the trench floor, are interpreted to reflect a sudden release of pressurized pore water and liquefied sand from the sandy glaciofluvial deposits below the fine-grained sediments.*

Figure 5-25. *The southern part of the funnel-shaped sand filling at Torkelsbo. The folded fine-grained glacial sediments show an eroded, jagged contact against the densely packed sand.*

These features obviously reflect a massive release of pressurized pore water in the glaciofluvial sand, trapped by the covering of fine-grained and less permeable deposits. The site is located at the margin of the locally widened and very impressive esker and the amount of sand expelled indicates a major source of water. Seismically induced compaction – or purely gravitational settling – of the glaciofluvial deposits may have resulted in a sudden increase in pore-water pressure and expulsion of water, but puncturing of an artesian aquifer in the clay-draped deposit during or after land-upheaval is perhaps an alternative. The sand-filled funnel was partly covered by silt and clay of doubtful origin and it was not possible to accurately date the event relatively to sediment stratigraphy.

Unmistakable liquefaction features were encountered in a trench at Runhällen (E17), excavated in a sand pit situated along the Enköping esker (Figure 4-3). Convolute bedding, ball-and-pillow structures and dense, structureless sand and silt occurred in otherwise current-bedded silty and fine-sandy sediments resting on glaciofluvial sand (Figures 5-26 and 5-27). The nature of the distorted and compacted deposits may indicate a seismic origin but, being an isolated occurrence, alternative explanations for the features may exist. Due to exploitation of the sand pit, some 2–3 m of glaciofluvial sand was missing from the top of the deformed sequence, but nearby walls cut in these deposits displayed cross-bedded sand free from disturbance.

Figure 5-26. *Convolute bedding, with ball-and-pillow structures and pseudo-nodules, in densely packed fine-sandy and silty sediments of glacial origin at Runhällen (E17 in Figure 4-3). The deformations are interpreted as possible effects of earthquake-induced liquefaction and dewatering.*

Figure 5-27. *Close-up on pseudo-nodules at Runhällen. Erosional contact with overlying deposits indicates that the deformation is synsedimentary, i.e. occurred close to the receding ice sheet.*

5.5 Summary and discussion

No morphologically conspicuous lineaments or escarpments of any significance, i.e. possible candidates for late- or postglacial faulting, were noticed in connection with aerial photo interpretation. However, there are reasons why fault movements of moderate magnitude may easily escape detection after being subjected to post-movement erosion or sedimentation during land upheaval. Thus, the searching for evidence of recent faulting cannot rely merely on morphological expressions in the ground surface, but should also consider any secondary, seismically generated effects of faulting.

The stratigraphic investigations were focused mainly on seismically induced liquefaction phenomena. Although deposits susceptible to seismically induced liquefaction were encountered in most of the investigated sections along the eskers in the investigation area, liquefaction features or water escape structures of any significance were noted in only two instances. A seismic origin of the major dewatering features at Torkelsbo cannot be excluded, but there are alternative explanations for their formation. Likewise the liquefaction features at Runhällen may have a seismic origin but so far they occur isolated in the southwesternmost part of the investigation area. Whatever the explanation, it is excluded that any of these isolated features reflects a major or great earthquake in the vicinity of Forsmark, as no significant liquefaction phenomena were encountered along the much more closely situated Börstil esker.

A comparison with areas in similar geological settings elsewhere, where the relationship between major fault movements and secondary, seismically induced deformations has been studied, may be of some interest. Early postglacial faulting in the Lansjärv area in northern Sweden, generating an earthquake with a magnitude estimated to ~ Mw 7.8 /Muir Wood, 1993/, resulted in a great variety of deformations of the Quaternary overburden /Lagerbäck, 1990/. In the Burträsk area, likewise in northern Sweden, a fault of somewhat smaller magnitude was associated with extensive deformation of late-glacial sediments /Lagerbäck and Sundh, unpublished/. Laterally persistent and regionally distributed liquefaction features exist very frequently in both of these areas. The fact that no such features whatsoever were found in the trenches along the Börstil esker appears to exclude major postglacial earthquakes in the vicinity of Forsmark.

On the other hand, there is evidence of surprisingly extensive sliding down very gently sloping terrain along the Börstil, Västland and Vattholma eskers. It has not been possible to accurately date the individual sliding events but, based on the occurrence of the so-called spot zone clay and deglaciation chronology /Strömberg, 1989/, it appears that the most intense sliding occurred at least several hundred years after local deglaciation. Settling and dewatering of underlying glaciofluvial deposits provide a reasonable explanation of the extent of the sliding. Excess of pressurized pore water in glaciofluvial sand and coarse silt, trapped by the fine-grained and less permeable covering beds, may have triggered and facilitated sliding by lubrication. It is not evident if settling, dewatering and sliding occurred spontaneously due to loading alone, or whether the phenomena were triggered by the influence of any external factor. There is no evidence of simultaneous sliding at the investigated sites, something that would indicate influence of external forces, e.g. earthquakes, but nor can this alternative be excluded.

Hypothetically the sliding may have been triggered by moderately strong earthquakes in the vicinity or by more distant earthquakes of greater magnitude. However, if triggered by earthquakes in the Forsmark area, evidence of more intense effects would be expected along the northern than along the southern parts of the Börstil esker. The northernmost trenches are situated only a few kilometres away from the candidate area, whereas the distance to the southernmost is some 30 km. No such zonation is indicated in the trenches investigated.

In most of the investigated trenches, the upper parts of the sediment sequences appeared to be strongly eroded before the sites were raised above sea level. Typical postglacial clay was not found at any of the sites, whereas evenly spread sand or gravel, with a marked erosional unconformity with underlying deposits, occurred in the ground surface at most of them. It is conceivable that this sand and gravel correspond to the sandy or gravelly layer separating the postglacial clay from the glacial clay at the coring sites. A distinct sandy layer between glacial clay and overlying postglacial clay is a known characteristic element of the sediment stratigraphy in the region /e.g. Grånäs, 1985; Hedenström and Risberg, 2003/.

Erosional unconformity accompanied by a laterally persistent layer of coarse-grained sediments, occurring not only in places exposed to the waves of the ancient sea but also in sheltered places in the terrain, indicates that strong currents rather than wave-washing were responsible for the erosion and deposition /cf Persson, 1985/. Currents of this magnitude, capable of transporting pebbles and cobble-sized clasts, appear to be an unexpected phenomenon in this type of environment. According to /Brydsten, 1999/ the prevailing opinion among oceanographers is that the orbital motion of waves is the most significant resuspension process, while currents are the most important process for the transport of already suspended particles. However, field evidence strongly suggests that much of the former clay was remobilized as the result of corrasion by sand and gravel carried as bedload in bottom currents. The scattered distribution of minor glacial clay deposits in sheltered positions, particularly in the eastern parts of the investigation area (see e.g. Figures 5-8 and 5-28), indicates that practically all of the glacial clay, once deposited, was worn away. A similar conclusion was drawn by /Hedenström and Risberg, 2003/ who suggested that the flat topography of northern Uppland, in combination with strong currents, resulted in erosion and transport of fine-grained particles towards the deeper parts of the Baltic basin.

Together with sliding, this erosion at the bottom of the ancient sea resulted in an extensive redistribution of sediments and in a substantial levelling of the terrain. It is strongly emphasized that geological development on the floor of the ancient sea was obviously complicated and is by no means fully understood. Due to the very extensive erosion, important pieces of information about the geological course of events are forever lost, or at least very difficult to retrieve. The excavations have probably elicited no more than fragments of the relevant information needed for a more comprehensive understanding of what took place at the bottom of the ancient sea.

The discovery of freshly fractured bedrock at deep drilling site BP5 and exploratory trenches LFM00810–11 within the Forsmark candidate area raised the question of the origin and significance of the features. The subsequent finding of principally identical, sediment filled fractures near Björklinge in the southern part of the investigation area /Lokrantz, 2004/ indicate that the features are not unique for the Forsmark area. The relation between the disrupted bedrock at *Gillberga gryt, Trollberget, Bodagrottorna*, etc, and the frequency of boulders on the ground may have some relevance for our understanding of the phenomenon. The extreme abundance of glacially transported boulders in the vicinity of these intensely fractured and somewhat displaced bedrock exposures spontaneously indicates a causal relationship between the fracturing and the massive production of angular boulders. Whereas *Bodagrottorna, Gillberga gryt* and *Trollberget* are located within or at marginal parts of areas of high boulder frequency, deep drilling site BP5 and trenches LFM00810–11 are located at some distance (Figure 5-28). The spatial and temporalrelationships between all these phenomena suggest that *Bodagrottorna,*

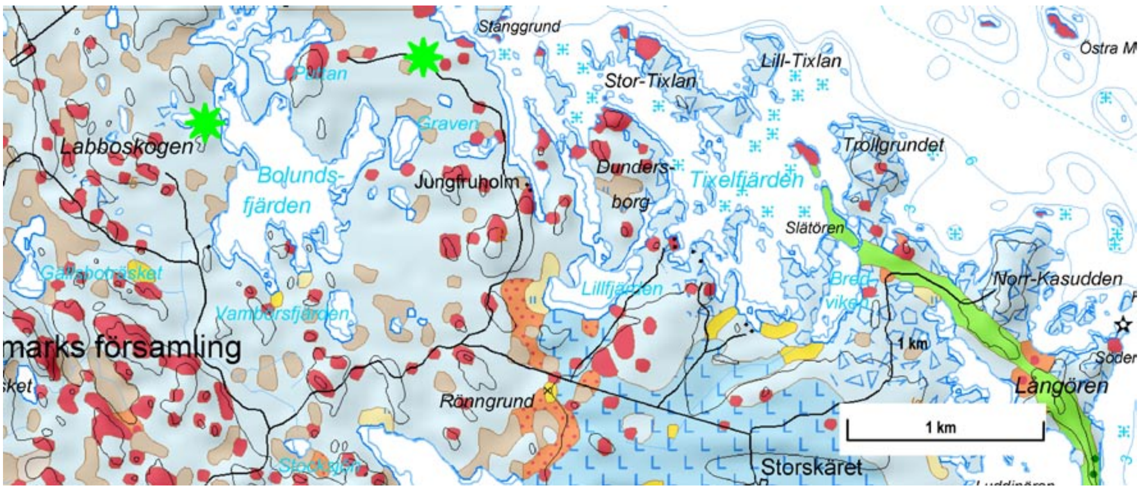


Figure 5-28. *Excerpt from the Quaternary map Östhammar NO /Persson, 1985/. Green stars mark observations of fresh looking fractures in bedrock at deep drilling site BP5 (left) and exploratory trenches LFM00810–11 (right). The sites are located west of an area with numerous angular boulders, most likely reflecting an intense quarrying of the local bedrock. Outcrops in red, till in light (sandy) or dark (clayey) blue, glaciofluvial deposits in green, peat deposits in brown, sand in orange with red dots, and clay in yellow. Blue triangles or pentagons depict high frequency of boulders.*

Gillberga gryt and *Trollberget* represent an intermediate stage of a process of locally strongly enhanced late glacial rupturing and quarrying, while the fracturing found at BP5 and LFM00810–11 represent an initial, immature stage in peripheral positions.

The process, or rather processes, of plucking appears to be enigmatic and a variety of different mechanisms have been suggested /e.g. Robin, 1976; Röthlisberger and Iken, 1981; Iverson, 1991; Hallet, 1996/. The stereotype for the plucking process is when blocks of rock are loosened, detached and carried away by the ice from the lee-side (relatively to ice-flow) of a bedrock obstacle. Field evidence certainly speaks in favour for this principal process, as asymmetrical bedrock mounds (*roche moutonées*) with gently sloping, smoothly abraded and striated stoss-sides and steep and rough lee-sides are very common. However, this one-by-one production of boulders is hardly relevant for the massive quarrying of bedrock that has occurred in parts of the investigation area or elsewhere. The extremely high frequency of only shortly transported boulders, in close association with completely disrupted and slightly dislodged outcrops, rather indicate a massive detachment of boulders during a very short and late phase of the deglaciation. Field evidence clearly indicates that significant parts of the superficial bedrock, previously protruding bedrock knobs included, were disrupted and transformed into sheets of boulders (Figure 5-13).

The scattered distribution of the boulder-rich till occurrences does not indicate any relation to linear tectonic features (faults etc) in the bedrock. Nor does there appear to be any definite connection with any particular rock type, but a dependence on bedrock properties cannot be ruled out. Very likely, pre-glacial joints and sheeting may to some extent have governed the intense quarrying but the observations at BP5 and LFM00810–11 indicate that the inland ice sheet was capable of producing new fractures as well. The association with the deglaciation phase suggests that the main factors responsible for the fracturing and intensified quarrying should be sought in terms of changes in the ice-induced stress pattern in surficial parts of the bedrock near the margin of the receding inland ice sheet. It is beyond the scope of this study to speculate on glaciological processes but, as quarrying is of crucial importance for our understanding of and rate of erosion by ice sheets during glaciations, it is suggested that the matter should be the subject for further research.

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