P-06-160

Oskarshamn site investigation

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

Results from 2005

Robert Lagerbäck, Martin Sundh,
Sven-Ingemund Svantesson
Geological Survey of Sweden (SGU)

September 2006

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

ISSN 1651-4416
SKB P-06-160

Oskarshamn site investigation

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

Results from 2005

Robert Lagerbäck, Martin Sundh,
Sven-Ingemund Svantesson
Geological Survey of Sweden (SGU)

September 2006

Keywords: P-06-160, Late- or postglacial faulting, Earthquake, Quaternary deposits, Seismically induced liquefaction.

Abstract

Complementary reconnaissance of one of the most prominent, probably fault related escarpments identified in the mainland part of the investigation area revealed that the vertical cliff was so severely weathered that a late- or postglacial age of the feature is deemed unlikely. There are similar escarpments in several places in this part of the area, but as glacial erosion during the Quaternary was very modest here, these features may very well have survived several glaciations. Field reconnaissance of some minor sheers in the archipelago, identified in aerial photographs, suggested that the features are generally the result of glacial plucking, governed by vertical joints and sheeting, and not to faulting

Stratigraphical investigations in machine-dug trenches were carried out at 11 localities within the investigation area. 41 trenches with a total length of some 570 m were excavated along the flanks of eskers or other types of glaciofluvial accumulations. Several of the encountered stratigraphies were unexpected. At several sites, sandy-silty deposits, usually occurring between the glaciofluvial gravel and overlying glacial clay, were missing. At some of the sites, fairly thin-varved clay rested directly on gravel. The most remarkable observation, however, was the occurrence of a till-like, diamict bed covering glacial sandy-silty sediments in many of the trenches. At some of the sites a diamict bed also covered fairly thick glacial clay. Similar sequences were also observed during previous reconnaissance of sandpits, but not during the excavations in 2004 along the Fårbo esker where more typical stratigraphies were encountered.

Judging by their appearance, the diamict deposits could readily be interpreted as till beds composed of reworked local sediments. Alternative processes for the formation of the diamictons, e.g. subaqueous slumping or debris flowage, are possible perhaps, but it is difficult to imagine how very coarse deposits like gravel and minor boulders could detach from the slopes of the eskers and integrate with the fine-grained matrix material. If these diamict beds are of glacial origin, their frequent presence in the investigation area implies that short standstills or minor oscillations of the ice margin during the latest deglaciation can scarcely explain the stratigraphies encountered. Rather, several of the eskers – and many of the other glacial deposits in the region – may derive from a previous glaciation and escaped obliteration by the last ice sheet. This interpretation is not consistent with current opinion on the glacial geology of the area and should in the present state of knowledge be regarded as speculation only. However, the matter may have relevance for the question at issue; if deposited during a previous deglaciation, the sandy-silty sediments have had the capacity to register earthquakes, or lack of earthquakes, not only during the present but also during a previous ice-free period.

Although deposits of loosely packed sand and coarse silt were still present in many of the trenches, no deformational features unambiguously related to earthquakes were noticed. Sand injections, hypothetically seismically induced, were encountered at one of the sites, but as they occurred in connection with fold structures the features may equally well have been caused by sliding or glaciotectonics. However, as several of the investigation sites are located fairly high above present sea level, this means that they were lifted above sea level shortly after sedimentation and, thus, were saturated and susceptible to liquefaction during only a short period.

Sammanfattning

Kompletterande rekognosering av ett längre, sannolikt förkastningsorsakat, berggrundshak i den västra delen av undersökningsområdet visade att den lodräta klippväggen var mycket starkt vittrad. Detta talar emot att haket bildats i samband med förkastningsrörelser under sen- eller postglacial tid. Ett flertal liknande berggrundshak förekommer inom fastlandsdelen av undersökningsområdet, men eftersom den sammanlagda glacialerosionen under kvartärtiden varit mycket svag inom regionen kan de mycket väl ha överlevt flera nedisningar. I samband med tidigare genomförd flygbildstolkning noterades också ett antal helt korta men markerade berggrundshak i skärgårdsområdet. Några av dessa besöktes och bedömdes huvudsakligen ha uppkommit genom glacial plockning som styrts av bankningsplan och vertikala sprickor. På någon plats har sannolikt kraftig vågverkan eller isskjutning, eventuellt i kombination med frostsprängning, bidragit till utbildandet.

Stratigrafiska undersökningar genomfördes i maskingrävda schakt på 11 platser inom den östra delen av undersökningsområdet. De 41 schakten hade en sammanlagd längd på ca 570 m och grävdes i flack terräng längs åsar eller invid andra isälvsavlagringar. De påträffade lagerföljderna bjöd på flera överraskningar. På flera platser saknades de sandiga och siltiga sediment som normalt förekommer mellan isälvsgrus och ovanpåliggande glaciallera och leran vilade i stället relativt tunnvarvig direkt på gruset. Den mest anmärkningsvärda observationen var emellertid att en diamikt, moränliknande, bädd påträffades på de glaciala sedimenten i många av schakten. På flera av grävplatserna överlagrade den diamikta bädden även relativt mäktig glaciallera. Liknande lagerföljder påträffades redan i samband med tidigare rekognosering av sand- och grustäkter, medan däremot grävningarna 2004 längs Fårboåsen uppvisade mer triviala lagerföljder.

Av utseendet att döma kan de diamikta bäddarna mycket väl utgöras av morän, sammansatt av material som tagits upp från de lokala sedimenten. Alternativa förklaringar, som skred och slamströmmar från de intilliggande åsslutningarna, är svårare att föreställa sig, bl.a. eftersom materialet delvis är grovt och dessutom väl blandat. Om det verkligen rör sig om moränbäddar får det vittgående konsekvenser för tolkningen av jordartsgeologin och den glaciala utvecklingen inom området. Eftersom även glaciallera är täckt av, eller ingår i, de diamikta bäddarna på flera av platserna, kan lagerföljderna svårligen förklaras av kortare stillestånd eller mindre oscillationer hos den retirerande iskanten. Den rimligaste tolkningen blir då i stället att flera av åsarna, och därmed naturligtvis även mycket av övriga jordlager inom området, härrör från äldre nedisningar. Detta är inte i överensstämmelse med den gängse uppfattningen och får mot bakgrund av den mycket begränsade informationen endast ses som spekulationer. Om det skulle visa sig att mycket av de glaciala sedimenten är avsatta i samband med en äldre isavsmältning, öppnas emellertid möjligheten att spåra eventuella jordskalv, eller frånvaron av sådana, under en tidigare isfri period.

Lagerföljder med löst lagrad sand och grovsilt förekom trots allt i många av schakten, men några störningar som säkert kan kopplas till jordbävningar påträffades inte, och inte heller vid grävningarna 2004 längs Fårboåsen. Uppumpad sand från djupare liggande lager påträffades på en av undersökningsplatserna, men att sandintrusionerna uppträdde i anslutning till veckstrukturer antyder att de uppkommit i samband med skredrörelser eller glacialtektonik, snarare än som en följd av skakningsorsakad liquefaction. Att flera av undersökningsplatserna är relativt högt belägna betyder emellertid att de höjdes ovanför havsytan relativt kort tid efter sedimentens avsättning och att sedimenten därför var helt vattenmättade och känsliga för seismiska störningar endast under en begränsad tid.

Contents

1 Introduction

This document reports parts of the results obtained from *Searching for evidence of late- or postglacial faulting in the Oskarshamn region*, which is one of the activities performed within the site investigation at Oskarshamn. The work was carried out in accordance with Activity plan AP PS 400-03-011 and Method description MD 133.001 (both SKB internal controlling documents, Table 1-1). Previous investigations carried out during 2003–2004 are reported in /Lagerbäck et al. 2004, 2005a/. The area under investigation is shown in Figure 1-1. Data are stored in the SICADA database.

Table 1-1. Controlling documents for the performance of the activity.

Activity plan	Number	Version
Undersökning av(eventuell) sen förkastningstektonik	AP PS 400-03-011	1.0.
Method descriptions	**Number**	**Version**
Neotektoniska undersökningar	SKB MD 133.001	1.0.

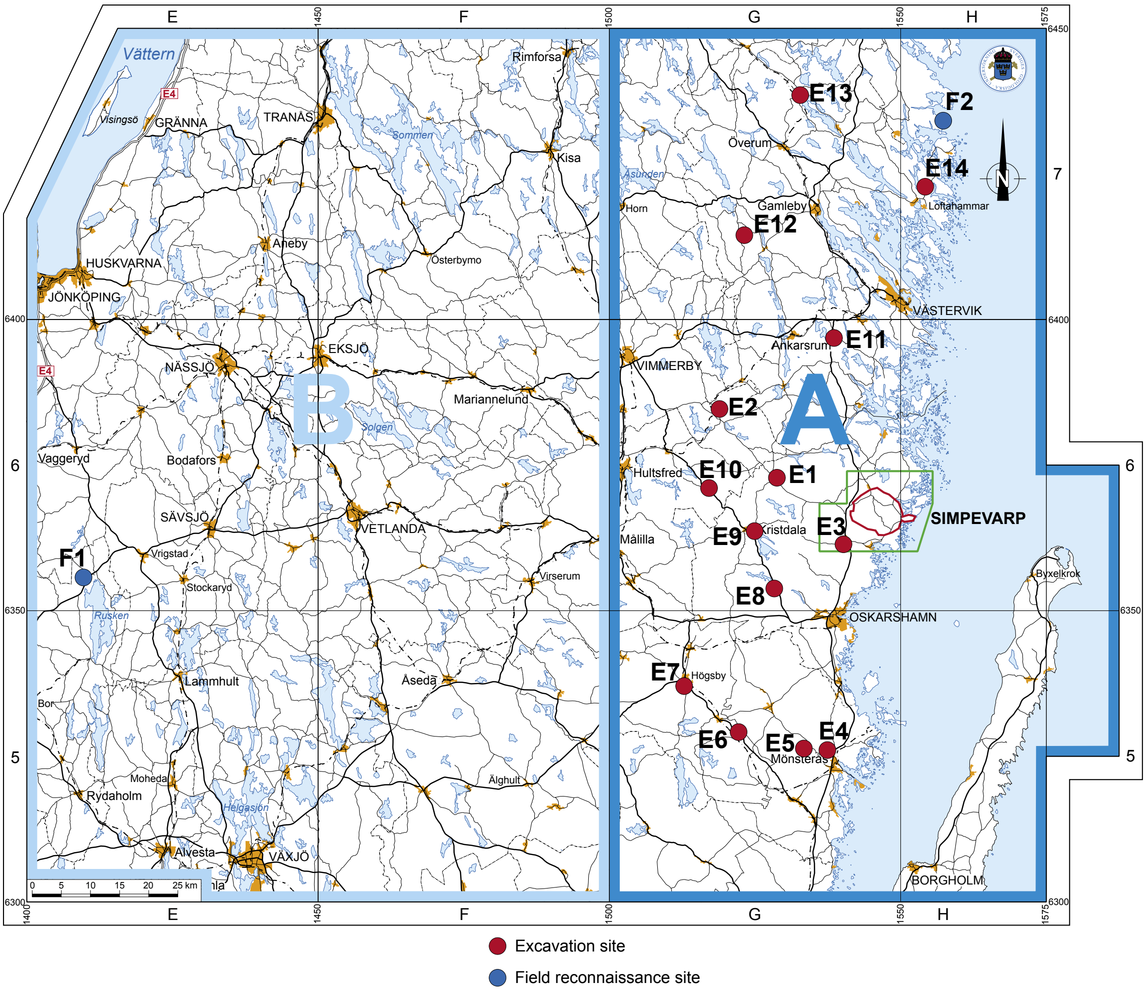

Figure 1-1. *Map of the investigation area in eastern Småland and southern Östergötland. The area, covering some 24,000 km², is divided into two subareas. The eastern subarea (A) is situated mainly below the highest coastline, while the western subarea (B) lies mainly above it. A continuous red line outlines the candidate area for detailed site investigations and the green line marks the area covered by low-altitude aerial photographs. Excavation sites: E1 Ishult. E2 Malmgrava. E3 Fårbosjön. E4 Mölstad. E5 Högalid. E6 Långemåla. E7 Staby. E8 Björnhult. E9 Malghult. E10 Träda. E11 Dockrössle. E12 Karrum. E13 Ukna. E14 Mistekärr. Sites E1–E3 were excavated and investigated in 2004. Field reconnaissance sites: F1 Klevaberget. F2 Stora Rotskär.*

Topografiskt underlag: Översiktskartan.
© Lantmäteriet, Gävle. Dnr L 2002/174

2 Objective and scope

The study is intended to establish whether any major late- or postglacial faulting had occurred in the proposed repository area at Simpevarp 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 the bedrock surface or covering regolith, or indirectly by seismically derived deformation 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.

3 Equipment

3.1 Description of equipment

Excavators (preferably of crawler type for moist or cultivated ground) capable of digging trenches to a depth of some 5 m were used for the stratigraphical work (Figure 3-1). Trench wall sections were cleaned manually with shovels, bricklaying trowels etc., and then documented with sketches and photographs.

GPS (hand-held) was used for positioning.

Figure 3-1. *In 2005 the investigations were concentrated on stratigraphic work in machine-dug trenches. Excavators of crawler type were used.*

4 Execution

4.1 General

The study comprises four main stages according to SKB MD 133.001:

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

Activities according to 1–3 were carried out mainly in 2003, while during 2004 and 2005 the study was concentrated on stratigraphical work in machine-dug trenches.

4.2 Field reconnaissance

Scarcely any field reconnaissance was carried out in 2005 but a few escarpments noted in connection with previous aerial photo interpretation and hypothetically indicating late- or post-glacial faulting were inspected. Two of the sites visited are commented on in Section 5.1 and marked out in Figure 1-1 (F1 and F2).

4.3 Stratigraphical investigations in machine-dug trenches

On the basis of aerial photo interpretation a great number of conceivable excavation sites were singled out within subarea A (see Figure 1-1) and, after a process of application for permissions, an acceptable number of excavation sites remained. Altogether 41 trenches with an overall length of some 570 m were dug and investigated at 11 different sites in the eastern part of the investigation area (E4–14 in Figure 1-1). The trenches were excavated on the flanks of glaciofluvial deposits, mainly eskers, with the intention of reaching sandy or coarse silty deposits, covered ideally by a moderately thick bed of finer grained sediments (Figure 4-1). All trenches were dug in level or only gently sloping ground and reached to depths between about 1.5 and 4.5 m (Figure 4-2). Trench walls were trimmed manually and afterwards documented in sketches and photographs (Figure 4-3). Documentation had to be brief; the time available for excavation and documentation averaged 2 days at each site. After documentation the trenches were filled in and the cultivated ground was restored to its former state (Figure 4-4).

4.4 Data handling

The positions of stratigraphical and geological observations were determined by GPS. The dates of the observations were noted and all were given PSM numbers. All points and dates were later stored in SICADA. The geological information connected with the PSM numbers was stored in the SGU database (*Jorddagboken,* version 5.5.1). Data from the SGU database were transferred to Excel files.

Figure 4-1. *This trench section at Staby along the Högsby esker (E7 in Figure 1-1) shows thin-bedded and loosely packed fine sand and silt covered by glacial clay. Extended excavation revealed that the sandy-silty deposits are underlain by glaciofluvial sand and gravel at a depth of 3.5 m. In a waterlogged state the stratigraphy is deemed to be highly susceptible to liquefaction, but the fact that the site is located some 70 m a.s.l. means that the deposits were raised above the sea, and therefore drained, fairly soon after deglaciation.*

Figure 4-2. *Typical excavation site in gently sloping, cultivated ground at Ukna (E13 in Figure 1-1), centrally located in the Uknadalen valley. The pits in the distance (see earth-mounds) contained glacial clay to a depth of at least 3.5 m and were not considered appropriate for investigation, while the trench under excavation contained thick deposits of loosely packed glaciofluvial sand and silt.*

Figure 4-3. *Trench walls were trimmed manually and documented in sketches and photographs. Trench A at Långemåla (E6 in Figure 1-1).*

Figure 4-4. *After documentation the trenches were filled in and, by returning the former topsoil to the ground surface, the cultivated ground was restored. Excavation site E7 at Staby.*

Delivery to SKB from the investigations carried out during 2005 consisted of:

1. Data files with stratigraphical and other geological information.

   GE141_PSM_NEO_060125.xls

   GE509_PSM_NEO_060125.xls

   SKB_PSM_NEO_060125.xls

2. Data file with photos and sketches.

   Bilder_PSM_NEO_060125 (jpg and tif) (80 photos, 53 sketches)

4.5 Basic principles for analyses and interpretation

In connection with the air-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 /see e.g. Figure 5-3 in Lagerbäck et al. 2004/. 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 in the terrain, 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 stratigraphical information obtained from the machine-dug trenches, i.e. were there any major post-glacial earthquakes in the vicinity of Simpevarp?, is based mainly on the concept of earthquake-induced liquefaction. When loosely packed, water-saturated, frictional sediments are subjected to strong ground shaking they can 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 (Figure 4-5). 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 the earthquake epicentre. It is commonly considered that liquefaction phenomena can develop in highly susceptible sediments at magnitudes as low as M5, but become more common at M6 or greater. A shallow-focus M6 earthquake can cause liquefaction at a distance of some 20 km from epicentre, a M7 earthquake within some 100 km, while a great M8 earthquake can 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 eastern Småland, may serve as reference areas when the results of the present investigation are evaluated. In both these areas, postglacial faulting induced a wide variety of regionally distributed liquefaction phenomena /Lagerbäck 1990, Lagerbäck and Sundh 2006 in preparation/.

***Figure 4-5.** Intensely deformed sandy-silty, glaciofluvial sediments at Flarken in the county of Västerbotten, northern Sweden. The deformations are interpreted as being due to seismic shaking resulting in liquefaction, dewatering and compaction. The deformed bed is covered by undisturbed sand and silt (above the base of the scale), indicating an earthquake during the build-up of the sequence /Lagerbäck and Sundh 2006 in preparation/.*

5 Results

5.1 Field reconnaissance

In connection with previous aerial photo interpretation a number of prominent escarpments, hypothetically indicative of late- or postglacial faulting, were noted in different parts of the investigation area /see Figure 5-2 in Lagerbäck et al. 2004/. Although often severely weathered, most of the scarps in the mainland part of the investigation area, when field-checked, appeared to be more or less glacially abraded and striated, i.e. are not postglacial in age. However, a few of the bedrock scarps did not display evidence of glacial impact and one of the most prominent of these scarps, at Klevaberget (F1 in Figure 1-1) was therefore revisited in 2005 (Figure 5-1). Only the uppermost parts of the cliff displayed traces of glacial abrasion but the entire cliff proved to be so severely weathered that a late- or postglacial age is considered highly unlikely. It should be noted that the glacial erosion during the entire Quaternary is so modest in this part of Sweden /e.g. Lidmar-Bergström 1997, Olvmo et al. 2005/ that features like this one may well have survived several glacial cycles without being significantly altered (Figure 5-2).

Likewise in connection with the aerial photo interpretation, a number of fairly conspicuous but very short sheers were noted in the coastal areas and in the archipelago. Some of these features were field-checked and generally appeared to be the result of glacial plucking governed by vertical joints and sheeting. In one case, impact of sea ice pressure or wave abrasion may have contributed to a more recent formation of scarps (Figure 5-3). None of the features visited in the archipelago was interpreted as being a result of faulting.

Figure 5-1. *Part of a 700 m long bedrock scarp at Klevaberget (F1 in Figure 1-1) some 25 km south-west of Sävsjö. The fact that the entire cliff wall is intensely weathered speaks against a late- or post-glacial development of the scarp.*

Figure 5-2. *The frequent occurrence of pre-Quaternary saprolites and weathering features like these corestones in primary positions (along road E22 some 20 km to the north of Gamleby) is indicative of a very limited glacial impact on the landscape.*

Figure 5-3. *Parts of two minor scarps at Stora Rotskär some 15 km NNE of Loftahammar. The presence of glacial striations and a slight smoothing on the vertical cliffs contradicts a postglacial age of the scarp to the left. Rugged cliffs and piles of angular boulders along the shore in front of the scarp to the right indicate that this scarp developed later than the other, possibly quite recently as a result of sea ice pressure or wave abrasion on severely fractured bedrock. Vertical joints and horizontal sheet structures in the bedrock probably governed the formation of the scarps.*

5.2 Stratigraphical investigations in machine-dug trenches

The stratigraphies encountered in the trenches differed greatly, not only from site to site but also between the different trenches at individual sites, and it is readily admitted that several of these stratigraphies were not expected and are not fully understood. The exterior ground surface gave hardly any guidance as to what might be found at depth, and afterwards the selection of excavation sites, performed by means of aerial photo interpretation and field assessment, proved to be sheer guesswork.

The typical stratigraphy along the flanks of eskers located below the highest coastline consists of glaciofluvial deposits, fining upwards from gravel and coarse sand to fine sand and coarse silt, followed by fairly thick "bottom varves" of mainly silt and thin clay laminae. Upwards the bottom varves successively turn into thinner varves of glacial clay. In sheltered positions, especially in depressions in the terrain, postglacial clay can be expected on top of the glacial clay. The thickness of the different units can vary considerably but at least one or two metres of glaciofluvial sandy and silty deposits are usually found along the flanks of most subaqueously deposited eskers. Although sometimes greatly disturbed by sliding, such stratigraphies were usually found along the eskers in northern Uppland in connection with site investigations for SKB in Forsmark /Lagerbäck et al. 2005b/.

When planning for the investigations in the Oskarshamn area there was no reason to suspect a differing geological setting. A number of north-westerly oriented esker trains, indicating ice recession towards the inland areas, run through the determined investigation area and the prerequisites for finding suitable investigation sites appeared to be favourable. Neither a brief review of the geological literature nor maps of Quaternary deposits in the area gave any ground for concern. A striking dearth of clay in the southern and central parts of the investigation area (Figure 5-4) was surprising, but, as glacial clay appears to occur in abundance on the sea bed outside the investigation area /e.g. Elhammer and Sandkvist 2005/, a geological setting similar to that found in the Forsmark region was anticipated. In this region the sediment stratigraphy and scattered distribution of glacial clay in sheltered sites indicates that practically all of that clay, once deposited on the ancient sea bed, was worn away by erosional processes before it was lifted above sea level /Lagerbäck et al. 2005b/.

However, in connection with reconnaissance of sand and gravel pits in 2003 it was observed that many of the glaciofluvial deposits in the investigation area were covered by a bed of till-like, diamict material and sometimes also by scattered, superficial boulders. It was concluded that the glaciofluvium at some sites was most likely overridden by glacial ice /Lagerbäck et al. 2004/. Thus, it was with some concern that a minor excavation programme was carried out in 2004 along the Fårbo esker, west of Simpevarp /Lagerbäck et al. 2005a/. Deformations of the sediment stratigraphy, attributed to sliding and periglacial cryoturbation, were encountered, but nothing indicating post-sedimentary impact by glacial ice was found, and the prospects for continued stratigraphic work in other parts of the investigation area appeared to be favourable.

Nevertheless, unexpected sediment stratigraphies were encountered at most of the sites excavated in 2005 and it proved quite difficult to find suitable deposits for investigation. In some of the trenches the glacial clay was rather thin varved or homogeneous throughout and rested directly on coarse glaciofluvial gravel, i.e. without any intervening thick bottom varves or sandy-silty glaciofluvial deposits (Figure 5-5). Deposits capable of becoming liquefied were encountered in fewer than half of the trenches and the appropriate kinds of stratigraphy searched for, fairly thick deposits of glaciofluvial sand and coarse silt covered by glacial clay or fine silt, were found in only a few trenches (e.g. at Staby, Figure 4-1).

The perhaps most puzzling observation made during the investigations, however, was the occurrence of till-like, diamict deposits covering the waterlain glacial sediments in many of the trenches (Figures 5-6, 5-7 and 5-8). Not only glaciofluvial sandy-gravelly sediments, but at several sites also glacial clay and silt, were covered by and even incorporated in these diamict

Figure 5-4. *Glacial clay is rare or almost absent below the highest coastline in much of the investigation area. This is especially noteworthy as frequent eskers indicate an abundant discharge of glacial meltwater in the area. Glaciofluvial deposits are shown in green and clay in yellow. Excerpt from Quaternary map database Oskarshamn SO /Rudmark 1988/.*

deposits. A local origin of the deposits is indicated, as the composition of matrix generally reflects the underlying waterlain sediments. The clasts are mostly well rounded and, thus, probably derive from the nearby glaciofluvial deposits. The origin of the diamict beds is not evident, however. Two main alternatives appear to exist: either the deposits are the result of subaqueous slumping of unconsolidated sediments from the slopes of the eskers, or they are till beds composed of glacially reworked local sediments. In some of the trenches the uppermost parts of underlying sediments were intensely deformed, possibly glaciotectonically, and judging from their appearance, the diamict deposits may very well have a glacial origin. A bed of clayey diamicton, interpreted as unmistakable clay till, was encountered at Mistekärr in the northern part of the investigation area (Figure 5-9).

Figure 5-5. *In most of the trenches the sandy-silty glaciofluvial deposits searched for were missing. In this section, at Mölstad close to Mönsterås (E4 in Figure 1-1), fairly thin varved glacial clay rests directly on top of coarse glaciofluvial gravel.*

Figure 5-6. *A variety of till-like, diamict deposits were found to cover the glacial sediments in many of the trenches. Here, at Högalid along the Fliseryd esker (E5 in Figure 1-1), the diamict deposits are divided by a thin layer of fine sand. The lower bed is mainly clayey with a moderate content of coarser material and has an erosional contact with underlying homogeneous clay. The upper bed is mainly sandy-gravelly but contains lumps of clay and underlying clayey diamicton. A thin bed of littoral sand and gravel covers the sequence.*

Figure 5-7. *Similar to Högalid (Figure 5-6) the diamict deposits at Dockrössle (E11 in Figure 1-1) is divided by a thin sand layer but here the two beds have a similar, mainly silty-clayey composition. Coarser clasts and sheared lenses of sand, gravel and laminated clay-silt float in a silty-clayey matrix. The contact with underlying laminated silt and clay is gradual and the bottommost parts of diamicton have an increased content of silt and clay.*

Figure 5-8. *At Träda (E10 in Figure 1-1) along the Påskallavik esker a stony diamicton with silty matrix covers structureless silt, downwards gradually merging into folded and, finally, undisturbed thin-bedded silt.*

Figure 5-9. *A bed of clayey diamicton covers intensely deformed and very compact silt at Mistekärr (E14 in Figure 1-1). Inclusions of silt occur in the bottommost parts of the bed. The diamicton is interpreted as a basal till and the deformation and compaction of underlying silt is believed to be glaciotectonically induced.*

It should be observed that the deformations related to the diamict beds occur superficially in the sequences. Although covered by diamict deposits and deformed in the uppermost parts, the sandy-silty deposits present at several of the sites were generally loosely packed and scarcely affected by any disturbances at depth, except for occasional moderate folding (Figure 5-10). Minor fold structures were also encountered in some of the glacial clay sequences (Figure 5-11). Whatever the nature of the enigmatic diamictons, this implies that the stratigraphies at these sites may still have been able to liquefy during earthquakes.

No deformational features unambiguously related to seismic shaking were noted in any of the trenches. Features indicative of liquefaction were observed at only one site, Dockrössle (E11 in Figure 1-1), where a few sand injection features may hypothetically indicate seismically induced liquefaction and fluidization of underlying sandy sediments (Figures 5-12 and 5-13). However, as the origin of the diamict bed covering the waterlain sediments at the site is uncertain, there may very well be alternative explanations for the features, e.g. gravitational slumping or glaciotectonic deformation.

Figure 5-10. *Moderate folding in well-bedded fine sand and silt at Björnhult (E8 in Figure 1-1). The deformation is probably purely gravitational and due to locally sloping terrain.*

Figure 5-11. *Minor folding in varved glacial clay at Staby (E7 in Figure 1-1).*

Figure 5-12. *Minor sand-filled dikes and settling in thin-bedded fine sand and silt intercalated by a layer of clayey sand. The overlying diamict bed is not affected by the sand injection and appears to have eroded the underlying sediments. Dockrössle (E11 in Figure 1-1).*

Figure 5-13. *A body of structureless fine sand (light brown) with silty inclusions occuring between deformed sandy-silty deposits and covering clayey-silty diamicton at Dockrössle (E11 in Figure 1-1). The process of deformation is uncertain. The sand may hypothetically have become injected due to seismically induced liquefaction and fluidization of underlying sandy sediments, but the occurrence of folding (near trowel) and overlying diamicton (upper brownish bed) may indicate that the sediments were subjected to gravitational slumping or glaciotectonic deformation.*

To sum up, the conditions for development of liquefaction, at least as concerns the composition of deposits, were considered favourable at four of the investigated sites (E7 Staby, E8 Björnhult, E12 Karrum and E13 Ukna, see Figure 1-1 for location). Less favourable stratigraphies were encountered at three of the sites (E6 Långemåla, E10 Träda and E11 Dockrössle), whereas scarcely any adequate deposits were found at the remaining four sites (E4 Mölstad, E5 Högalid, E9 Malghult and E14 Mistekärr). The total length of trenches containing reasonably favourable deposits is some 200 metres, but, as most of the excavation sites are located fairly high above present sea level, they were lifted above the ancient sea fairly soon after deposition of the glacial sediments. Whereas deglaciation of the investigation area occurred some 14,000–13,500 years BP /Lundqvist 2002/ and most of the excavation sites were lifted above sea level before 11,000 years BP /e.g. Påsse and Andersson 2005/, the deposits were, accordingly, entirely waterlogged during only a short period of time. However, a fairly high groundwater table at some of the sites means that those deposits have to some degree remained susceptible to liquefaction throughout the Holocene (Figure 5-14).

Figure 5-14. *Trench dug at Träda (E10 in Figure 1-1) along the Påskallavik esker some 30 km west of Simpevarp. Although raised above the sea before 12,000 years BP and, thus, entirely water-logged during only some 1,500 years, the silty deposits at depth have to some degree, due to a fairly high groundwater table, remained susceptible to seismically induced deformation.*

6 Summary and discussions

Complementary reconnaissance of one of the most prominent escarpments identified in the mainland part of the investigation area, a 700 m long scarp at Klevaberget some 25 km south-west of Sävsjö (F1 in Figure 1-1), revealed that the vertical cliff was so severely weathered that a late- or postglacial age of the feature is deemed unlikely. Field reconnaissance of some minor sheers in the archipelago, identified in aerial photographs, suggested that these features are generally the result of glacial plucking, governed by vertical joints and horizontal sheet structures, rather than to faulting. This implies that the only morphological feature remaining under suspicion of late- or postglacial faulting in the investigation area, is the minor but very prominent scarp on the island of Öland /Lagerbäck et al. 2004, 2005a/.

In 2004 and 2005 a total of 53 trenches with an overall length of some 740 m were dug and investigated at 14 different sites in the eastern part of the investigation area (E1-14 in Figure 1-1). The trenches were excavated on the flanks of glaciofluvial deposits, mainly eskers, with the intention of reaching sandy or coarse silty deposits, covered ideally by a moderately thick bed of finer grained sediments. However, several of the stratigraphies encountered during the stratigraphical investigations were unexpected and scarcely suitable for tracing palaeo-earthquakes. In many of the trenches, deposits of loosely packed sand or coarse silt, i.e. deposits susceptible to liquefaction, were either missing or covered by diamict deposits of unknown origin. Similar deposits covering glaciofluvial sand and gravel were found also in sand and gravel pits in connection with previous reconnaissance in the investigation area /Lagerbäck et al. 2004/. At several sites the diamict beds were found to cover not only glaciofluvial sediments but also fairly thick sequences of glacial clay. At Långemåla (E6 in Figure 1-1) a 2-metre thick diamict bed covered a clay sequence containing several hundred clay varves – representing an equal number of years.

By appearance, and by their relationships with underlying sediments, these diamictons could easily be interpreted as till beds, but this interpretation brings complications for the traditional, and current, conception about the age and formation of glacial deposits in this part of Sweden. If indeed these diamict beds are of glacial origin, their frequent occurrence in the investigation area implies that short standstills or minor oscillations of the ice margin during the last deglaciation can scarcely explain the stratigraphies. Given that the course of the region's deglaciation is reasonably well known /e.g. Lundqvist 2002/, several of the eskers and consequently much or probably most of the other glacial deposits in the region may derive from a previous glaciation and have escaped obliteration by the last ice sheet.

Alternative processes for the formation of the diamictons, e.g. subaqueous slumping, sliding or debris flow may be conceivable. /Svensson 1989/ reported a "coarse-grained" stratigraphic unit with an "often rather unsorted appearance" below c. 55 m above sea level. in the Oskarshamn region. This information is of interest and may be relevant to the problem in question. /Svensson 1989/ calls these deposits "drainage sediments" and attributes them to the final drainage of the Baltic Ice Lake, when the water-level fell 25 m during a short period of time. Svensson suggests that unconsolidated sediments underwent gravity slumping and wave erosion, resulting in increased deposition of relatively coarse-grained sediments.

Except for a recent questioning of the nature and drainage of the Baltic Ice Lake /Påsse and Andersson 2005/ it is difficult, however, to attribute the diamictons found in the investigation trenches to this drainage. Two of the sites with diamict deposits covering glacial sediments (E6 Långemåla c. 60 m and E10 Träda 75–80 m) are probably located slightly too high to accord with Svensson's scenario /cf. Figure 118 in Svensson 1989/, and similar stratigraphies were found at still higher elevation in connection with previous inspection of sand and gravel pits.

The apparently local origin of the diamict deposits might fit a pattern of subaqueous sliding or slumping of unconsolidated deposits from the nearby eskers. It is, however, difficult to imagine how not only fine-grained but also very coarse deposits, such as gravel and minor boulders, could detach from the slopes of the eskers and integrate with the fine-grained matrix material. Evidence of extensive sliding and folding of clayey and silty deposits was found along the eskers in northeastern Uppland /Lagerbäck et al. 2005b/, but nowhere any diamict deposits of the kind encountered in the Oskarshamn region. Further, diamict deposits were found along only some of the eskers in the Oskarshamn region but not along others, e.g. the Fårbo esker that only displayed slide and folding features similar to those noted in Uppland. It is strongly emphasized that the information gained in connection with the stratigraphical investigations and previous inspection of sandpits is only fragmentary, but may be indicative of the weak erosional capacity of the last inland ice and that the glaciofluvial deposits occurring in the investigation area derive from different deglaciations.

The matter may be relevant to the question at issue. If deposited during a previous deglaciation, the sandy-silty sediments would have been able to register earthquakes not only during the present, but also during one (or more?) previous ice-free period. Although this possibility is mere speculation in the present state of knowledge, the significance of the matter for the palaeoseismic research may justify some effort to elucidate the problem.

Whatever the origin and age of these enigmatic diamict deposits, the underlying sandy-silty sediments are deformed and compacted only in the uppermost parts, whereas unconsolidated and, if saturated susceptible to liquefaction, are present at depth. The total length of sections containing reasonably favourable deposits, the trenches excavated along the Fårbo esker in 2004 and previously visited sandpits included, measures roughly some 500 metres. Deformations related to gravitational sliding and folding of the sediments were noted, but no liquefaction features unambiguously indicating seismic shaking. Hypothetically an earthquake may have triggered fluidization, resulting in sandy dikes and sand intrusions at Dockrössle (Figures 5-12 and 5-13) but there are equally credible alternatives for their formation.

Previous aerial photo interpretation, field reconnaissance and literature review indicated a concentration of rockfalls, landslide scars and soft-sediment deformation features, all hypothetically indicative of earthquakes, in the northeastern part of the investigation area /Lagerbäck et al. 2004/. The excavation sites at Karrum and Ukna (E12 and E13 in Figure 1-1) are interesting in this context. The stratigraphies at both sites include thick deposits of loosely packed sand and silt (Figure 6-1 and 6-2). If a major earthquake had occurred in the region while these sites were still submerged in the ancient sea, extensive deformation of these deposits would have been anticipated, but no indication of liquefaction whatsoever was noted.

The greatest shortcoming of the stratigraphical investigations is that the excavation sites are situated fairly high above present sea level. Most were raised above the ancient sea fairly soon after the deposition of sediments and, accordingly, the deposits were entirely saturated and susceptible to liquefaction during only a short period. On the other hand, in accordance with the co-seismic postglacial faulting in northern Sweden /Lagerbäck 1990, Lagerbäck and Sundh 2006, under preparation/, any major faulting in this area would perhaps be expected to have occurred in close connection with deglaciation when the rate of glacio-isostatic uplift was at its highest. During the first thousand years after deglaciation, practically all sites having excavated trenches and previously visited sandpits were still submerged by the sea /e.g. Svensson 1989, Påsse and Andersson 2005/ and therefore susceptible to liquefaction.

Figure 6-1. *Evenly bedded, sandy and silty glaciofluvial sediments covered by homogeneous clay and silty diamicton at Karrum (E12 in Figure 1-1). The sandy deposits reached to a depth of at least 4.5 m.*

Figure 6-2. *Trench dug in loosely packed glaciofluvial sand at Ukna (E13 in Figure 1-1). The excavation site is centrally located in the rather impressive Uknadalen valley, one of the few morphological features in the investigation area that might conceal major recent fault movement from detection (cf. Figure 4-2). Deformational features interpreted as caused by sliding and debris flow were met with but no indication of liquefaction whatsoever was noted in the thick deposits of loosely packed sand.*

References

Elhammer A, Sandkvist Å, 2005. Detailed marine geological survey of the sea bottom outside Simpevarp. SKB P-05-35, Svensk Kärnbränslehantering AB.

Lagerbäck R, 1990. Late Quaternary faulting and paleoseismicity in northern Fennoscandia, with particular reference to the Lansjärv area, northern Sweden. Geologiska Föreningens i Stockholm Förhandlingar 112, 333–354.

Lagerbäck R, Sundh M, Svedlund J-O, 2004. Searching for evidence of late- or postglacial faulting in the Oskarshamn region. Results from 2003. SKB P-04-192, Svensk Kärnbränslehantering AB.

Lagerbäck R, Sundh M, Svantesson S-I, Svedlund J-O, 2005a. Searching for evidence of late- or postglacial faulting in the Oskarshamn region. Results from 2004. SKB P-05-232, Svensk Kärnbränslehantering AB.

Lagerbäck R, Sundh M, Svedlund J-O, Johansson H, 2005b. Searching for evidence of late- or postglacial faulting in the Forsmark region. Results from 2002-4. SKB R-05-51, Svensk Kärnbränslehantering AB.

Lagerbäck R, Sundh M, 2006. Early postglacial faulting and paleoseismicity in northern Sweden (preliminary title). Manuscript in preparation.

Lidmar-Bergström K, 1997. A long-term perspective on glacial erosion. Earth Surface Processes and Landforms 22, 297–306.

Lundqvist J, 2002. Weichel-istidens huvudfas. In Fredén, C. (red.): Berg och Jord, 120–135. Sveriges Nationalatlas, tredje upplagan.

Obermeier S F, 1996. Use of liquefaction-induced features for paleoseismic analysis – An overview of how seismic liquefaction features can be distinguished from other features and how their regional distribution and properties of source sediment can be used to infer the location and strength of Holocene paleo-earthquakes. Engineering Geology 44, 1–76.

Olvmo M, Lidmar Bergström K, Ericson, Bonow J M, 2005. Saprolite remnants as indicators of pre-glacial landform genesis in southeast Sweden. Geografiska Annaler 87 A (3), 447–460.

Påsse T, Andersson L, 2005. Shore-level displacement in Fennoscandia calculated from empirical data. Geologiska Föreningens i Stockholm Förhandlingar 127, 253–268.

Rudmark L, 1988. Jordartskartan 5 G Oskarshamn SO. Sveriges Geologiska Undersökning, Ae 84.

Svensson N-O, 1989. Late Weichselian and early Holocene shore displacement in the central Baltic, based on stratigraphical and morphological records from eastern Småland and Gotland, Sweden. Lundqua Thesis 25.