P-04-192

Oskarshamn site investigation

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

Results from 2003

Robert Lagerbäck, Martin Sundh, Jan-Olov Svedlund
Geological Survey of Sweden (SGU)

June 2004

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Keywords: P-04-192, Late- or postglacial faulting, Earthquake, Quaternary deposits, Seismically induced deformations, Unstable boulders.

Summary

The study aims to elucidate whether any major late- or post-glacial faulting has occurred in the proposed repository area at Simpevarp or in its vicinity. The investigation area comprises some 6,000 km^2 and is divided into two subareas (Figure 1-1). Within the eastern subarea (A), situated mainly below the highest coastline, it is planned for more comprehensive investigations (including stratigraphical examination of machine cut trenches) than in the western subarea (B) which is situated mainly above the highest coastline. During 2003 the study focussed on air-photo interpretation and field reconnaissance in sand and gravel pits

The entire investigation area was interpreted from aerial photographs and anything that might be indicative on recent faulting or earthquakes was noted for later field-checking. All gravel and sandpits detected in subarea A as well as many of those situated below the highest coast-line in subarea B were marked out on topographical maps for later field-checking. A number of pregnant escarpments, that is, possible reverse- or normal faults, were indicated during the air-photo interpretation (Figure 5-2). Isolated, relatively short escapments were noticed at many places, but when some of these were inspected in the field they proved to be affected by glacial abrasion and, thus, were formed prior to the last deglaciation. A set of more sustained scarps to the south of lake Vättern and a north-southerly directed lineament on the island of Öland remain to be examined in the field.

Except for the escarpments, a number of landslides and rockfalls were indicated in the air-photos and a few of these were later inspected and verified in the field. These features appear to cluster in the northeastern part of the investigation area, hypothetically mirroring that co-seismic faulting has occurred there, but the pattern may just as well reflect a regional divergence in topography and geological setting.

Field reconnaissance in the numerous gravel and sandpits was very little rewarding. Deposits susceptible for development of seismically induced liquefaction were found only in some fifteen of the pits and in very small amounts. Soft-sediment deformation features tentatively caused by seismic shaking were encountered at two sites, but the processes responsible for deformation will remain uncertain until more thorough investigations have been carried out. In addition to seismic shaking, glaciotectonic impact of overriding inland ice and periglacial processes during the Younger Dryas have to be considered as possible sources for deformation.

The abundant surficial boulders in parts of the investigation area provides an additional possibility for tracing the presence or, rather, the absence of major postglacial earthquakes in the vicinity. Many of these boulders proved to be situated in such unstable positions, e.g. on steeply sloping bedrock surfaces, that they hardly would remain in their present positions if subjected to very strong ground shaking. No attempts to quantify the relation between any of these boulders and earthquake ground motion have been made so far but are urgently needed. Extended reconnaissance for such boulders, field-checking of some of the escarpments and, above all, stratigraphical investigations in machine cut trenches remain to be done before it is possible to have a firm idea of whether any significant late- or postglacial faulting or earthquakes have occurred near Simpevarp or anywhere else in the investigation area.

Sammanfattning

Syftet med undersökningarna är att undersöka om större förkastningsrörelser inträffat inom kandidatområdet vid Simpevarp eller inom de närmaste områdena däromkring. Undersökningsområdet är ca 6,000 km^2 stort (figur 1-1) och har indelats i två delområden av vilka det östra (A) huvudsakligen ligger under högsta kustlinjen medan det västliga (B) huvudsakligen ligger ovanför. Undersökningarna kommer att ha något olika omfattning inom de två delområdena såtillvida att planerade stratigrafiska arbeten främst kommer att genomföras inom A-området. Arbetena under 2003 omfattade främst flygbildstolkning och fältrekognosering i sand- och grustäkter.

Hela undersökningsområdet har flygbildstolkats i avsikt att försöka spåra eventuella unga förkastningsrörelser eller jordbävningar. Ett antal mer eller mindre uthålliga terränghak, dvs presumtiva revers- eller normalförkastningar, har noterats på olika håll inom området. Några av dessa kontrollerades i fält och visade sig vara påverkade av inlandsis och således äldre än den senaste inlandsisen. De besökta terränghaken är sannolikt inte heller orsakade av förkastningsrörelser utan snarare resultatet av olikformig glacialerosion utmed sprickzoner. Ett system av mer uthålliga terränghak söder om Vättern, liksom ett visserligen lågt men ändå mycket pregnant terrängbrott norr om Borgholm på Öland, återstår att kontrollera i fält.

Ett antal presumtiva jordskred och bergras noterades vid flygbildstolkningen och några av dessa verifierades senare vid fältkontroller. Flertalet ligger samlade i den nordöstra delen av undersökningsområdet, vilket skulle kunna betyda att jordskalv förekommit inom dessa områden, men lika gärna återspegla skillnader i topografi och geologiska förutsättningar inom olika delar av undersökningsområdet.

I samband med flygbildstolkningen noterades även sand- och grustäkter inom framförallt A-området. Praktiskt taget samtliga täkter inom A-området förutom Öland, samt ett flertal inom B-området, har senare inspekterats i fält, men utbytet blev magert. Jordlager med förutsättningar för att utveckla seismiskt orsakad liquefaction påträffades endast i ett fåtal av täkterna. Störningar som möjligen kan vara seismiskt orsakade påträffades i två täkter inom den norra delen av A-området, men mer ingående undersökningar behövs för att kunna fastställa störningarnas orsak. Periglaciala processer, som varit verksamma inom högre liggande delar av undersökningsområdet, kan ge upphov till störningar som påminner om seismiskt orsakade. Dessutom finns indikationer på att många isälvsavlagringar inom området överskridits av inlandsis, något som också kan ha lett till störningar i de vattenavsatta sedimenten.

En riklig förekomst av ytligt liggande block inom delar av undersökningsområdet erbjuder ytterligare en möjlighet att bedöma om stora jordbävningar förekommit. Många av blocken befinner sig i instabila lägen, antingen på relativt brant sluttande hällar eller med små stenar inkilade mellan sig och underliggande häll. Inga försök att uppskatta hur starka markskakningar som skulle behövas för att välta ned blocken eller mosa underliggande stenar har gjorts, men mycket starka skalv kan sannolikt uteslutas i blockens närområden. Utökad rekognosering efter sådana block, fältkontroller av vissa terränghak och, framför allt, stratigrafiska undersökningar i maskingrävda schakt återstår att genomföra innan några slutsatser om eventuella förkastningsrörelser inom kandidatområdet eller någon annanstans inom undersökningsområdet kan dras.

Contents

1 Introduction

This document reports the results gained during 2003 by the Searching for evidence of late- or postglacial faulting in the Forsmark 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). The area under investigation is shown in Figure 1-1. Data are stored in the SICADA database, field note no Simpevarp 250.

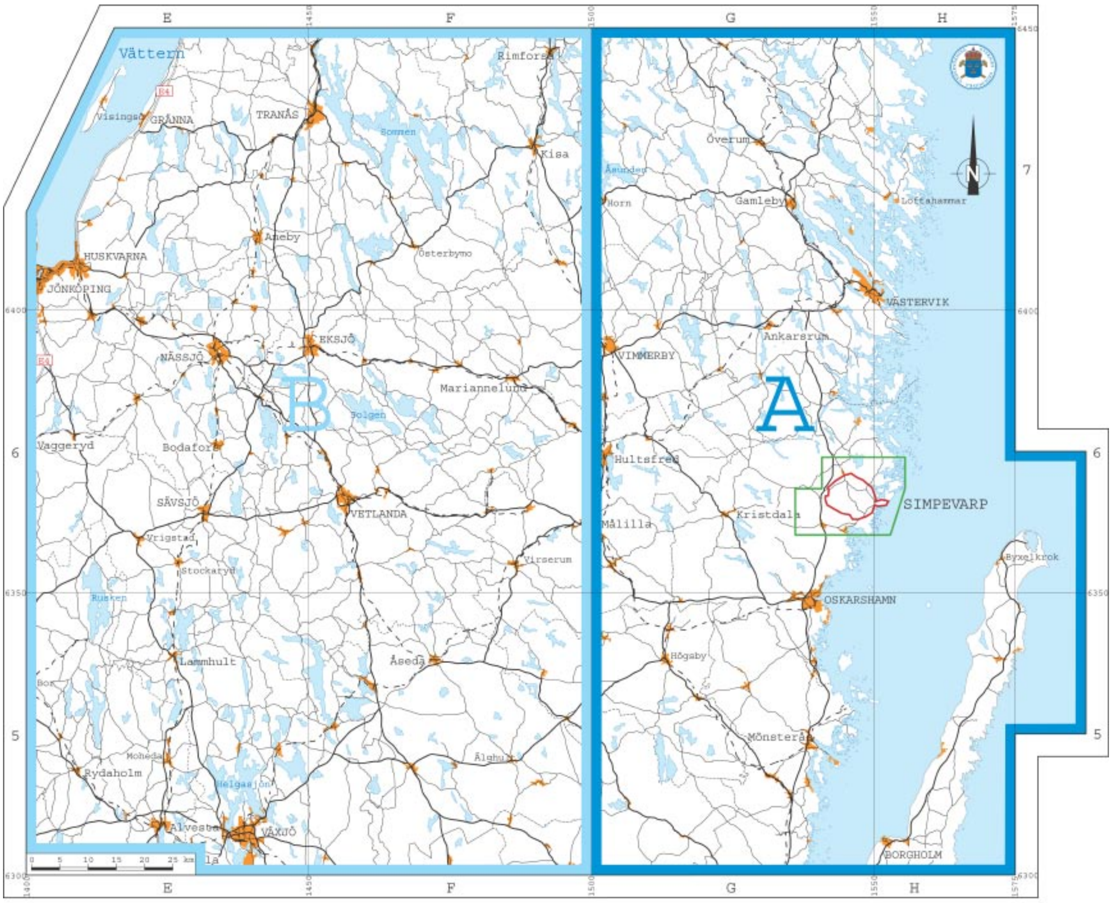

Figure 1-1. Map of the investigation area in eastern Småland and southern Östergötland. The area comprises some 6,000 km^2 and is divided into two subareas. Within the eastern subarea (A), situated mainly below the highest coastline, it is planned for more comprehensive investigations than in the western subarea (B) which is situated mainly above the highest coastline. A continuous red line marks the candidate area for detailed site investigations and the green line marks the area covered by low-altitude aerial photographs.

Topografiskt underlag: Översiktskartan.

2 Objective and scope

The study aims to elucidate whether any major late- or postglacial faulting has 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 of several kilometres length. Faults of these dimensions may, if conditions are favourable, be detected by means of air-photo interpretation and, furthermore, generate high magnitude earthquakes that may produce characteristic distortions in water-saturated 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 deformations 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

Air-photo interpretation was performed in a Wild Aviopret stereoscope (Figure 3-1) using IR-images at the scale of 1:30,000 (1:15,000 within the site-investigation area).

Cuttings in sand and gravel pits were cleaned by shovels, scrapers, etc.

Cameras for documentation.

GPS (hand-held) was used for positioning in terrain where orientation by map was difficult.

Figure 3-1. *Air-photo interpretation was the most important step in the study during 2003.*

4 Execution

The study includes several steps according to SKB MD 133.001.

1. A brief review of geological literature and other relevant information from the area. Any information that may indicate recent faulting or earthquakes is recorded for later following-up in the field.
2. Air-photo interpretation. Any indications of recent faulting or earthquakes (landslides, etc) are recorded for later following-up in the field. Gravel and sandpits are marked out on maps for later examination in the field.
3. Field reconnaissance. Any indications of recent faulting or earthquakes recorded during the literature study or air-photo interpretation are checked. Stratigraphies in gravel and sandpits in operation, temporary road cuttings, etc, are examined for any seismically induced distortions. Bedrock exposures in parts of the coastal areas are inspected for any fault-related displacements in the glacially polished rock surface. Reconnaissance for unstable boulders, contradicting strong seismic shaking, was originally not planned for but has been included in the study.
4. Stratigraphical investigations in machine-cut trenches, mainly dug in sediments of favourable composition for developing earthquake-induced liquefaction phenomena.

During 2003 the investigations focussed on a review of geological literature, air-photo interpretation and field reconnaissance in sand and gravel pits (1, 2 and 3 above).

4.1 Review of literature

The literature review in 2003 was principally confined to descriptions relating to geological maps in SGU series Aa, Ab, Ac and Ae. All of the descriptions relevant for the investigation area were briefly looked through for any information indicative of recent faulting or earthquakes.

4.2 Air-photo interpretation

The entire investigation area (Figure 1-1) was interpreted in aerial photographs at the scale of 1:30,000 and the candidate area at the scale of 1:15,000 as well. Anything that might be indicative of recent faulting (principally fresh-looking escarpments) or earthquakes (principally landslide scars and rockfalls) was noted for later field-checking. All gravel and sandpits detected in subarea A (Figure 1-1), as well as many of those situated below the highest coastline in subarea B, were marked out on topographical maps for later field-checking.

4.3 Field reconnaissance

Practically all of the gravel and sandpits located in subarea A and a few located below the highest coastline in subarea B, in all some 280 objects, were visited in the field. However, the absolute majority of the pits proved to be out of operation and "restored". Likewise, a few indicated landslide scars, rockfalls and pregnant escarpments were inspected. During reconnaissance it soon became evident that parts of the investigation area were very rich in superficial boulders that might provide an additional possibility for tracing the presence or, rather, absence of major postglacial earthquakes in the vicinity. In some of these areas, boulders occasionally proved to be situated in such unstable positions, e.g. on steeply sloping bedrock surfaces, that they hardly would remain unaffected if subjected to very strong ground shaking. In order to take advantage of this fact, three days of reconnaissance with the focus on such unstable boulders were concentrated to a few small areas situated above the highest coastline within subarea A.

4.4 Data handling

The positions of stratigraphical and geological observations, photos, etc were determined by GPS or topographical maps. The dates of the observations were notified and they were all given PSM numbers. All points and dates were later stored in SICADA under field note no 250. The geological information connected to the PSM numbers was stored in SGUs database (Jorddagboken Version 5.4.3). Data from the SGU database was exported to Excel and JPG files.

The deliverance to SKB from the investigations carried-out during 2003 consists of:

1. Data files with stratigraphical and other geological information.

SKB_PSM_NEO_040401.xls

2. Data files with photos and sketches.

Foton_PSM_NEO_040401 (jpg) (22 photos)

Skisser PSM_NEO_040401 (jpg) (2 sketches)

4.5 Basic principles for analyses and interpretation

In connection with the air-photo interpretation, any linear escarpment or other type of lineament that is atypical for the general landscape and protrudes as an anomalous feature will be noted for later field-checking. However, there are many reasons to why faults easily may escape detection. A rough topographical relief (highly relevant for parts of the investigation area) may mask normal or reverse fault movements of minor magnitude, fault scarps below the highest coastline may have been abraded by the sea or become hidden by sediments, strike-slip movement along fissure valleys subjected to post-movement erosion or sedimentation will not leave any significant morphological imprints, etc.

Thus, the searching for evidence of recent faulting cannot rely merely on morphological expressions in the ground surface, but should also consider any secondary effects of faulting. The stratigraphical investigations are mainly focused on seismically induced liquefaction phenomena. If loosely packed and waterlogged frictional sediments are subjected to strong ground shaking they may lose their strength and behave like liquids. As a consequence of liquefaction, the primary sedimentary structures will be destroyed and replaced by a variety of deformational features. Whereas the presence of liquefaction features may be indicative of strong paleoearthquakes, an absence of such features, under the assumption that susceptible sediments are widespread, strongly indicates that no major earthquakes have occurred in the vicinity since the deposition of the sediments. The Lansjärv and Burträsk areas in northern Sweden, in similar geologic settings as eastern Småland, may serve as reference areas when the results of the present investigation eventually are evaluated. In both of these areas, postglacial faulting induced a great variety of regionally distributed liquefaction phenomena /Lagerbäck, 1990; Lagerbäck and Sundh, unpubl/.

Presence of numerous rockfalls, or landslides developed in frictional deposits, may indicate strong earthquakes, while an absence of falls or slides hardly excludes earthquakes, etc. Unstable boulders may serve as non-recurrent seismoscopes and provide evidence that no major earthquakes have occurred in the vicinity since they came to rest in their current unstable positions. In glaciated areas like Småland, some of the erratic boulders constitute analogues to the "precarious (-ly balanced) rocks" in arid areas described by Brune /e.g. Brune et al. 1996/.

Thus, any phenomenon that might be indicative of recent faulting or earthquakes, but likewise also circumstances that are contradictive to such events, are of interest for the study. When, ultimately, the results of the study, which is still in its very beginning, are to be interpreted and evaluated, the outcome of all these and any other relevant aspects should hopefully be consistent with each other and fit into a clear-cut pattern.

5 Results

5.1 Review of literature

Besides professional papers, the literature review in 2003 was primarily concentrated on descriptions of geological maps. Some information on features that may be indicative of recent faulting or earthquakes was found. Among the more modern reports, /Svantesson, 1989/ describes a fractured and dislocated bedrock outcrop on the small island of Kalen in the archipelago of Loftahammar. The vertical offset of the bedrock surface measures c 0.5 m and from the appearance of glacial striae on each side of the fracture Svantesson concludes that the displacement may have a neotectonic origin.

Among earlier work, /Sandegren and Sundius, 1926/ report on supposed landsliding at Falerum, located in the valley of Uknadalen some 50 km to the northwest of Västervik. Based on clay-varve stratigraphy, they claim that sliding occurred 278 years after local deglaciation and suggest that an earthquake, associated with the rapid late-glacial isostatic uplift, may have triggered the slide.

Trollegater is a well-known fissure cave some 7 km to the west of Rimforsa in the northernmost part of the investigation area. According to an information sign at the site, the intense fracturing of the bedrock was caused by earthquakes following the last deglaciation (Figure 5-1). Features like this are often routinely claimed as results of earthquakes, but credible evidence for this is commonly missing. It appears that the old problem of "the hen and the egg" is applicable. Generally, fracturing and displacement of bedrock generate earthquakes, but not the reverse.

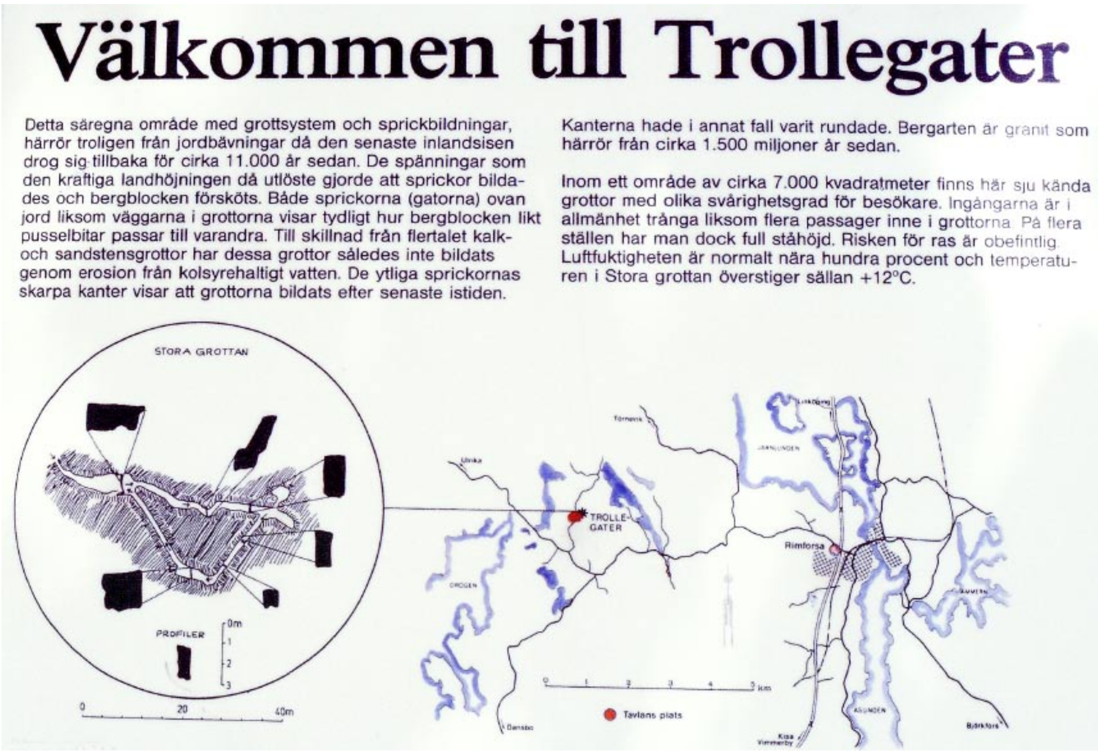

Figure 5-1. Tourist information sign at Trollegater, a "fissure cave" near Rimforsa in the northernmost part of the investigation area. According to the sign, the fracturing probably originates from earthquakes following the deglaciation some 11,000 years ago.

Perhaps still more spectacular are the information and the cryptic interpretation given by /Svenonius, 1914/ about two “earthfalls” (Sw.: “strandras”) along the shore of Gamlebyviken, a long and narrow inlet of the Baltic to the northwest of Västervik. The documentation of the events, which occurred in 1824 and 1886 respectively, is difficult to interpret but Svenonius appears to favour a tectonic explanation, which includes a local subsidence of the bedrock, triggered by exceptional meteorological and hydrogeological conditions.

5.2 Air-photo interpretation

In addition to all sand and gravel-pits, a number of inferred rockfall deposits and landslide scars as well as rather pregnant escarpments were noticed in connection with the air-photo interpretation (Figure 5-2). At the foot of several steep cliffs in the northeastern part of the investigation area, not at least along the valley of Uknadalen, a number of rockfalls or intermediary forms between rockfalls and more typical taluses were indicated.

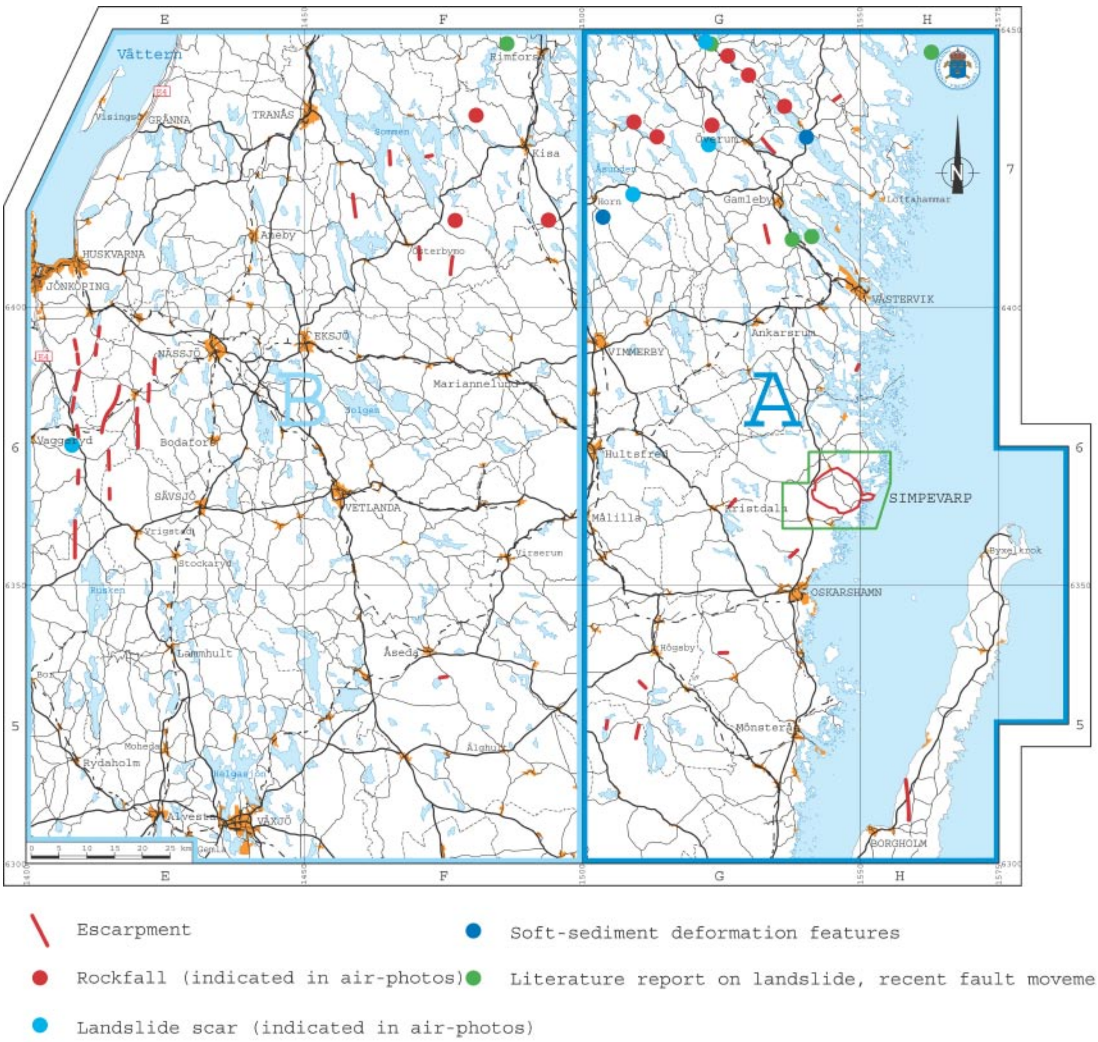

Figure 5-2. Map showing the location of possible landslides, rockfalls and escarpments noticed in air-photos as well as literature reports on landslides, recent fault movements, earthquakes, etc.

Topografiskt underlag: Översiktskartan.

Features interpreted as landslide scars were noticed at a few isolated places. The most interesting ones, both probably developed in glacial till, are a fairly impressive slide near Skärsjöbråten some 7 km to the east of Vaggeryd and a minor slide at Dalhem some 15 km NNW of Gamleby (see further 5.3.3).

Most of the investigation area displays only weak impact of the repeated Quaternary glaciations. The gross morphology of the mainland areas is not characterized by glacial smoothening, but rather by a long-term weathering and stripping concentrated to fracture zones. Consequently, it is somewhat problematic to identify linear features as anomalously deviating from a glaciated landscape and, therefore, minor late- or postglacial fault offsets may be obscured in the generally rough relief. Nevertheless, a number of late- or postglacial fault candidates were indicated during the air-photo interpretation (Figure 5-2). Isolated, relatively short but fairly pregnant escapments were noticed at many places, whereas a set of more sustained, north-southerly directed scarps were identified to the south of Lake Vättern. An interpretation of the latter features as related to the pre-Quaternary Vättern graben presents itself immediately, but that perhaps does not exclude minor, more recent movements. The most puzzling feature however is a north-southerly directed lineament to the north of Borgholm on the island of Öland. The feature appears as a c 7 km long, very low but still pregnant scarp (Figure 5-3) running from the ruins of the ancient castle at Hässleby in the south to Gullehamn in the north, where it disappears into the sea.

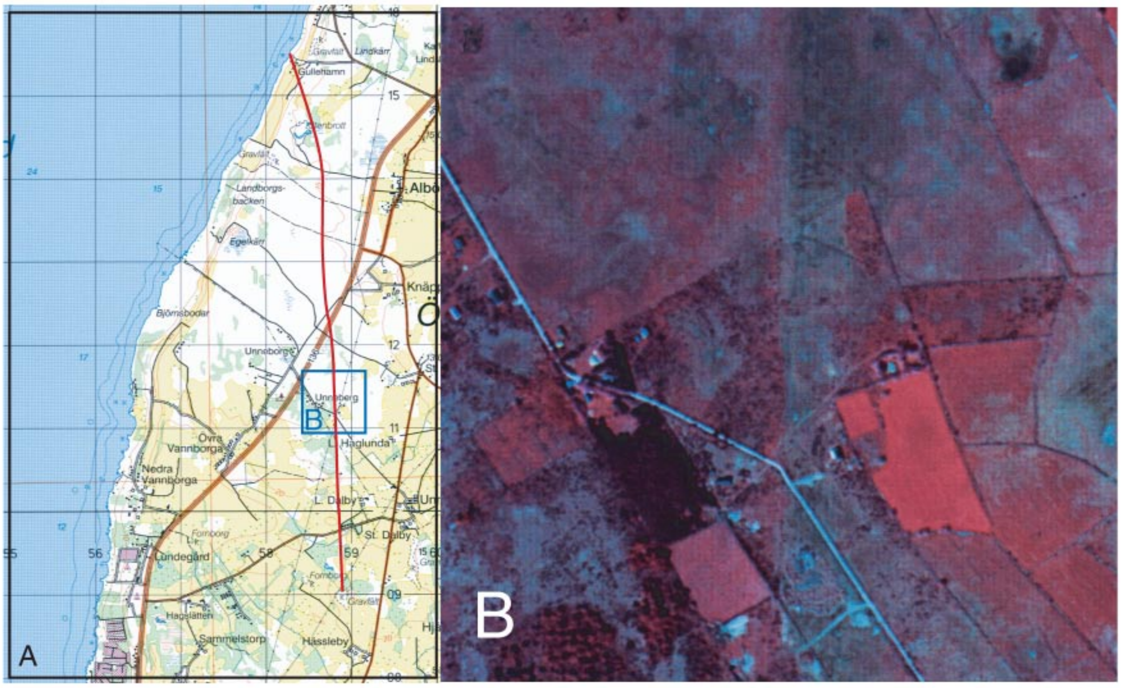

Figure 5-3 A and B. A. *Excerpt from the topographical map 5H Borgholm SV showing the trace of a c 7 km long, north-southerly directed lineament (depicted by a red line). (B) In air-photos the structure stands out as a very low but distinct step in the ground, where the eastern side appears to be somewhat more highly situated than the western one. The photo shows the area marked out with a square in Figure A. Topografiskt underlag:*

Översiktskartan och flygfotografi (IRF 9,200 m)

5.3 Field reconnaissance

5.3.1 Lineaments

Some of the isolated lineaments marked out in Figure 5-2 were inspected in the field. Although protruding as persistent lineaments in the air-photos, the features proved to be composed of shorter escarpments placed in a row. The single escarpments were glacially abraded and thus significantly older than deglaciation (Figure 5-4). Many of these isolated and fairly short features are probably not fault scarps but rather the result of differential glacial erosion governed by fracture zones.

5.3.2 Sand and gravel-pits

Practically all of the gravel and sandpits observed in the air-photos in subarea A, except for those on Öland, were visited in 2003. Inspection of gravel and sandpits on Öland will be co-ordinated with a closer look at the lineament to the north of Borgholm in 2004. However, the majority of the pits was out of operation and "restored", and of the remaining ones only about fifteen displayed minor deposits of coarse silt or sand, i.e. deposits susceptible for development of liquefaction. Soft-sediment deformations tentatively caused by seismic shaking were encountered at two of these sites but the nature of the deformational processes is not clear (Figures 5-5 and 5-6).

Figure 5-4. *Glacially abraded escarpment at Stora Vadsbro some 35 km N of Västervik*

Figure 5-5. *Complex sediment stratigraphy of alternating sandy and clayey layers in a gravel pit at Helgenäs some 25 km NNW of Västervik. Extensive deformations of unknown origin occurred in two horizons, of which one is shown in the close-up photo in the lower right-hand corner. Due to a long period of drought the clayey beds were extremely tight and difficult to clean, and therefore a more thorough examination had to be postponed.*

Figure 5-6. *Strongly deformed bedding in sandy-silty deposits at Finede c 20 km to the north of Vimmerby. The water-lain sediments are partially covered by a thin bed of diamicton, probably glacial till, but to judge by appearances, glaciotectonics can probably be excluded as a cause of deformation. The features resemble seismically induced liquefaction features but the alternative, periglacial involutions developed during the Younger Dryas period, perhaps cannot be ruled out.*

In most of the gravel-pits visited, from the very south to the very north of the investigation area, the glaciofluvial deposits were covered by a bed of diamictic material and sometimes also by scattered, superficial boulders. Where the diamictic deposits are thin and diffusely defined, they may possibly be the result of uprooted and overturned trees or caused by periglacial processes during the Younger Dryas period, but where a rather thick and clearly-defined bed of till-like material occurs on an erosional unconformity cut into the glaciofluvial deposits, it appears evident that the glaciofluvium was overridden by an ice sheet (Figure 5-7).

No matter if these stratigraphies are the result of oscillations during the last deglaciation or represent deposits from two separate glaciations, glaciotectonics has to be considered a cause for deformational features in the water-lain sediments. Likewise, in areas that are situated above the highest coastline or were raised above the sea during the Younger Dryas period, periglacial processes may have contributed to the deformation of sediments (Figures 5-6 and 5-8)

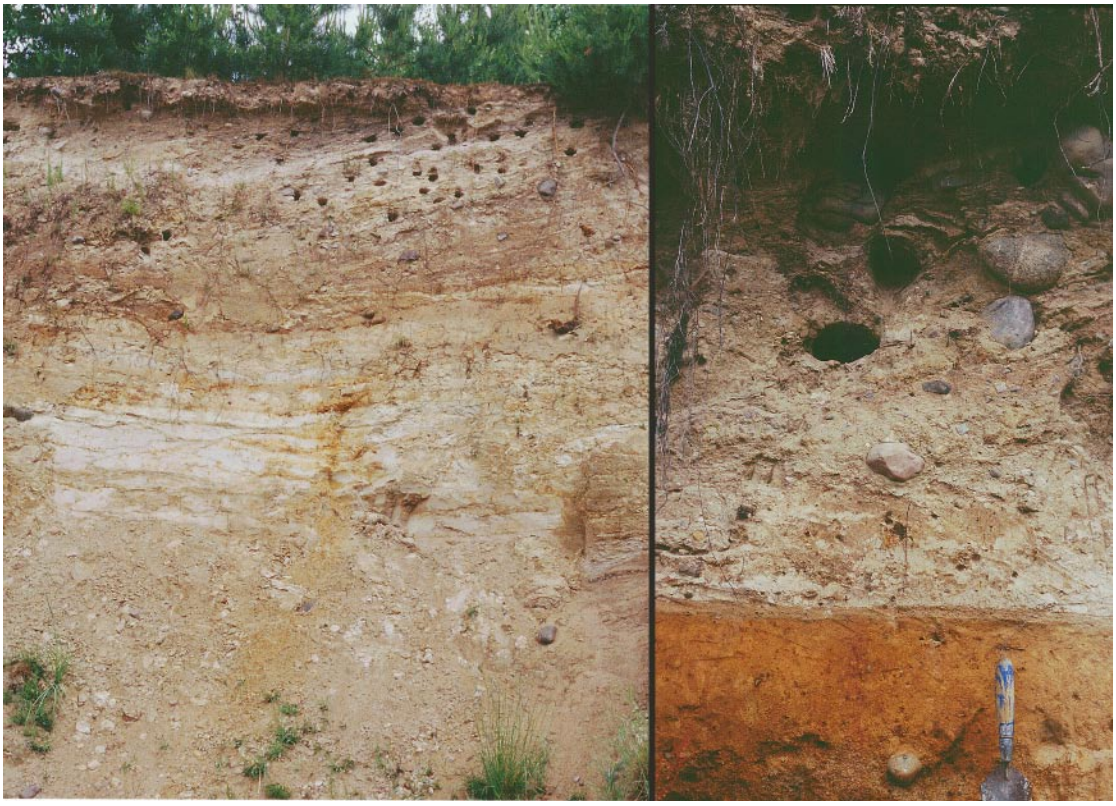

Figure 5-7. *Glaciofluvial sand and coarse silt covered by a bed of diamictic material, most likely glacial till, at Hälgsjö c 10 km to the northwest of Västervik. The upper part (2–3 dm) of the glaciofluvial sand is tectonized and contains incorporated pebbles. Well-rounded clasts in the diamicton indicate reworked glaciofluvium of local origin.*

Figure 5-8. *Ice-wedge cast in a gravel pit 1.5 km to the northwest of Södra Vi. Together with numerous ventifacts in the region the feature provides evidence of the periglacial environment prevailing during the Younger Dryas period shortly after deglaciation. Periglacial processes have to be considered when evaluating the origin of deformational features in areas that were raised above the sea during the Younger Dryas.*

5.3.3 Landslides and rockfalls

Two of the landslide scars and three of the rockfalls indicated in connection with the air-photo interpretation were inspected and confirmed in the field. Judging from the boulders occuring in the ground surface, the landslide scar at Skärsjöbråten appears to be developed in glacial till (Figure 5-9). Diamictic material was likewise found in the slide deposits at Dalhem, but according to the local farmer the uppermost deposits in the surroundings are clayey. The stratigraphies at both of these sites have to be better examined before any speculations about possible triggering mechanisms can be made.

The rockfalls as well as the taluses visited appear to be fairly stable features in present times. At the present stage of knowledge, it is neither possible to speculate on ages nor on processes, or whether the rockfalls are merely the result of strongly fractured bedrock and gravitation, or if they may have been released by frost shattering or triggered by seismic shaking.

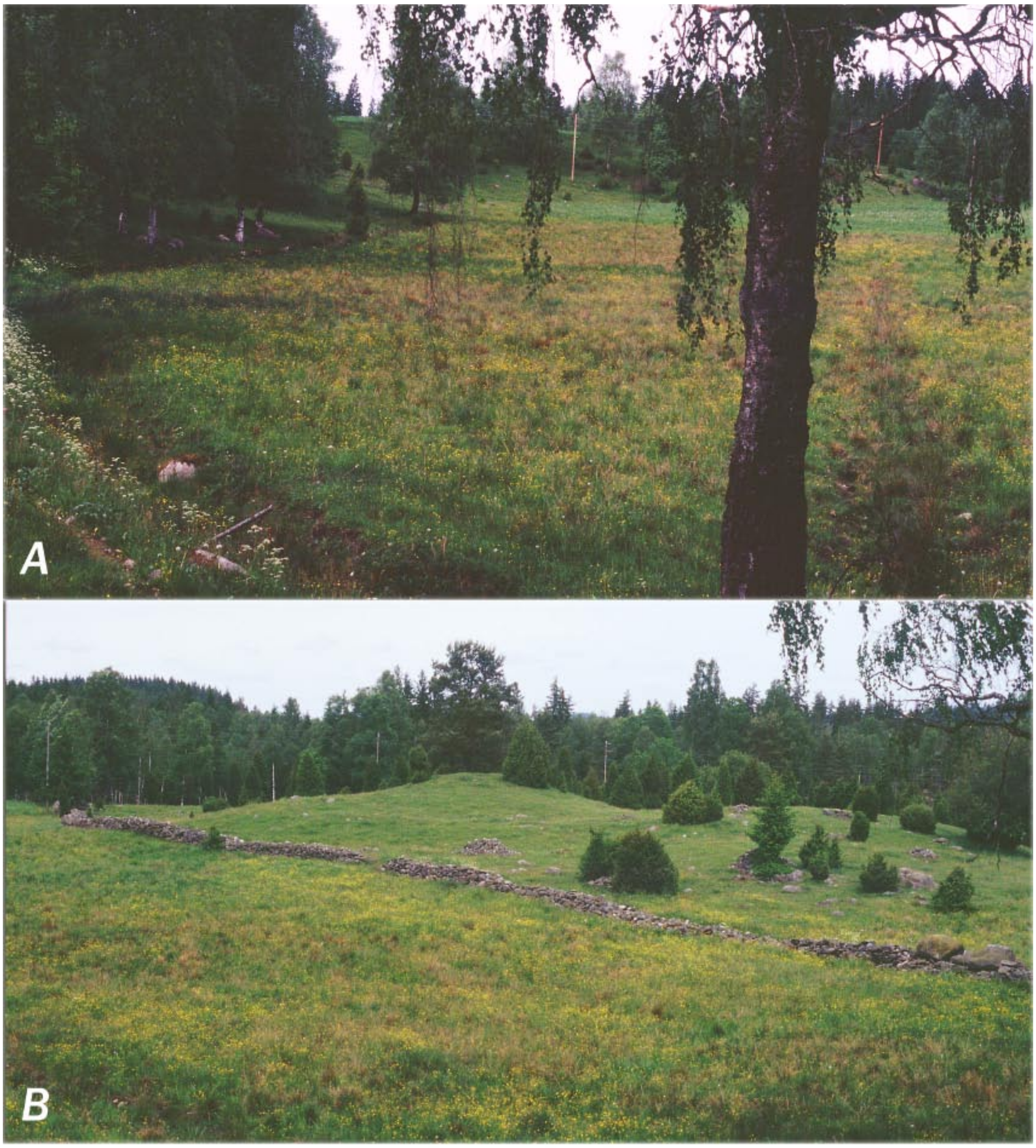

Figure 5-9 A. *Landslide scar (notice scarp in background and lower left-hand corner) and (B) slide deposits (behind the stone wall) in gently sloping ground at Skärsjöbråten some 7 km to the east of Vaggeryd. No thorough examination of the ground has been carried out, but superficial boulders indicate that the landslide was developed in glacial till.*

5.3.4 Unstable boulders

Most of the boulders encountered and considered "unstable" within the investigation area can principally be divided into two categories; a) boulders located on sloping bedrock surfaces (Figure 5-10) and b) large boulders wedged up on small stones (Figure 5-11). Intermediate forms, at one end resting on bedrock and in the other end on one or more minor stones, occur as well (Figure 5-12). A third category, c) boulders perched on top of another boulder, should also be considered. A few boulders belonging to this category were also encountered but not considered very useful as paleoearthquake indicators (Figure 5-13).

A thorough examination to reveal man-made seismoscopes of varying ages may sometimes be motivated. “Lying hens”, large boulders resting on minor stones (“eggs”, preferably three), is a well-known concept among archeologists. Undoubtedly a few of these “hens”, occurring at ancient cult sites and brooding on fairly large “eggs”, are genuine artefacts, whereas the vast majority of the hens breeding in remote areas are the result of natural processes, principally glaciofluvial erosion above and wave washing below the highest coastline. On sloping ground, solifluction may as well have contributed to strip bedrock surfaces free of soil, except for those stones that were retained by the load of big boulders.

Boulders in varying degrees of instability were accidentally encountered along many of the roads but were also actively sought for, and found, in a few small areas above the highest coastline some 35–40 km to the west of the candidate area at Simpevarp. A few fairly unstable boulders were also encountered below the highest coastline but here they appear to be far less common.

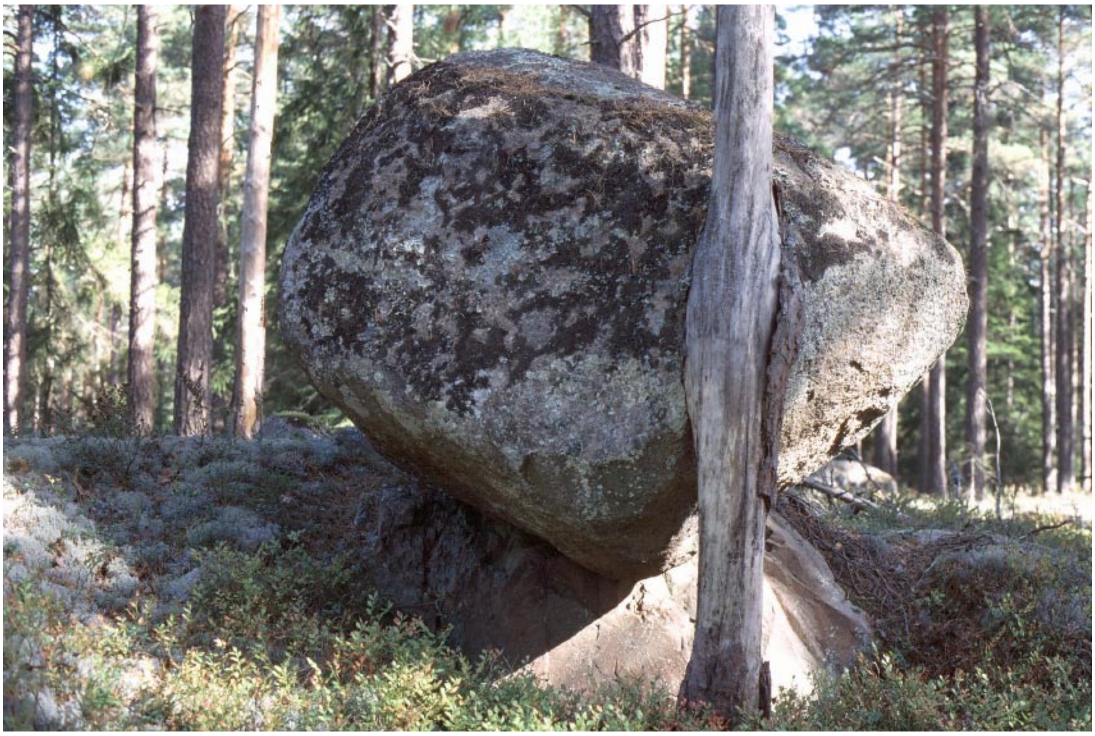

Figure 5-10. *To avoid falling over, this boulder seemingly appears to be supported by the tree. However, as situated above the highest coastline the boulder has probably, without any support, remained in the same position for thousands of years. Boulders in unstable positions occur rather frequently in parts of the investigation area and preferably above the highest coastline, where they have escaped the impact of waves and sea ice.*

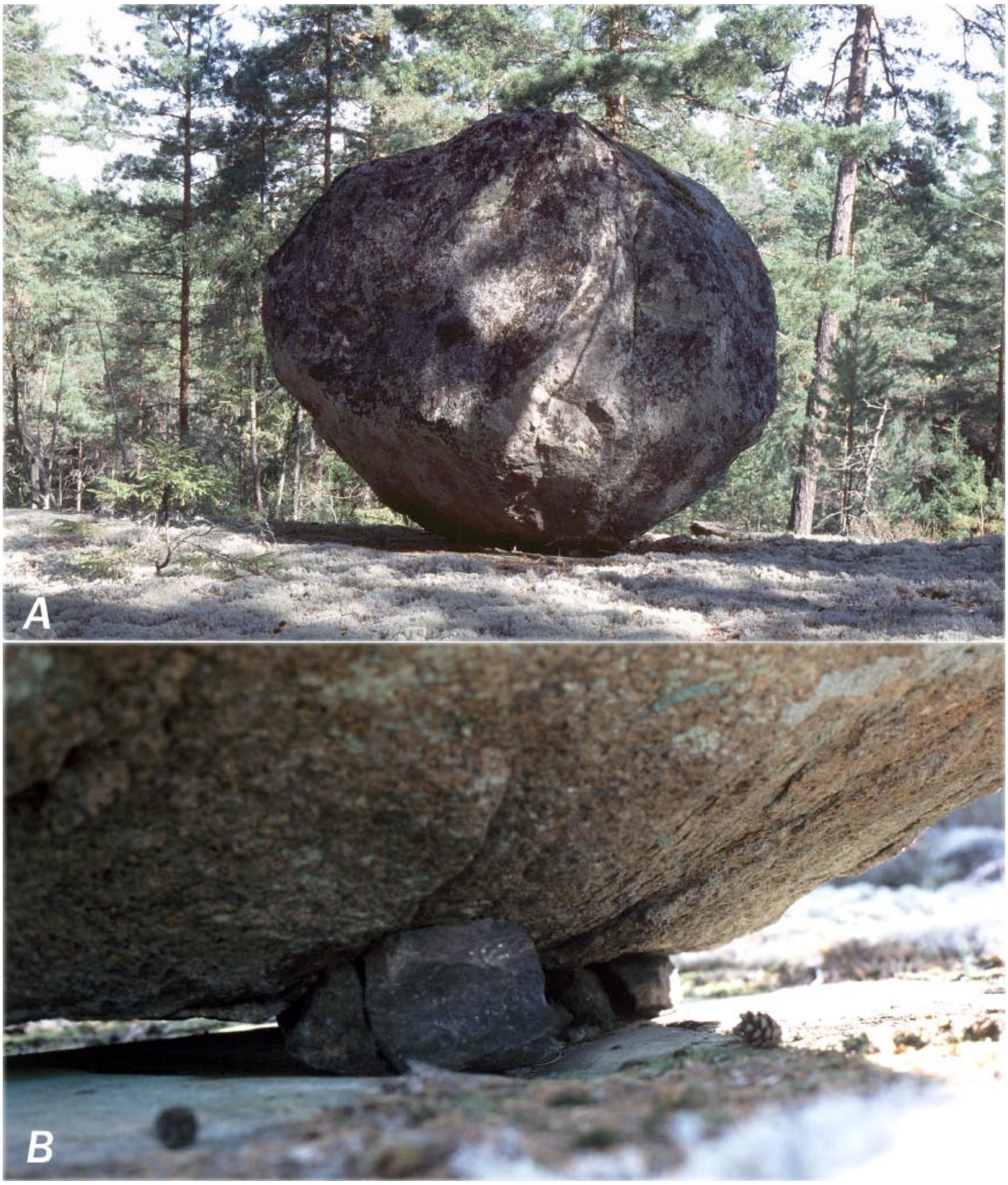

Figure 5-11. *(A) In contrast to the Colossus of Rhodes, who was toppled over by an earthquake in 226 BC, after only 56 years in an upright position, this "colossus with clay feet" has remained steadfast since it was carefully deposited by the inland ice sheet some 13,000 years ago. The weight of the boulder is estimated to c 20 tons, whereas its tiny feet (B) measure no more than c 10 cm. Certainly they are slightly broken by the load of the giant, but if only the slightest pinching had occurred by rocking during strong seismic shaking, these stones would have been grinded like peppercorns in a mortar.*

Figure 5-12. *Bottom of a big boulder, in the foreground resting on the fragments of a shattered stone but on bedrock at the very back. The primary, pre-shattering surfaces of the fragments as well as the bedrock surface displayed wind-polish, whereas the secondary, cracked surfaces were quite rough. As the wind-polishing probably dates back to the harsh climate prevailing during the Younger Dryas event, the stone obviously resisted the load of the boulder for at least several hundreds of years, but for some reason it cracked sometimes during the Holocene. If more examples of this phenomenon prove to be frequent in the area it might be indicative of a post-Younger Dryas earthquake, but so far this fragile fellow stays without known friends.*

Figure 5-13. These two perched boulders may serve as low-resolution seismoscopes for the time being, but cannot be used for the refuting of earthquakes in the distant past. The boulders proved to be quite recently piled up by human beings, probably the native people (so-called "smålänningar") who appears to be genetically predestined to collect and pile stones and, thus, cannot give up this habit despite it no longer being of vital importance for their survival.

5.4 Summary and discussions

The study is still in its infancy. In connection with the air-photo interpretation a number of features, tentatively related to young fault movements or earthquakes, were indicated. In Figure 5-2 these features appear to cluster in the northeastern and to some extent also the westernmost parts of the investigation area. Hypothetically this image may mirror that co-seismic faulting has occurred in, or been concentrated to, these areas. The allocation of the different phenomena may, however, just as well reflect a regional divergence in topography and geological setting. A thin overburden and a low relief without high cliffs in wide areas simply means that conditions for the development of landslides or rockfalls are missing, differences in tectonic style may explain the distribution of escarpments, etc. The lineament on Öland may illustrate the problem; although isolated it is for the present considered to be one of the most promising candidates for recent faulting within the investigation area.

The field reconnaissance in gravel and sandpits gave very little. Deposits susceptible for development of seismically induced liquefaction were found only in about fifteen of the pits and in very small amounts. Soft-sediment deformation features tentatively caused by seismic shaking were encountered at two sites, but the processes responsible for deformation will remain unclear until more thorough investigations have been carried out. In addition to seismic shaking, glaciotectonic impact of overriding inland ice and periglacial processes during Younger Dryas have to be considered as possible sources for deformation.

The unstable boulders may prove to be useful tools for the study. No attempts to quantify the relation between any of these boulders and earthquake ground motion have been made so far but are urgently required. Numerical modelling and dynamic field-testing have indicated that the precarious rocks described by Brune and co-workers could be toppled by accelerations of about 0.2–0.3 g /Bell et al. 1998/. Some of the unstable boulders encountered within the investigation area occur in similar positions as the "precarious" or "semiprecarious rocks" described by Brune. Estimates of how much earthquake-induced ground motion a particular boulder could withstand before it is knocked down (category A and C) or pounds its "feet" (category B) can provide constraints on the ground accelerations experienced during previous earthquakes. Findings of highly unstable boulders in the areas above the highest coastline some 35 km to the west of Simpevarp would strongly indicate that no major or great earthquakes have occurred in the candidate area since the last deglaciation some 13,000 years ago.

At the present stage of knowledge it is not possible to have a firm idea of whether any significant late- or postglacial faulting or earthquakes have occured near Simpevarp or anywhere else in the investigation area. Until field inspections have rejected recent displacement along the escarpments marked out in Figure 5-2 they remain postglacial fault candidates. The most crucial step of the study, extensive stratigraphical investigations in strategically located machine-cut trenches, remains to be done.

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