Research Paper C 836

Early Holocene faulting and paleoseismicity in northern Sweden

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Cover and above: “Like a breaking wave” – this attempt to explain the meaning of the untranslatable lappish word “Pärvie” was made by Mr Aslak Partapuoli who drew attention to the Pärvie phenomenon in the 1970s (see Lundqvist & Lagerbäck 1976). “Like a breaking wave” aptly describes the way the early Holocene faults break through the ground in northern Sweden, but may also symbolically signify the seismic waves that radiated from the faults to break down the grain structure of loosely packed and saturated sediments in surrounding areas. Both photographs show the Pärvie fault between Lake Kamasjaure and Mt. Tsåktso (seen in upper left corner on cover photograph), some 70 km north of Kiruna in northern Sweden. Photo: R. Lagerbäck.

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Contents

Abstract

The last deglaciation of northern Fennoscandia was accompanied by an episode of widespread reverse faulting associated with major (magnitude 7 or greater) earthquakes. The earthquakes triggered hundreds of landslides in glacial till, and seismically-induced soft-sediment deformation structures, "seismites", are common in trench exposures in the vicinity of the faults in northern Sweden. The episode of pronounced tectonic activity occurred as the ice sheet finally melted, strongly suggesting a causal relationship between faulting and deglaciation. However, such an outburst of faulting has not been a consistent feature of previous deglaciations, at least not in this part of Sweden, where the modest glacial erosion would allow fault scarps of a similar magnitude as the Pärvie, Lainio–Suijavaara and Lansjärv faults to be preserved, had they occurred. This indicates that the stress state history of the crust beneath the ice-sheet through the last deglaciation had a different trajectory than prevailed in previous glacial loading and unloading cycles. Deformation of sandy–silty sediments, potentially caused by earthquakes, have also been encountered in central and southern Sweden, but are less common than in the north and as yet no conclusive evidence for late- or postglacial faulting has been found south of Västerbotten County. While late- or postglacial faulting in more southern parts of Sweden can by no means be dismissed, if present, fault movements are thought to have been of minor magnitude as compared with the north.

Introduction

The low level of current seismicity in northernmost Sweden (Fig. 1) contrasts by many orders of magnitude with the seismic energy release that prevailed some 10 000 years ago. While present-day tectonics is dominated by a smooth regional uplift due to glacio-isostatic rebound after depression of the crust and lithosphere during the last glaciation, there is widespread evidence for extensive faulting and paleoseismicity in connection with the disappearance of the inland ice sheet. Since Kujansuu (1964) first announced the presence of presumed late- or postglacially developed fault scarps in Finnish Lapland, many similar features have been described from northern Fennoscandia (e.g. Lundqvist & Lagerbäck 1976, Lagerbäck 1979, Olesen 1988, Kuivamäki et al. 1998, Olesen et al. 2004).

The overall pattern of fault scarps identified in northern Sweden has not changed or been supplemented significantly since the 1970s. The Pärvie fault system and the Lainio–Suijavaara, Lansjärv, Burträsk and Röjnoret faults are still the most outstanding features. However, more recent mapping of Quaternary deposits has disclosed a few relatively short or less distinct fault scarps of supposed late- or postglacial age. The total length of the mapped fault traces in northern Sweden today slightly exceeds 400 km. Almost all of the faults have a north-north-easterly trend and the majority of the fault scarps downthrow to the west. The bedrock along the faults is generally covered by glacial deposits, but some natural rock exposures as well as observations in trenches cut across some of the fault scarps indicate reverse fault displacements.

The dimensions of the faults, extending up to some 155 km along strike and with measured vertical offsets commonly between 5 and 10 m, suggest that individual fault scarps formed in a single episode accompanied by major earthquakes estimated to reach magnitudes of c. M 7–8.2 (Muir Wood 1989, 1993, Johnston 1996, Arvidsson 1996). The coseismic connection between the formation of the fault scarps and strong ground shaking was corroborated by paleoseismic field evidence. Kujansuu (1972) reported on the occurrence of early postglacial landslides in the vicinity of the faults in Finnish Lapland, and similar landslides were subsequently found in adjacent parts of Sweden (e.g. Lagerbäck & Witschard 1983). As a result of more comprehensive mapping using air photographs, the number of identified landslides in northern Sweden was significantly increased (e.g. Lagerbäck 1990) and additional slides continue to be disclosed in connection with further mapping of Quaternary deposits in the region. An updated version of the presumed late- to postglacial faults and landslides in northern Fennoscandia is shown in Figure 2.

Inspired by the inferred relationship between landslides and faults in northern Sweden and adjacent parts of Finnish Lapland, in the early 1980s an active search for seismites was initiated in the Lansjärv area. The study revealed a great variety of soft-sediment deformation structures, interpreted to be seismically induced and formed soon after local deglaciation. The results of these initial investigations and the arguments for a connection with strong and prolonged ground shaking were summarized in Lagerbäck (1990, 1991). Since 1990, the search for seismites has been widened to comprise the coastal areas of the Gulf of Bothnia, from Norrbotten in the north down to Uppland in the south. An extensive excavation programme has been carried out, not least in the vicinity of the Röjnoret and Burträsk faults in Västerbotten, and sediment sequences in sand and gravel pits have been widely investigated. Exploratory trenches were also excavated across the Röjnoret fault in an attempt to date fault movement relative to the Quaternary stratigraphy. Furthermore, searching for potential evidence of late- or postglacial faulting has also been undertaken in the Forsmark and Oskarshamn regions in southern Sweden, at the request of the Swedish Nuclear Fuel and Waste Management Co (SKB). The present paper gives a brief account of the previous as well as the more recent paleoseismic research.

Fault-scarps of the magnitudes in question, forming in a narrow time period, are highly unusual, if not unique, in intraplate regions. The temporal connection between faulting and regional deglaciation clearly indicates a causal connection. Although the crustal shortening associated with the faulting is clearly a response to a crustal stress state that was determined by the loading and unloading of the inland ice sheet and was triggered at the final stages of the deglaciation process, there remains debate as to the precise stress trajectory and the relative contribution of tectonic plate boundary stresses stored during the existence of the ice sheet load, (e.g. Johnston 1989, Muir Wood 1989, 1993, Johnston et al. 1998, Wu et al. 1999, Lund 2005). Rather than enter into this debate, the intention with this report is to provide basic information about the fault scarps themselves and the earthquakes that accompanied their creation. By providing a rather detailed overview on these structures in Sweden it is our hope that we can contribute to a better understanding of this enigmatic episode of tectonic violence during the last deglaciation of northern Fennoscandia.

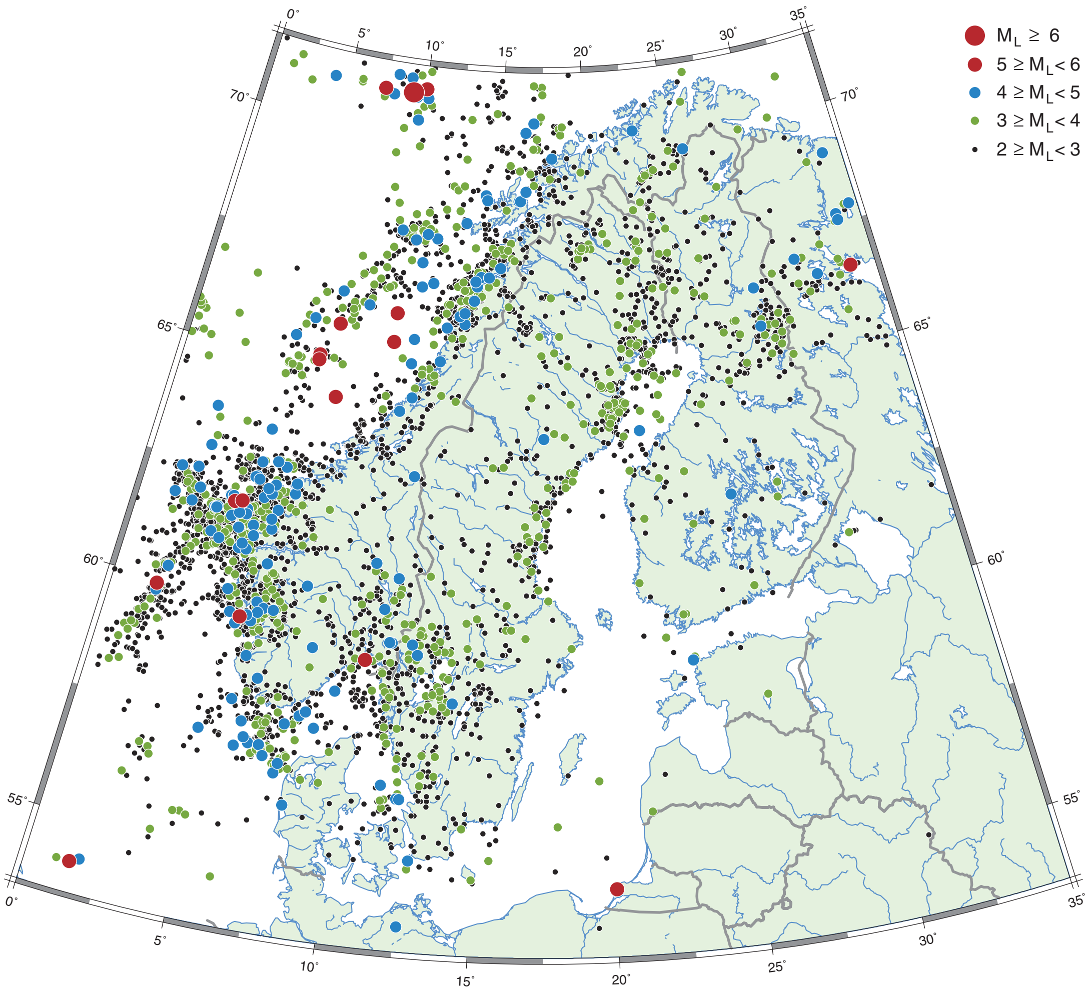


Fig. 1. Seismicity of Scandinavia and Finland 1904 to 2005, according to the Nordic earthquake catalogue maintained at the Institute of Seismology, University of Helsinki, Finland. The magnitudes have been homogenized to the local magnitude scale used by the Swedish National Seismic Network (Björn Lund, University of Uppsala, personal communication, 2008). Only events of M_L 2 or larger are included in the figure as such earthquakes have been detected and located with approximately the same accuracy in all the Nordic countries during this time period. The coverage may not, however, be complete to the south of the Baltic Sea.

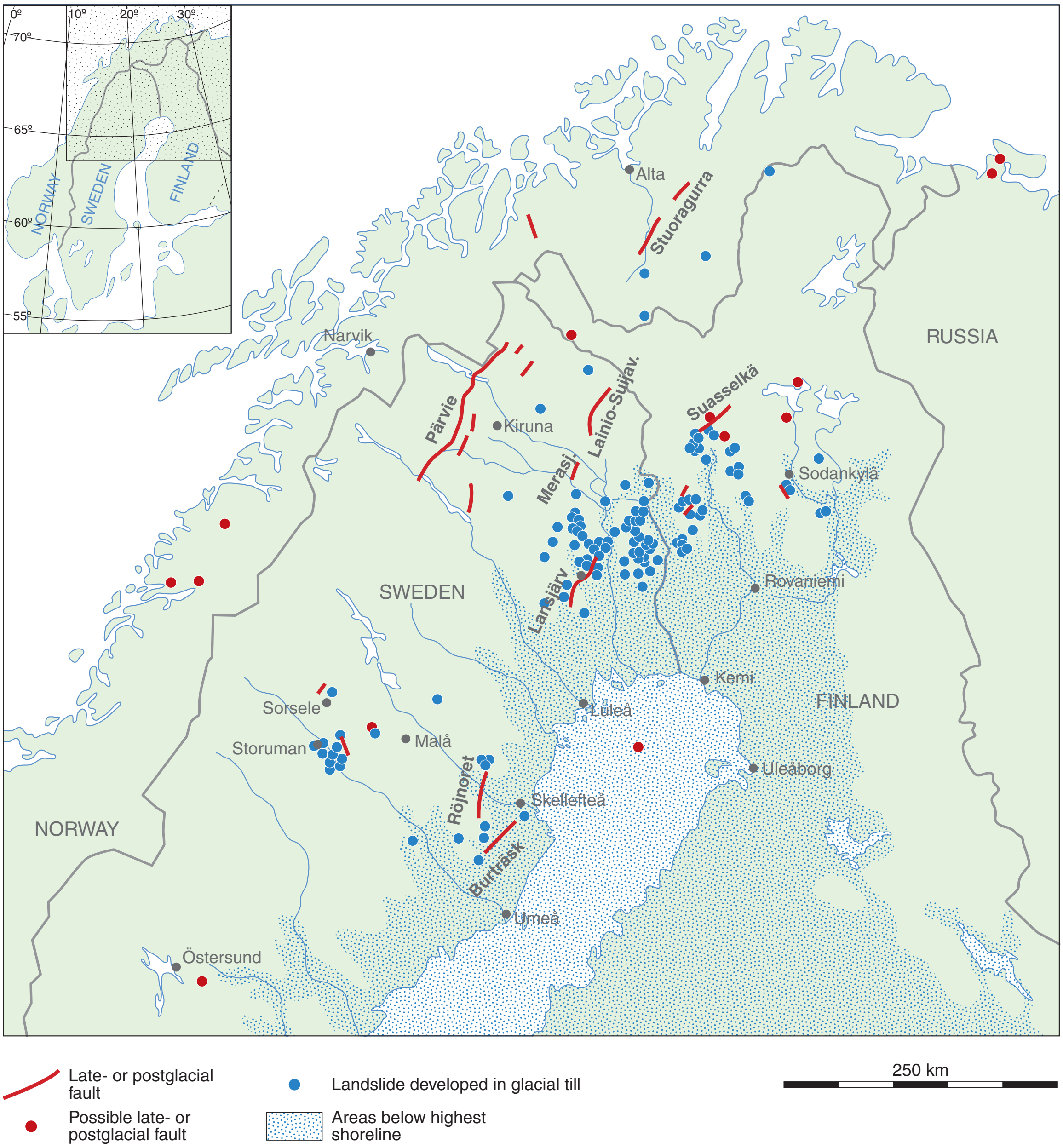


Fig. 2. Location of faults and landslide scars interpreted to be late- or postglacial in age in northern Fennoscandia. The landslides in the north-easternmost part of Sweden are so densely clustered that only a quarter of them are depicted on the map. Information has been obtained from Tanner (1930), Kujansuu (1964, 1972), Lagerbäck (1990, 1994 and previously unpublished information), Andrén (1990), Johansson et al. (1993), Ransed et al. (1994), Kuivamäki et al. (1998), Olesen et al. (2004), Johansson & Ransed (2003) and Ransed & Wahlroos (2007).

Above all the Lansjärv fault and to some extent also the Pärvie fault have been the subject of numerous investigations over the years. It is not possible here to give an account of all the research dealing with these faults and related topics, but if interested in digging deeper into the matter the reader is directed to e.g. Bäckblom and Stanfors (1989), Ericsson and Stanfors (2008), Stanfors and Ericsson (1993) and Muir Wood (1993) for reviews of some of the research carried out during the first, most intense phase of investigation in the late 1980s. A review of investigations dealing with corresponding features in Finland up to 1998 is given in Kuivamäki et al. (1998) and a review and assessment of claims of neotectonic deformation in Norway is given by Olesen et al. (2004).

Geological setting and preconditions for tracing and dating of faulting and paleoseismicity

The terrain in northern Sweden generally rises from the coastal areas in the east towards the mountain range in the west, where peaks reach some 1 500–2 100 m a.s.l. To the east of the mountains, the landscape is characterized by plains at successively lower levels towards the Gulf of Bothnia (Lidmar-Bergström 1998). Scattered residual hills, or groups of hills, occur on these plains but the terrain is mostly gently undulating and smoothly modelled. The inland and coastal areas are forested but mires and lakes largely occupy the lower parts of the terrain.

The late- to postglacial fault scarps identified in northern Sweden are all developed in the Precambrian crystalline basement, and mainly in rocks of Proterozoic age. Morphologically prominent faults occur also in the Caledonian bedrock in the mountain range, but so far no Recent fault movements along any of these features have been indicated. In contrast to the extensively exposed bedrock in the mountain range, the bedrock in the basement area is mostly covered by regolith, chiefly composed of glacial till. The average thickness of the overburden is probably some 5–10 m, but there is significant local as well as regional variation. In vast areas the Quaternary stratigraphy is complex and contains two or more till beds (Nordkalott Project 1986a, Bargel et al. 1999b). In most cases these till beds derive from different glaciations, indicating that the erosional impact of some ice sheets was very weak. This is particularly true for the most recent ice sheet, which in wide areas in northernmost Sweden left the previous landscape largely unaltered (e.g. Lagerbäck 1988a, 1988b, Lagerbäck & Robertsson 1988, Rodhe 1988, Kleman & Hättestrand 1999).

Moreover, a fairly common occurrence of saprolites (Fig. 3) beneath the glacial deposits in wide areas of northern Sweden (e.g. Nordkalott Project 1986a) indicates that the total accumulated glacial erosion during the Quaternary was generally not sufficient for any significant reshaping of the pre-Quaternary relief (cf. Kleman & Stroeven 1997, Hättestrand & Stroeven 2002). The limited erosional impact of the Quaternary glaciations implies that any significant high-angle normal or reverse fault scarps potentially developed prior to the last glaciation would probably not have become

Fig. 3. Extraction of gravelly saprolite in a drumlinoid ridge at Kompelusvaara, some 20 km south-west of Tärendö in northern Sweden. Although the area is heavily drumlinized, the glacial erosion during the Quaternary has not been sufficient to remove all of the Tertiary weathering crust. The material is covered only by a few decimeters of glacial till and is almost as easily excavated as any sand or gravel deposit. Photo: R. Lagerbäck.

completely obliterated but should be possible to trace morphologically in the present-day landscape. On the other hand, the insignificant erosional impact of the last ice sheet in certain areas implies that it is not possible to rely merely on the external, morphological appearance of the fault scarps when claiming a late- or postglacial age of the faulting. This is especially true for the Lansjärv fault, but fortunately parts of this fault are located below the highest shoreline, which allowed for dating of fault movement relative to the postglacial land upheaval (e.g. Lagerbäck 1988c).

Due to the ice load during the last glaciation, the Earth's crust became depressed by several hundred metres so that glacio-isostatic rebound began as the ice sheet started to diminish. The land uplift was at its fastest during the final phase of deglaciation and shortly after, but has continued at a decreasing rate until the present. As the ice sheet finally melted, large parts of today's coastal areas of northern Sweden lay beneath the sea (see Fig. 2) and during the subsequent land uplift pre-existing superficial deposits were reworked by waves and currents, while new sediments were deposited below the highest shoreline. The erosional and depositional processes in the contemporary sea may have caused some degradation of fault scarps and reduced their detectability, but have also created opportunities for dating the fault movements relative to the Holocene sediment stratigraphy and land upheaval history.

Furthermore, sandy–silty sediments deposited in the sea at this time are now elevated and available for trenching on dry land and provide excellent conditions for tracing paleoearthquakes throughout the Holocene. Low elevation sandy and coarse silty glaciofluvial sediments are particularly favourable for this purpose as they remained entirely saturated, and thus susceptible to seismically induced liquefaction, from the moment of deglaciation until they emerged, fairly recently, above the sea. The most favourable sites for tracing Holocene paleoearthquakes in excavated trenches occur along the margins of eskers in present-day coastal areas.

The relationship between fault scarps and various morphological features associated with ice-flow, glacial melting and marine erosion and deposition offers a wide range of possibilities to date fault rupture relative to deglaciation. Dating relative to local deglaciation, however, provides only a rough age estimate as neither the course nor the chronology of the deglaciation in northernmost Sweden are accurately known. According to Lundqvist (1998) the coastal areas of northern Sweden were deglaciated around 10 400–10 000 BP, whereas radiocarbon dates of lacustrine sediments suggest that the coastal areas of Norrbotten became ice-free somewhat earlier, at c. 10 500 BP (Lindén et al. 2006). Although only roughly outlined, Lundqvist (1998) favours a successive recession of an ice margin from the coastal areas towards the northern mountaineous area, where the last remnants of the ice sheet are supposed to have vanished at c. 9 500 B.P.

However, according to e.g. Karlén (1979), the northwestern parts of Norrbotten County were deglaciated before 9 000–8 500 ^{14}C-yrs B.P. and one of the present authors (Lagerbäck) has obtained ^{14}C-ages well above 9 000 BP when dating the bottommost parts of peat deposits in different areas of interior Norrbotten, e.g. 9 430 ± 115 (St 6840) at Abborrträsk in southern, 9 220 ± 190 (St 6834) at Hakkas in central and 9 620 ± 70 (St 13231) at Muodoslompolo in north-eastern Norrbotten. If calibrated into calender years, these ^{14}C-ages would indicate that the interior of Norrbotten was deglaciated more or less contemporaneously with, or even prior to, the coastal areas (i.e. provided that the estimated ages of deglaciation in these areas are reliable). Moreover, dating of peat in mires in principle yields only minimum ages for ice-free conditions. If considering the appearance of the glaciofluvial drainage pattern of the region (e.g. Nordkalott Project 1986b, Bargel et al. 1999a), it is, however, highly unlikely that the interior areas were deglaciated before the coastal areas.

An explanation of this incompatibility might be that the peat in some mires is "contaminated" by old organic matter and yields too high ages. Preserved organic matter from two Weichselian interstadials occurs commonly in wide areas of northernmost Sweden (Lagerbäck 1988a, Lagerbäck & Robertsson 1988) and may have been washed into mires and lakes at an early stage of peat and gyttja accumulation. It may be mentioned that Lindén et al. (2006) also received some remarkably high ages when dating the deglaciation of the coastal area but, for similar reasons, discarded these dates as "incorrect". Thus, it should be strongly stressed that the course of deglaciation is poorly known, and very likely a rapid amelioration of climate during the early Holocene after the Younger Dryas event may have resulted in an areal downwasting of a stagnant ice sheet, ending in an irregular pattern of ice remnants, rather than a successively receding ice margin. Accordingly, we only know imperfectly when the ice sheet finally disappeared from northern Sweden and it is not possible to give a detailed account of which area became ice-free before the other. This implies that, not only is it difficult to settle the absolute age of faulting, but even the relative order of rupturing of the different faults cannot be resolved relative to the chronology of local deglaciation.

The rupturing of the faults may, in principle, also be dated from the ages of the secondary, seismically induced phenomena. However, since the dating of these features likewise is based on radiocarbon dating of peat or by their temporal relation to deglaciation and land upheaval and, moreover, since there are areas in which it may be difficult to attribute a certain landslide or soft-sediment deformation feature to a particular fault scarp, this also cannot fully resolve the age problem. Cosmogenic dating of fault scarps or luminescence dating of sediments exposed in fault scarp development would theoretically offer possibilities for dating, but even these methods are not considered accurate enough for more precise dating. Radiocarbon dating of organic matter that became buried by masses that slumped from the collapsing hangingwalls in direct connection with fault scarp development would provide conditions for reliable direct dating, but any suitable soil horizon or the like was never found in the trenches excavated across the fault scarps.

Methods

AIR PHOTOGRAPH INTERPRETATION

The faults and landslides in northern Sweden have been detected and mapped principally by means of air photograph interpretation. After the disclosure and first mapping of the main Pärvie fault (Lundqvist & Lagerbäck 1976) some four-fifths of the territory of Sweden were examined in a few weeks by studying black-and-white photographs on a scale of 1:30 000 in a mirror stereoscope. During this extremely brief scanning, most of the presently known fault scarps in northern Sweden were discovered (Lagerbäck 1977, 1979), but

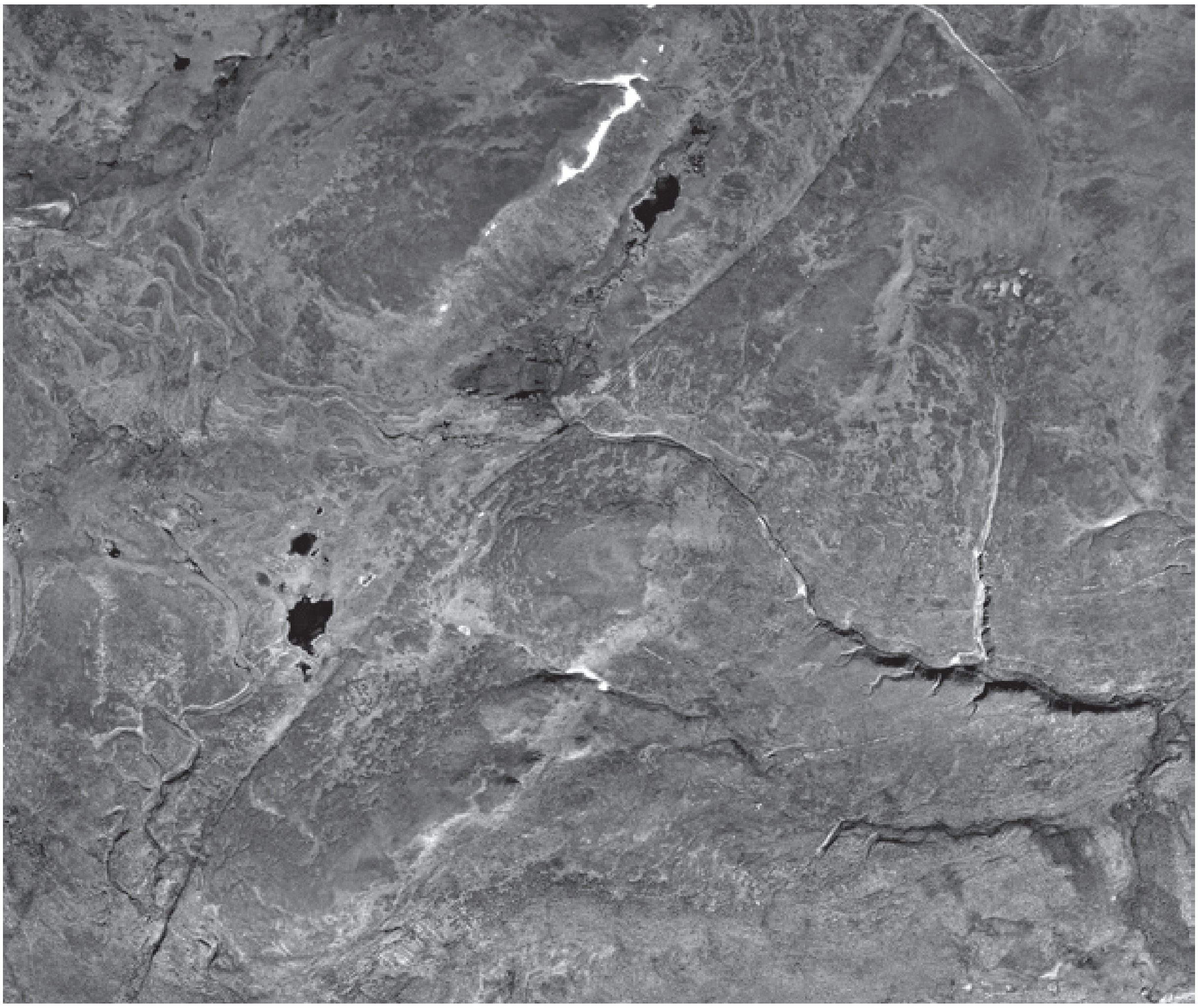


Fig. 4. Air photograph showing the Pärvie fault north-east of Lake Vuolep Kaitumjaure, some 60 km south-west of Kiruna (cf. Fig. 14). The fault scarp runs diagonally across the photograph, from lower left to upper right. Air photograph: National Land Survey of Sweden. © Lantmäteriverket Gävle 2008. Medgivande I 2008/1991 .

some additional, relatively short or less conspicuous fault scarps have later been detected by means of air photograph interpretation in connection with the local mapping of Quaternary deposits. Only a few landslide scars were identified during the first inventory of fault scarps, but their number has afterwards been greatly increased by means of more detailed air photograph interpretation.

Most of the fault scarps are fairly conspicuous and appear in air photographs as extended lineaments (Fig. 4). When looked at stereoscopically the fault scarps are, of course, so much more easily identified as anomalous features because of the steplike break in the landscape (Figs. 5, 27). Similarly, the landslide scars are usually clearly defined by the steep escarpments along their margins and stand out as atypical recesses in the otherwise smoothly shaped, gentle hillslopes (Figs. 6, 7). In fact, both the fault scarps and the landslides are generally more easily identified from the bird's-eye view than from the ground, and this is especially true in wooded areas where low relief and trees obstruct the potential to view the full extent of the scarp morphology. Though some of the fault scarps occurring in wooded areas are no higher than one or a few meters, it has been possible to trace them in air photographs due to their extension in the terrain.

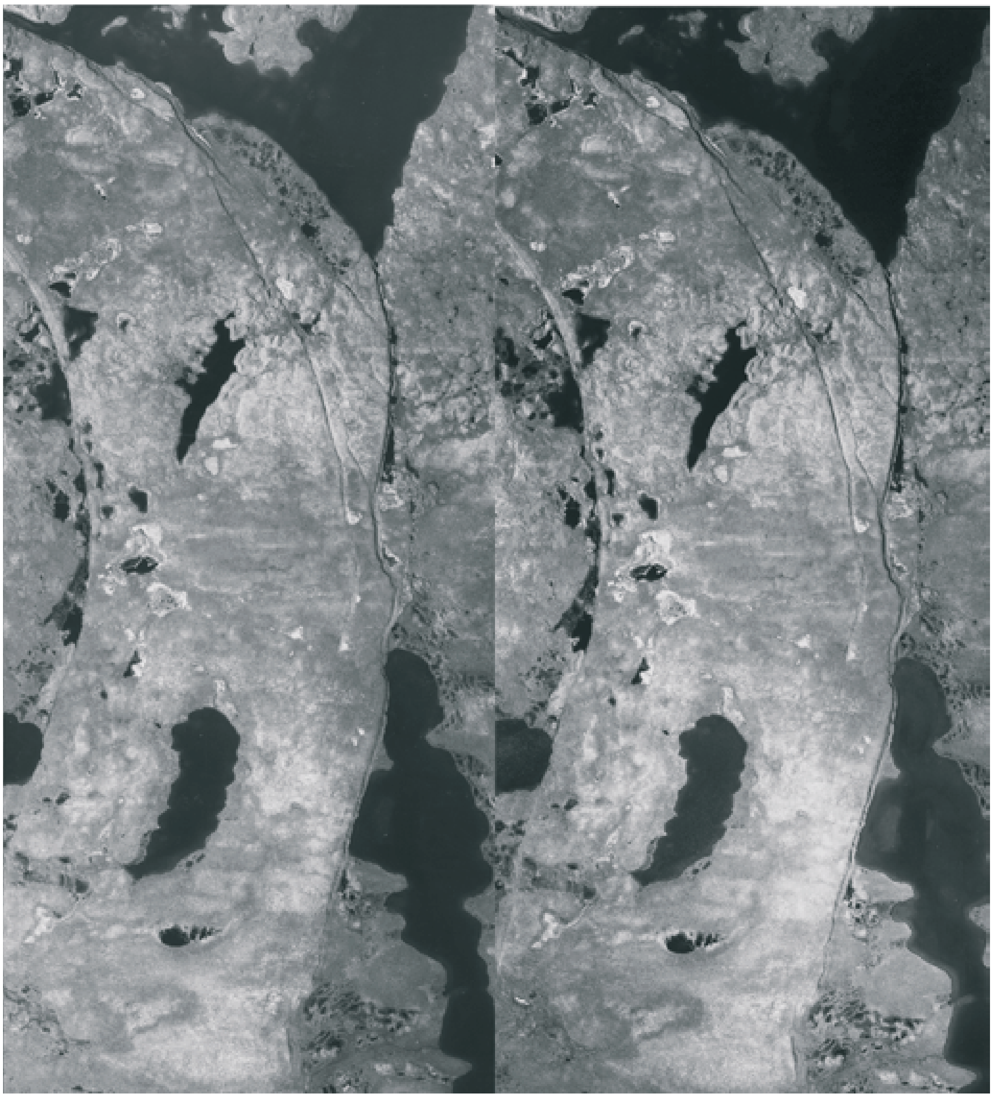


Fig. 5. Stereo-pair of air photographs showing the main Pärvie fault (right) and a minor antithetic fault scarp (left) at Lake Kamasjaure, some 70 km north of Kiruna. The arcuate fault traces are clearly governed by bedrock structures and contacts between different rock units (cf. Fig. 13, north is to the right in the image). Scale: approx. 1:30 000. Air photograph: National Land Survey of Sweden. © Lantmäteriverket Gävle 2008. Medgivande I 2008/1991 .

Fig. 6. Landslide scar at Lompolonvaara, some 20 km south-south-west of Pajala. When trees are clear-cut, the landslide scars are easily identified from the ground as well as from the air, but if densely vegetated they may easily be overlooked (cf. Fig. 7). Photo: R. Lagerbäck.

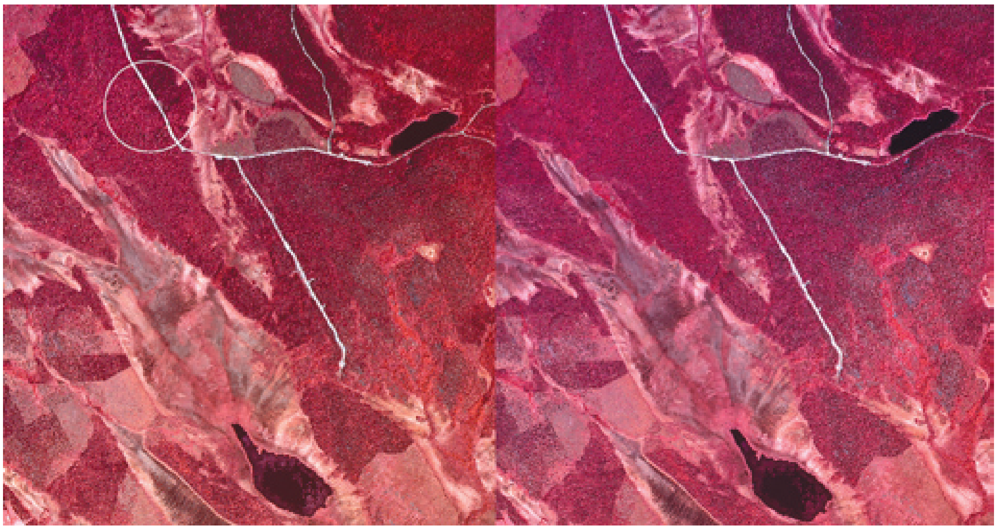


Fig. 7. Stereo-pair of infrared (IR) air photographs showing the landslide scar (encircled) at Lompolonvaara (Fig. 6) while the area was still forested. Scale approximately 1:60 000. Air photograph: National Land Survey of Sweden. © Lantmäteriverket Gävle 2008. Medgivande I 2008/1991 .

TRENCHING

Exploratory trenches have been very widely excavated in the investigation of the faults and associated paleoseismic phenomena. Two styles of trenching have been employed: (1) Some 10 trenches have been excavated intersecting fault scarps in order to determine the nature and age of dislocation (Fig. 8). Some of these trenches reached considerable depths, up to 12 m. Layers of glacial till and littoral sediments in the trench sections constitute reference structures for dating the fault movements relative to glaciations and land upheaval. (2) Many kilometers of trenches, with depths between

Fig. 8. Excavation of an exploratory trench across the Röjnoret fault at Stensberget (site 2 in Fig. 62), some 40 km west of Skellefteå. Photo: R. Lagerbäck.

Fig. 9. Typical exploratory trench excavated in level ground with the purpose of searching for evidence of seismically induced soft-sediment deformation. The trench is c. 3.5 m deep and cuts into sandy–silty deglaciation sediments. The investigator (M. Sundh) is occupied with trimming of the trench walls. Note deformation features in the c. 0.5 m thick sandy–silty layer in lower left. Flarken (site 10 in Fig. 62), some 50 km south of Skellefteå. Photo: R. Lagerbäck.

Fig. 10. Although very narrow at the base, this erratic boulder Spikstenen, at Ripsa some 25 km north of Nyköping in southern Sweden, has remained in its present position since it was raised above the sea thousands of years ago. When the inland ice melted away from the area, the boulder was probably partly embedded in glacial till, but after the till was washed away by waves and currents during land upheaval only a few small stones give support to the monolith. Photo: R. Lagerbäck.

2 m and 5–6 m, have been excavated in sediment deposits of different types and ages in order to search for seismically induced distortions of the primary layering (Fig. 9). Because of reasons given above, most of these trenches were dug in sandy–silty glaciofluvial deposits at sites located at low altitudes above sea level. To exclude distortions caused by creeping or sliding, the trenching was as far as possible carried out in level or only very gently sloping terrain.

RECONNAISSANCE IN SAND AND GRAVEL PITS

Complementary information on the presence or want of seismically induced deformation in certain areas has been gained from examination of sandy–silty sediments in sand and gravel pits. Unfortunately, in this context, the extraction of glaciofluvial sand and gravel has decreased during later years and abandoned pits are commonly "restored" so that sediment sequences are no longer available for examination. A total of some 300 sand or gravel pits have been visited in the whole of Sweden, most of them in the southern parts of the country and notably in Uppland and eastern Småland. Unfortunately, only a minor proportion of these pits contained significant amounts of loose sandy–silty sediments considered to be susceptible to liquefaction if saturated.

RECONNAISSANCE FOR UNSTABLE BOULDERS

In glaciated areas some erratic boulders are spectacularly deposited and constitute analogues to the "precariously balanced rocks" described by Brune (e.g. Brune et al. 1996). If markedly unstable, such boulders may serve as "non-recurrent seismoscopes" providing evidence that no major earthquakes have occurred in their vicinity since they came to rest in their current unstable positions (Fig. 10). However, for several reasons (besides potential earthquakes) such boulders are rare and usually only found where there is a high concentration of erratic boulders. A systematic reconnaissance for unstable boulders has been carried out only in parts of the eastern Småland investigation area in southern Sweden (Lagerbäck et al. 2004, 2005a), but spectacularly deposited boulders are also occasionally encountered in other areas.

Faults

The faults inferred to have been active during late- or postglacial times in northern Sweden are shown in Fig. 2. To those identified in Lagerbäck (1990) have been added a set of rather low scarps to the south-east of the main Pärvie fault, a few short scarps in the interior of Västerbotten County and a southern, isolated occurrence near Östersund. Most of the fault lines shown in Figure 2 are not continuous but composed of separate fault segments, together forming fault sets in line with one another with fairly consistent scarp elevations where the single segments are presumed to have ruptured in the same event. The fact that the traces and heights of the individual fault segments belonging to a certain fault set, as well as the gaps in between the separate segments, appear to be largely governed by the structures and composition of the superficial bedrock indicates that more continuous faulting and fault rupture must occur at depth.

Generally, the bedrock is poorly exposed along the fault scarps (Fig. 11), but the sporadic natural exposures as well as observations in trenches excavated across the scarps almost exclusively indicate dip-slip reverse (45–90°) movement. Where exposed, the bedrock in the fault zones is mostly strongly fractured, weathered and in places more or less disintegrated and, thus, clearly indicates failure along pre-existing faults or other zones of weakness (Fig. 12). At several sites, a close connection to older fault and fracture zones is demonstrated also by ground and airborne electromagnetic and magnetic surveys (e.g. Henkel et al. 1983). That at least some of the fault zones host an extensive network of open fractures and serve as conduits for large quantities of groundwater is demonstrated by numerous springs occurring along several of the fault scarps.

The argument that these fault scarps had a late- or postglacial age was originally based on their fresh appearance, as it was assumed that the features would not have survived the erosional impact of the latest inland ice sheet (Lundqvist & Lagerbäck 1976, Lagerbäck 1979). When the limited amount of glacial erosion during the most recent glaciations became known, this argument needed to be revisited. However, at many localities the relationship between fault scarps and various morphological features, unambiguously formed by the latest ice sheet or its melt water, demonstrates that the faulting occurred subsequent to, or in close

Fig. 11. Typical appearance of a fault scarp when developed in glacial till. The Pärvie fault at the western foot of Mt Tsåktso, some 70 km north of Kiruna. Photo: R. Lagerbäck.

Fig. 12. Where exposed along the fault scarps, the bedrock is often strongly fractured and weathered. The photograph shows a shattered bedrock outcrop along the southern part of the Pärvie fault to the north of Mt Pålnotjåkko, some 70 km south-west of Kiruna (cf. Fig. 14). The extension of the fault borders (and dams) the lakes in the background and can be traced up the slope of the mountain in the upper left, making a notch in the horizon. Photo: R. Lagerbäck.

connection with, local deglaciation. In the Lansjärv area, where the impact of the most recent ice sheet on previous deposits was more or less insignificant, the age of faulting was established by stratigraphical investigations in trenches excavated across the fault scarps (e.g. Lagerbäck 1988c, 1992).

A short description of the different faults is given below. The traces of the Pärvie (including subsidiary faults to the east of the master fault), Lainio–Suijavaara, Merasjärvi, Lansjärv, Burträsk and Röjnoret faults and their relations to bedrock geology are shown in Figures 13–17. For a more detailed account of fault traces, fault scarp heights and bedrock properties along the Pärvie, Lainio–Suijavaara, Merasjärvi and Lansjärv faults the reader is referred to Lagerbäck & Witschard (1983), although additional information has modified somewhat the mapped traces of the Pärvie and Lansjärv faults.

THE PÄRVIE FAULT SYSTEM

The main Pärvie fault consists of a linear series of fault scarps, almost all of them west-facing and together forming a north-north-east trending, 155 km long fault line (Figs. 13–14). Bedrock exposures occur rather frequently along parts of the fault, and at several locations overhanging cliffs indicate reverse movements on steeply dipping fault planes (Fig. 18). Field observations and photogrammetric measurements indicate that fault scarp heights generally vary between 3 m and 10 m, but locally somewhat greater heights were measured (Lagerbäck & Witschard 1983). At varying distances to the east of the master fault there is a number of subsidiary fault scarps, almost all of them eastward-facing, i.e. opposite to the master fault. The length of the subsidiary faults varies between a few kilometers and c. 30 km and their heights between 1–2 m and about 10 m.

One of these subsidiary faults consists of four separate, eastward-facing fault scarp segments, together

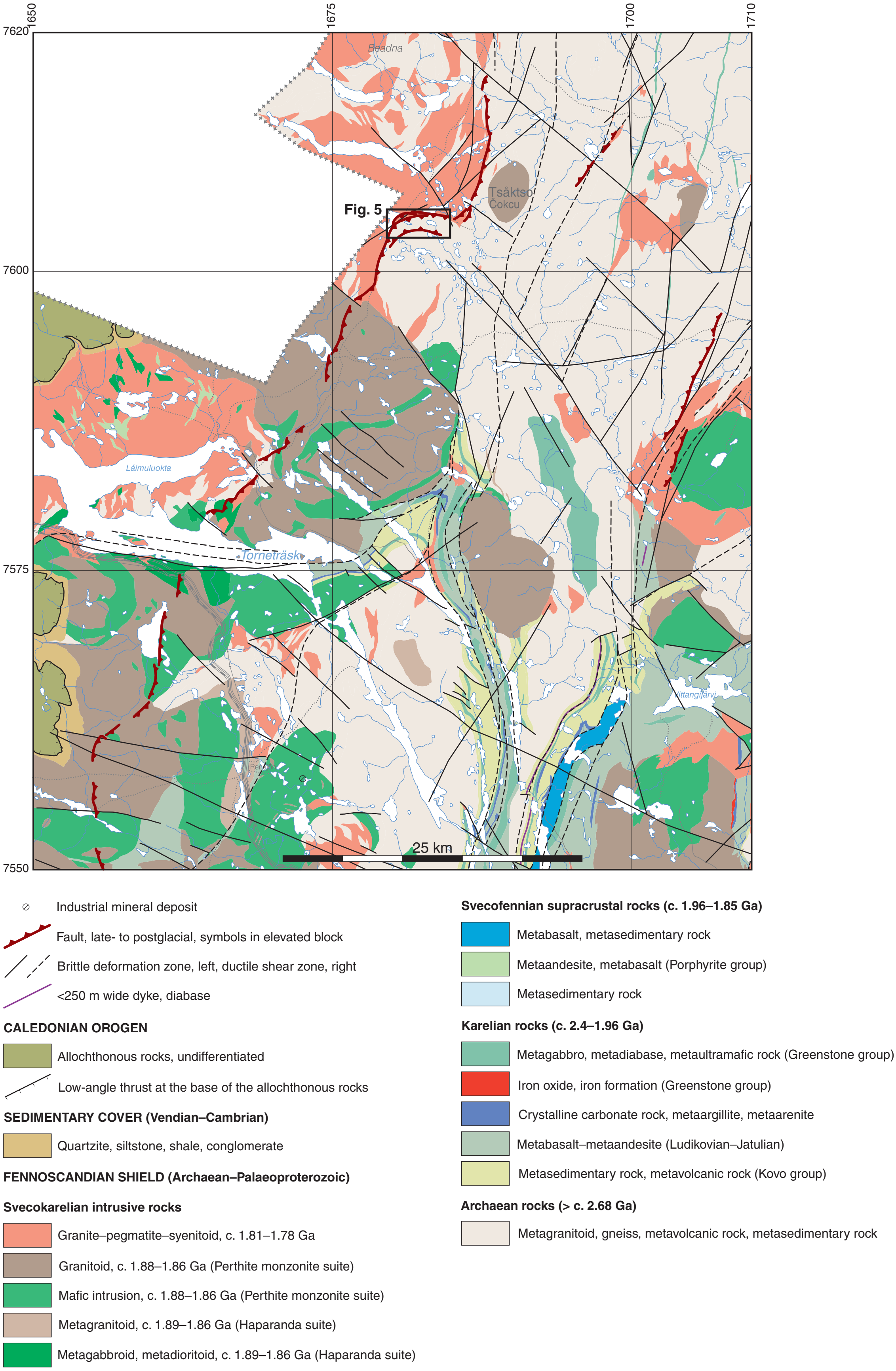


Fig. 13. The traces of the northern part of the Pärvie fault system depicted together with the bedrock of the area. Bedrock map simplified after Bergman et al. (2001).

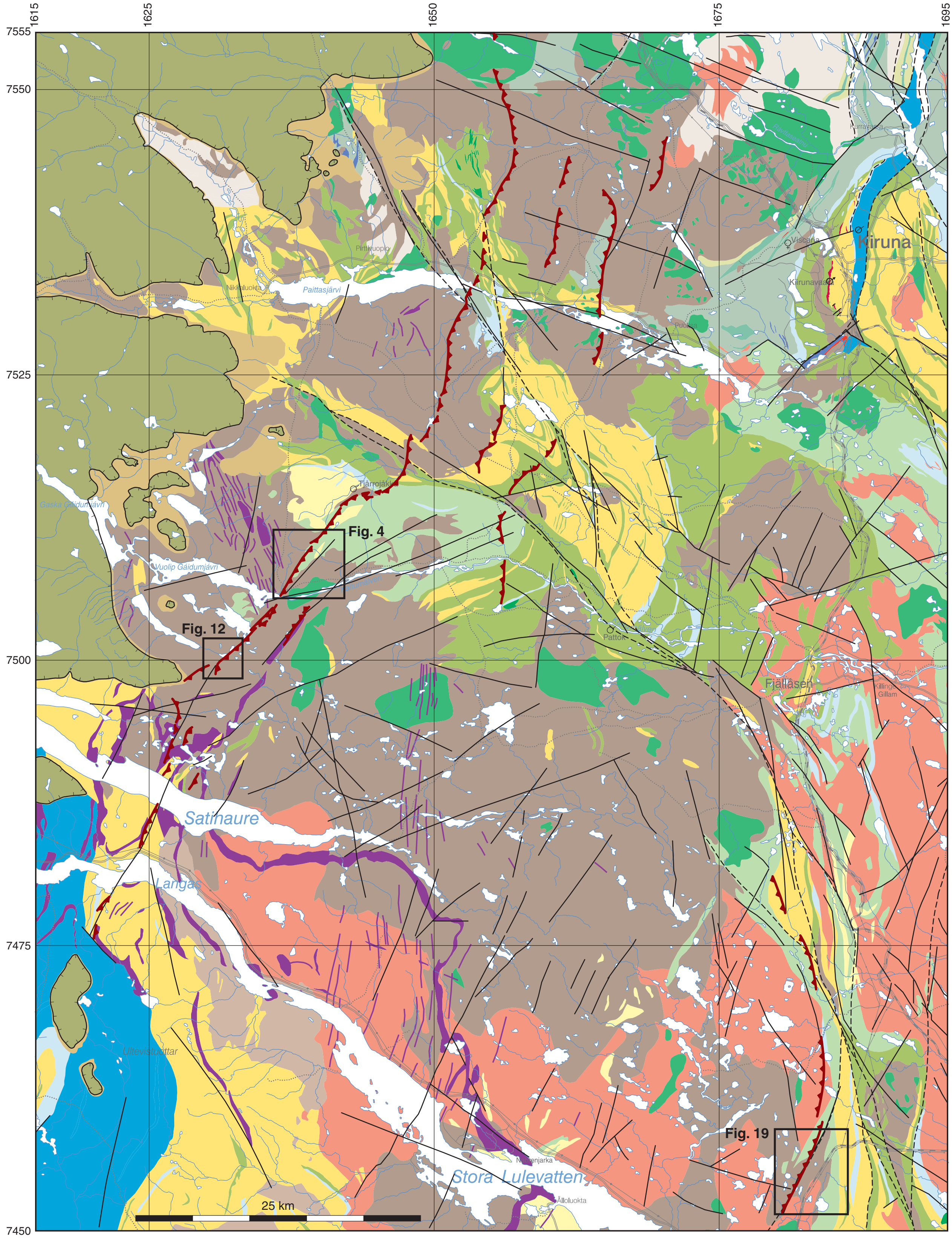
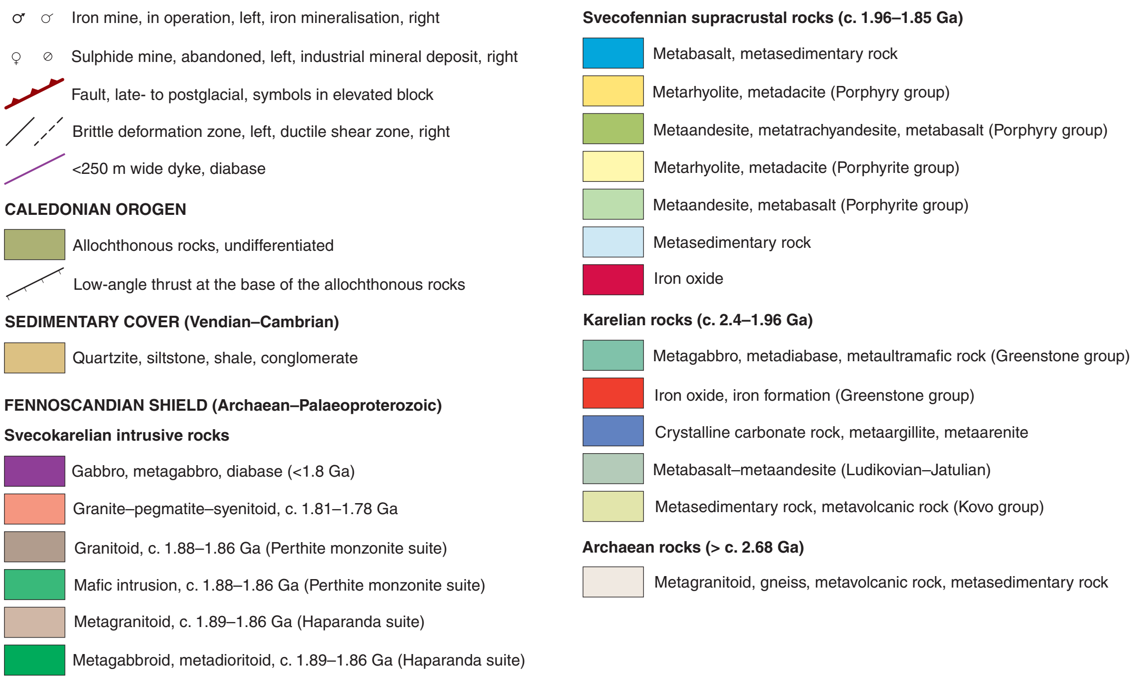


Fig. 14. The traces of the southern part of the Pärvie fault system depicted together with the bedrock of the area. Bedrock map simplified after Bergman et al. (2001)



forming a 30 km long, arcuate fault line some 60 km south-east of the southern part of the master fault (Fig. 14). The feature was early noticed in air photographs but has not previously been shown on maps since it was considered somewhat doubtful and not verified by field evidence. However, when later field-checked the individual fault scarp segments proved to be easily identified from the air (Fig. 19) as well as from the ground. Although no more than a few meters high and occurring in a swampy area, the scarps appear as well defined and anomalous steps in the otherwise level terrain and they are therefore considered to represent true fault scarps. As mentioned above, the trends of some of the fault traces are largely governed by bedrock structures and this appears to be true for this feature as well (Fig. 14).

Due to their location in remote areas, no excavations have been carried out across any of the scarps belonging to the Pärvie fault system. However, several of the individual fault scarps can be dated relative to different morphological features deriving from the most recent deglaciation (Lundqvist & Lagerbäck 1976, Lagerbäck & Witschard 1983). Presuming that the separate segments of the main Pärvie fault and the subsidiary fault to the east of it ruptured in close connection to each other, the rupturing of the Pärvie fault system can be closely related and dated to the deglaciation phase of the area. For instance, all but one of a series of beaches developed along the shores of a major ice-dammed lake are cut by the fault scarp at the southern end of the fault (Lagerbäck & Witschard 1983). Besides dating fault movement relative to deglaciation, the occurrence of this ice-dammed lake indicates that wide areas around the fault may have still been covered by ice during faulting.

THE LAINIO–SUIJAVAARA FAULT

The Lainio–Suijavaara fault displays an almost continuous, c. 50 km long fault scarp and three short (2–3 km) scarps centrally located in front of the main fault (Fig. 15). The main fault scarp as well as the frontal scarps all face westwards. The northern two-thirds of the fault strikes NNE–SSW but, clearly governed by the boundary between different bedrock units, it then bends into a southerly or slightly south-south-easterly direction (Fig. 15). The height of the main scarp at the fault generally ranges between c. 10 m and 20 m, while one of the frontal scarps, at Pyhävaara, is exceptionally high (25–30 m, although not all the height of the scarp may in fact reflect the fault displacement) and exhibits a spectacularly shattered bedrock at the edge of the raised block (Figs. 20, 21). An abundant groundwater discharge occurring at the foot of the latter fault scarp indicates an extensively fractured bedrock in the fault zone (Fig. 22).

It has not been possible to accurately date the faulting relative to deglaciation, but the fact that the northern part of the main fault scarp appears to have governed the course of a major melt-water stream, which excavated a rather impressive erosional channel along

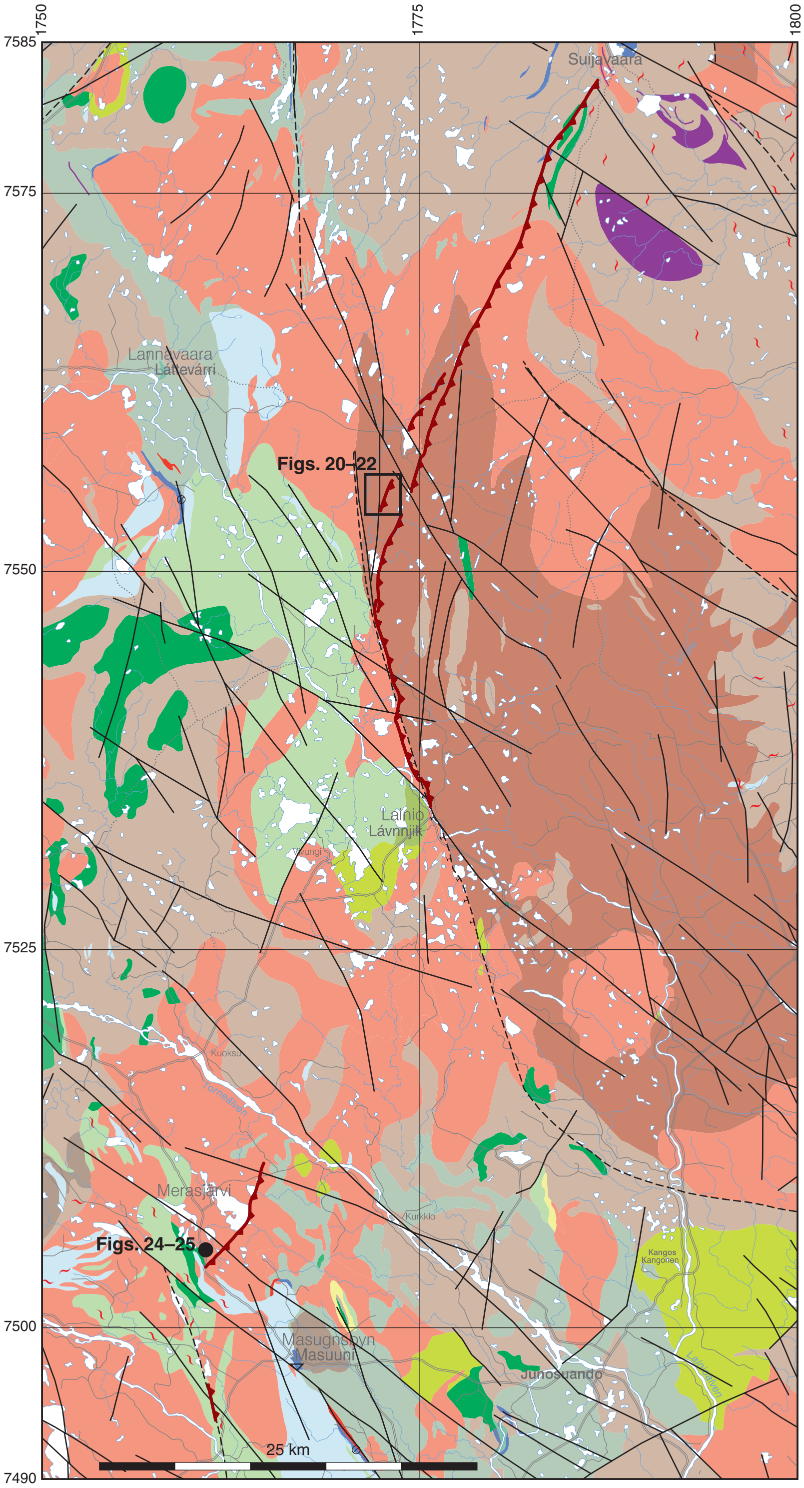
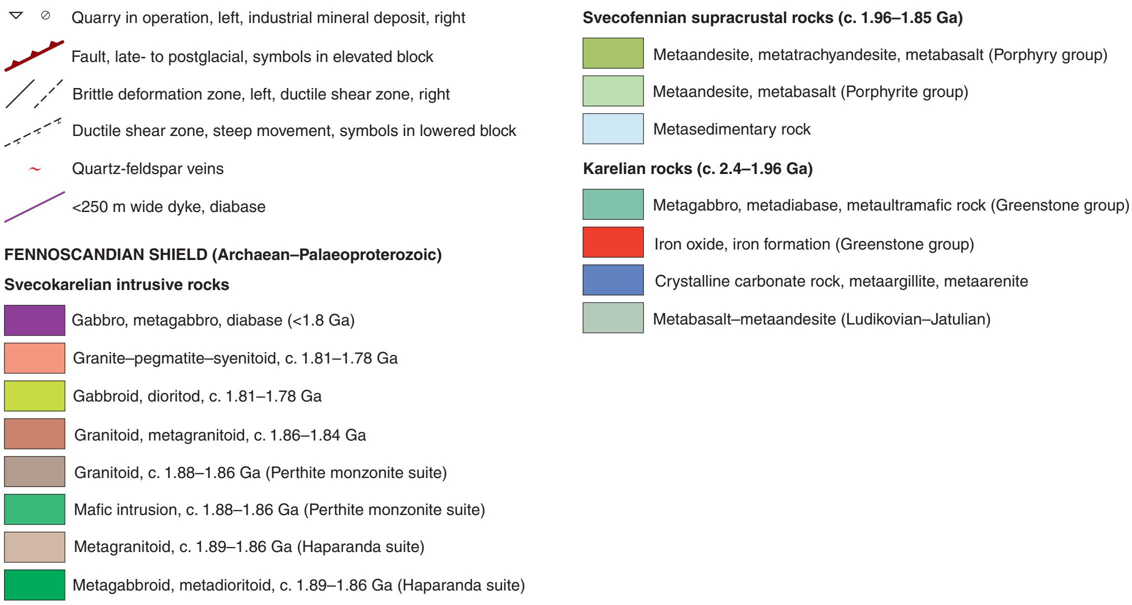


Fig. 15. The Lainio–Suijavaara and Merasjärvi fault traces depicted together with the bedrock of the area. The nature and age of the short scarp depicted to the south of the Merasjärvi fault is somewhat uncertain. Bedrock map simplified after Bergman et al. (2001).



the scarp, indicates that faulting pre-dates the deglaciation of the area (Fig. 23). On the other hand, the bouldery mass of the collapsed fault scarp at Pyhävaara (Fig. 21) appears to be completely unaffected by any glacial impact and no significant impact of glacial erosion can be seen anywhere along the master fault. As the last ice sheet is interpreted to have been actively flowing over the area during the deglaciation phase, and thereby slightly reshaping previous deposits, this implies that faulting most likely occurred only shortly before local deglaciation.

THE MERASJÄRVI FAULT

The Merasjärvi fault consists of a continuous, 8 km long and slightly arcuate fault scarp downthrowing to the west (Figs. 15, 24). Although relatively short when compared with the other fault lines, the scarp is remarkably high, c. 10–15 m or slightly higher in the southern part (Fig. 25). Similar to the main part of the Lainio–Suijavaara fault the Merasjärvi fault trends NNE–SSW and, with a 25 km gap in between, it is located in the extension of the former. The two faults are of similar heigth and it might be speculated that they are the surface ruptures of a more extensive dislocation at depth. The occurrence of another westward facing escarpment some eight kilometers to the south of the Merasjärvi fault (Fig. 15) may tentatively support this interpretation. Although no more than c. 2 km long this scarp is about 4–8 m high, but by no means as distinctly expressed in the terrain as the Merasjärvi fault, and no bedrock exposures were found along its trace. Very likely the feature represents a fault scarp but its age is considered uncertain until it is more thoroughly investigated.

Although the presence of well preserved deposits from a previous deglaciation in the surroundings of the Merasjärvi fault is indicative of an insignificant erosional impact of the last two ice sheets, the extremely fresh appearance of the fault scarp indicates that faulting occurred at the very end of, or most likely after the last deglaciation of the area (Fig. 26). As the area around the Lainio–Suijavaara fault probably was deglaciated prior to the Merasjärvi area, but the Lainio–Suijavaara fault still appears to have developed before local deglaciation, a simultaneous development of the Merasjärvi and Lainio–Suijavaara faults is considered less likely.

THE LANSJÄRV FAULT

The Lansjärv fault is composed of four major and several minor fault segments, together forming a c. 50 km long, SSW–NNE trending fault set (Fig. 16). The longest continuous fault scarp segment is 17 km. The individual fault scarps generally range in height between a few and some 10 m and most of them downthrow to the west. Centrally located in the fault set, there is a frontal fault scarp with abrupt changes in strike which rises in height from zero to c. 20–25 m over a distance of 2 km (Figs. 27–28). Similar to the Merasjärvi fault, the

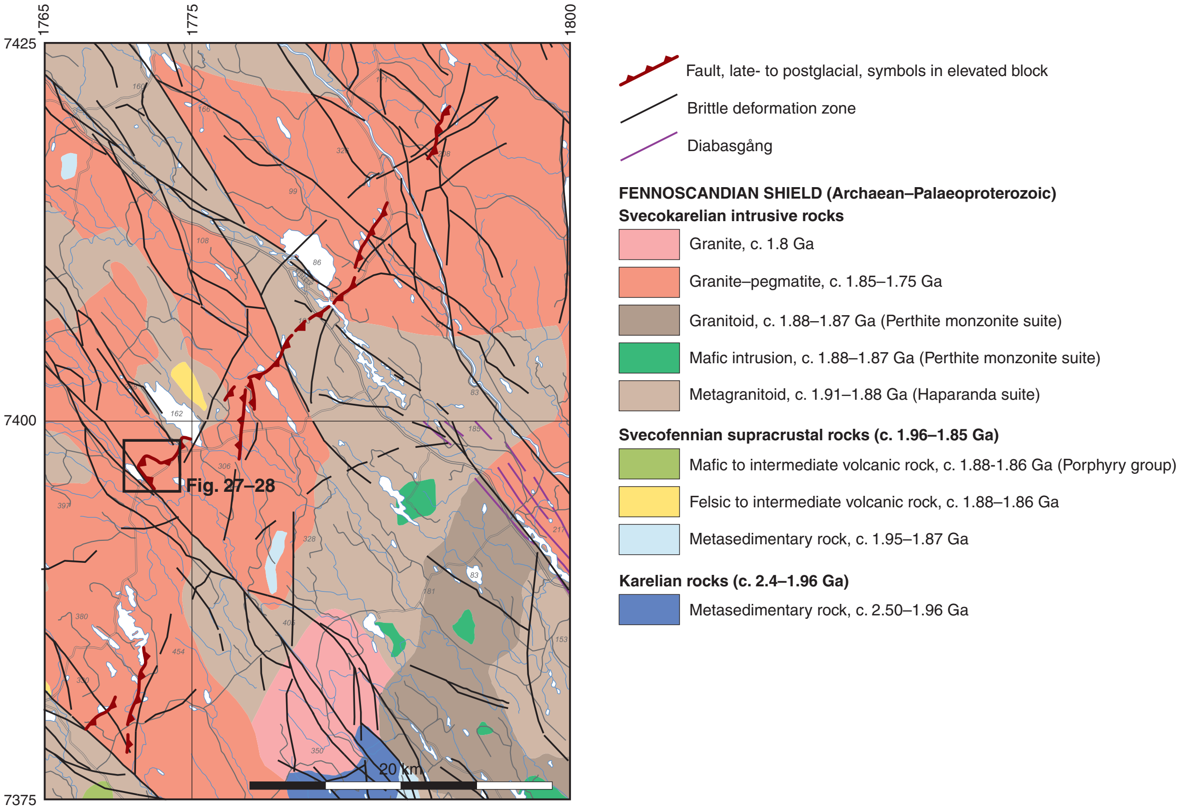


Fig. 16. The Lansjärv fault traces depicted together with the bedrock of the area. Bedrock map modified from the Geological map of the Fennoscandian Shield (Koistinen et al. 2001)

Lansjärv fault is located in an area largely unaffected by the last inland ice sheet and it is therefore not possible to claim a late- or postglacial age of the faulting based only on the fresh appearance of the fault scarps. Fortunately, a complex till stratigraphy in the area provides a good reference for dating the faulting relative to previous glaciations and the fact that the fault set is partly located below the highest postglacial shoreline also offers opportunities for dating fault movements relative to postglacial land upheaval.

In an attempt to refine the dating of the fault displacement, trenches across the fault scarps were excavated at eight localities, most of them at or slightly below the highest shoreline (Figs. 29–33). The impact of fault movement on the different stratigraphical units in these trenches clearly dated faulting to an early stage of the postglacial period, shortly after deglaciation and while the sea still covered the localities (Figs. 32–33). The characteristics of the disturbances of the overburden suggest a rapid one-step fault movement, and at several sites there was evidence for a contemporary expulsion of large quantities of water from the fault zone. Although the stratigraphy at one of the excavation sites suggested that minor fault movements may have occurred previously, several of the other trenches unambiguously demonstrated that the fault scarps were developed to their full heights in single-event movements shortly after local deglaciation (Lagerbäck 1988c, 1992). No signs were found in the trench sections for any fault displacements after that time. Where reached in the trenches, the bedrock fault scarps proved to be reverse, dipping between 40–50° and the near vertical, developed in strongly fractured and chemically weathered zones of pre-Quaternary age (Figs. 29–30, 34). Dip-slip movements were indicated by fresh slickensides in clayey fault gouge at several of the excavation sites (Fig. 35) but a minor dextral, strike-slip component was indicated by the way faulting had displaced the Quaternary stratigraphy in one of the trenches.

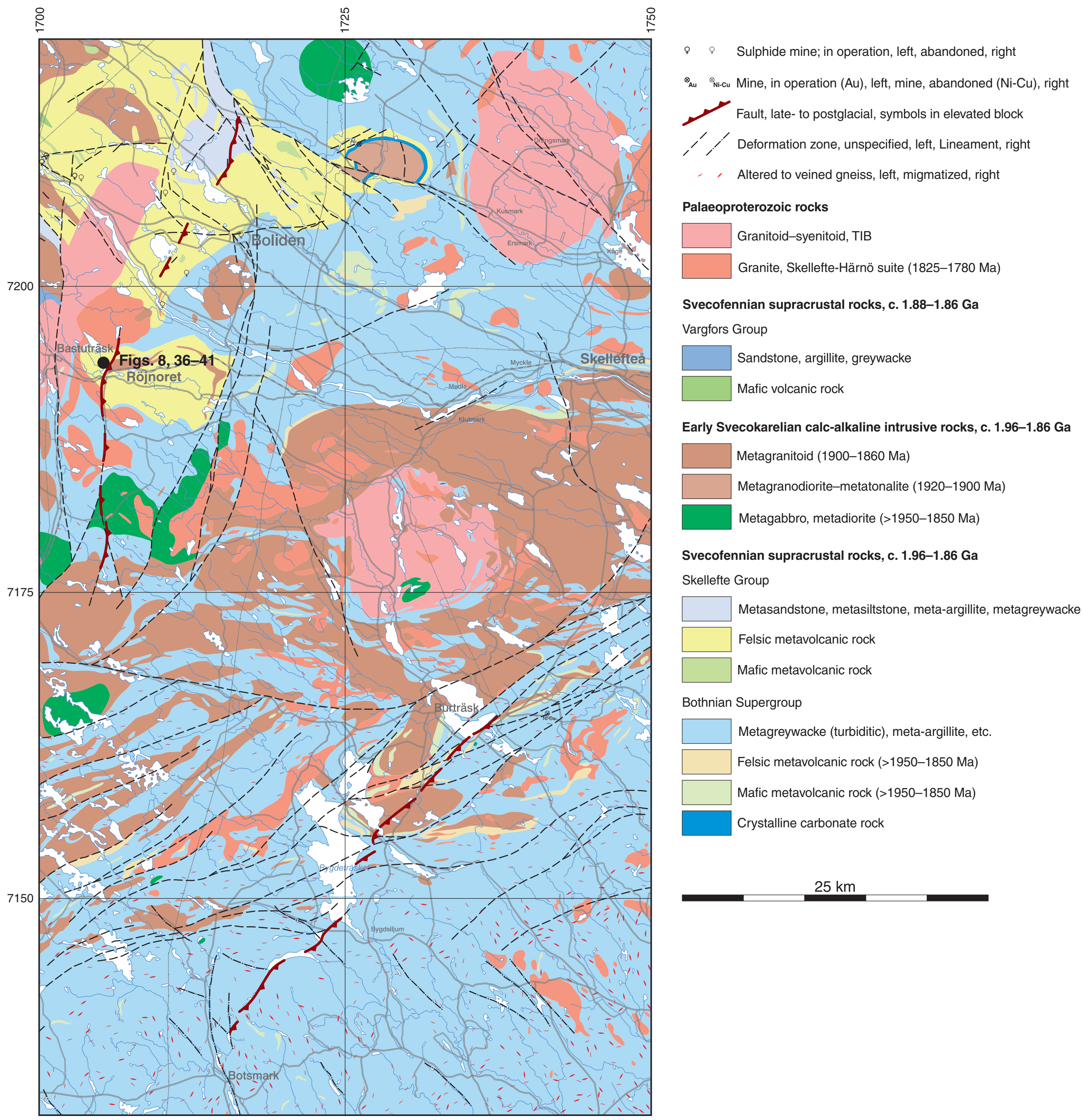


Fig. 17. The Röjnoret and Burträsk fault traces depicted together with the bedrock of the area. Bedrock map simplified after Kathol et al. (2005).

Fig. 18. The Pärvie fault at Lake Kamasjaure, some 70 km north of Kiruna. The c. 8 m high fault scarp forms steeply overhanging cliffs indicating reverse fault movement. See helicopter for scale. Photo: R. Lagerbäck.

Fig. 19. Although fairly diffusely expressed in the swampy area, the lineament running from the lower left to the upper right in the photograph is believed to mirror a bedrock fault scarp at depth. The feature occurs in a row with three similar lineaments, altogether forming a 30 km long, arcuate fault line some 60 km south-east of the southern part of the main Pärvie fault (cf. Fig. 14). Photo: R. Lagerbäck.

Fig. 20. The 20–30 m high scarp at Pyhävaara. The fault segment is c. 2 km long and occurs 1.5 km in front of a corresponding, 1.5 km wide gap in the main Lainio–Suijavaara fault trace (cf. Fig. 15). When the fault ruptured, the edge of the hanging wall collapsed to form heaps of rock rubble along the scarp (light grey i photograph, cf. Fig. 21). Photo: R. Lagerbäck.

Fig. 21. The collapsed edge of the hanging wall at Pyhävaara. The intense, almost explosive, shattering of the bedrock is believed to be a result of the sudden stress relief in the outer parts of the hanging wall when the fault ruptured the ground surface (cf. Fig. 20). Photo: R. Lagerbäck.

Fig. 22. An abundant discharge of groundwater occurring at the foot of the collapsed fault scarp at Pyhävaara feeds a major stream, indicating an extensively fractured bedrock in the fault zone (cf. Figs. 20–21). Photo: R. Lagerbäck.

Fig. 23. In its northern end the c. 50 km long Lainio–Suijavaara fault has determined the course of a major melt-water stream that excavated an erosional channel along the scarp, indicating that faulting pre-dates the deglaciation of the area. The eastern side of the fault (left) is displaced some 20 m above the western side. The continuation of the fault is indicated by a notch in the horizon. Photo: R. Lagerbäck.

Fig. 24. The c. 10–20 m high Merasjärvi fault scarp dams Lake Merasjärvi as well as the small lake behind. Cf. Figs.15, 25.
Photo: R. Lagerbäck.

Fig. 25. The Merasjärvi fault as seen from the ground. The fault scarp is here estimated to be almost 20 m high.
Photo: R. Lagerbäck.

Fig. 26. A sharp and fragile rock plinth that protrudes from the steep till slope of the Merasjärvi fault scarp strongly suggests that fault movement occurred after deglaciation of the area. Photo: R. Lagerbäck.

THE BURTRÄSK AND RÖJNORET FAULTS

The Burträsk and Röjnoret faults are of similar size and appearance. They are both composed of several separate, westward-facing fault scarp segments, together forming c. 35 km long fault-lines striking north and north-east respectively (Fig. 17). The height of the scarps is estimated to vary between some 5 m and 10 m but the Burträsk fault scarp may locally reach some 15 m in height. The bedrock along the Röjnoret fault is entirely covered by Quaternary deposits while a few outcrops, forming slightly overhanging cliffs, occur along the Burträsk fault. The traces of the faults are depicted at a scale of 1:100 000 in the Quaternary geological map sheets SGU Ak 1–3 (Svedlund 1985, Rodhe et al. 1990).

An excavation at the south-western part of the Burträsk fault revealed a chaotically disturbed till stratigraphy, but because of highly unstable trench walls it was not possible to establish the detailed relationship between fault movement and the different till beds (Jan-Olov Svedlund, Geological Survey of Sweden, pers. comm. 2006). The trench did not reach the bedrock but the extensive disturbances of the Quaternary stratigraphy, including the uppermost till bed, indicated that the faulting postdated the last ice sheet, which is believed to have been actively flowing throughout the deglaciation of the region (Rodhe et al. 1990). Neither did a trench cut across the central part of the Röjnoret–Boliden fault, c. 3 km south of the village Röjnoret, reach the bedrock, but a thinning out of the uppermost till bed over the fault scarp suggested a late- or postglacial age of the faulting (Rodhe et al. 1990).

Two rather long exploratory trenches excavated across the Röjnoret fault at Stensberget, 1.5 km north of Röjnoret, clearly demonstrated the impact of faulting on the overburden stratigraphy, which proved to be composed of several till beds. Although c. 6 m deep, the first trench did not reach the bedrock but all the till beds occurring in the trench walls were offset along a well-defined, east-dipping fault plane, indicating reverse movement in underlying bedrock. Reverse fault movement was later confirmed in another trench excavated a few hundred meters to the north (Fig. 36). This trench was excavated to a depth of 12 m and revealed a 7 m high reverse (c. 45°) bedrock fault scarp below c. 5 m of overburden (Figs. 37–40). The bedrock proved to be extensively disintegrated and weathered, indicating that fault movement occurred along a weakness zone of pre-Quaternary age.

Similarly to the observations in the first trench at the site, all till beds were offset by the fault and the trench wall stratigraphy indicated no post-faulting impact by glacial erosion or deposition (Fig. 41). Since the last ice sheet is believed to have been actively flowing even through the deglaciation of the region (Rodhe et al. 1990) the absence of glacial impact on the fault scarp is indicative of a postglacial age of faulting. Furthermore, the absence of any soil horizon developed in the former ground surface below the deposits of the collapsed hanging wall clearly indicated that faulting cannot have taken place long after the deglaciation. Thus, an early postglacial age of faulting is inferred.

SORSELE

A 2 km long and 1.5–2 m high, north-easterly trending and south-easterly facing escarpment was identified about 20 km north of Sorsele in connection with the mapping of Quaternary deposits (Ransed & Wahlroos 2007). Trenching across the feature revealed a 1.5 m high, reverse (45–50°) bedrock fault scarp developed in an intensely fractured granite, thus mirroring the c. 1.5 m high step in ground surface. The fault was offsetting the covering 4 m thick till and a surficial 1 m thick layer of silty glaciolacustrine sediments. The silty sediments are interpreted to have been deposited during the last deglaciation and the faulting must therefore have occurred postglacially.

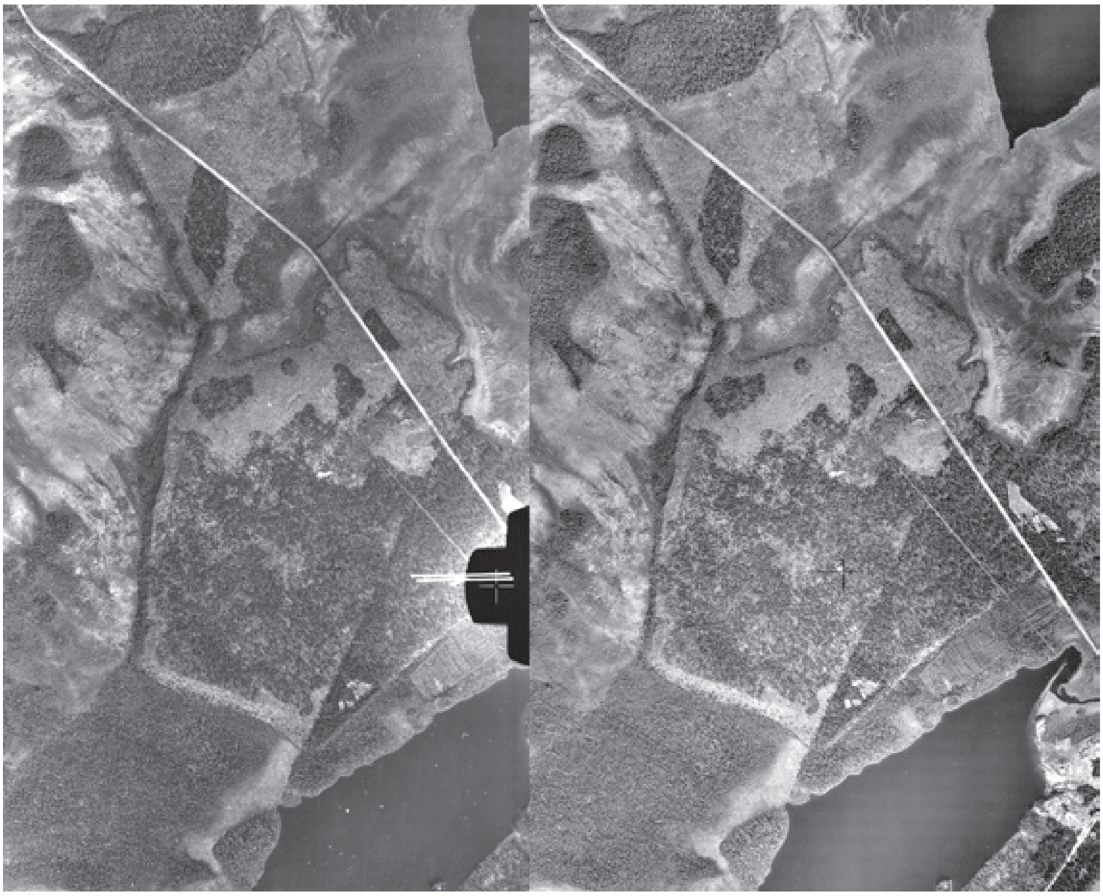


Fig. 27. Stereo-pair of air photographs showing the abrupt changes in the strike of the fault scarp that forms the Risträskkölen plateau, some 10 km south-west of Lansjärv. The slightly tilted bedrock block rises almost 25 m above the surroundings in its lower left corner. Open fractures in the fault zone give rise to numerous springs, and the wet fen to the left, called Källmyren (the spring mire), is dependent on these for its existence. Cf. Figs. 16, 28. North is to the left in the image. Scale approximately 1:30 000. Air photograph: National Land Survey of Sweden. © Lantmäteriverket Gävle 2008. Medgivande I 2008/1991 .

Fig. 28. The Risträskkölen plateau. The scarp in the foreground is some 20–25 m high. Cf. Fig. 27. Photo: R. Lagerbäck.

Fig. 29. Part of a 7–8 m deep exploratory trench excavated across the Lansjärv fault at Mäjärvberget (site 3 in Fig. 49), some 5 km north-east of Lansjärv. The strongly fractured and weathered bedrock of the fault zone (dark grey and pinkish) is seen just behind the 4 m long levelling rod. Three till units were identified in the trench and all were affected by the fault movement. Sand dykes formed by expulsion of water from bedrock in connection with faulting were also found intruded into the covering till on the hanging-wall block. The interrelationship between littoral sand at the foot of the scarp, interfingering debris flows and boulders which have tumbled down in connection with rupturing, demonstrates that fault movement occurred when the early postglacial sea still covered the locality. Photo: R. Lagerbäck.

Fig. 30. The strongly fractured and weathered edge of the hanging wall forms a 4 m high, vertical contact to the till covering the foot wall block at Molberget, located along the middle section of the Lansjärv fault, c. 8 km south-west of Lansjärv (site 6 in Fig. 49). The person (M. Sundh) is c. 1.8 m tall. Cf. Figs. 31–32. Photo: R. Lagerbäck.

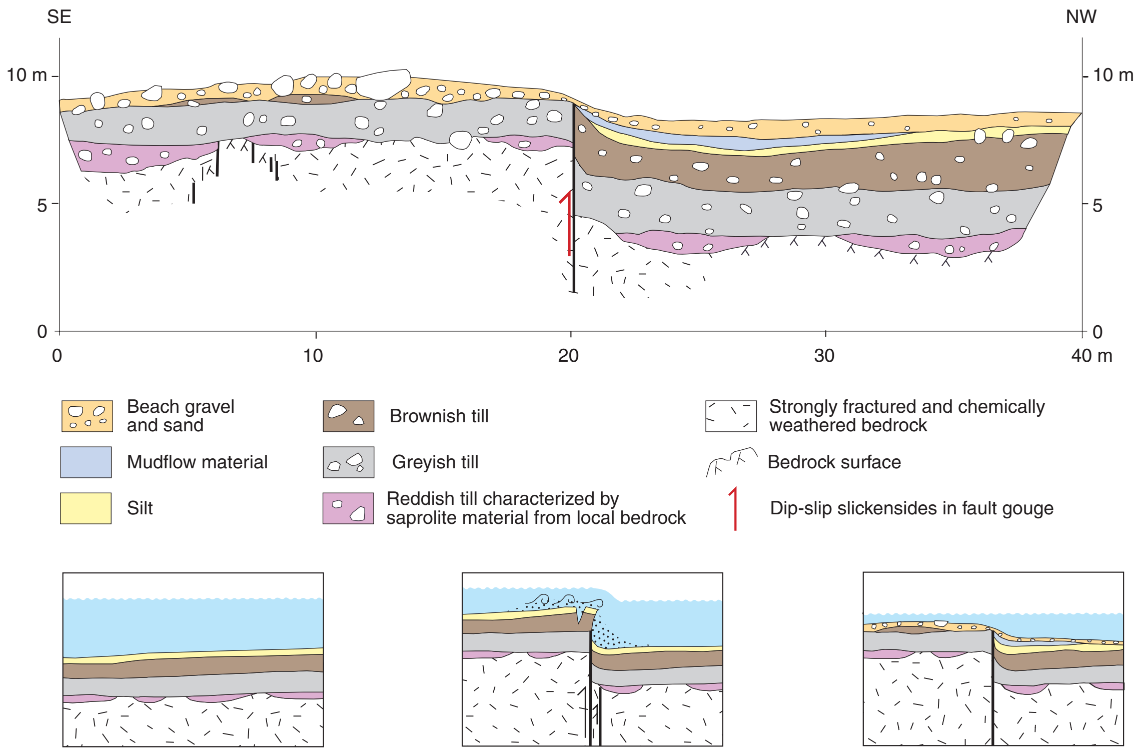
STORUMAN

A c. 10 km long, north-westerly trending set of south-westerly facing escarpments occur some 25 km east of Storuman (Fig. 42, Johansson & Ransed 2003). The length of the individual features varies from a few hundred meters to 2 km and the height between a few meters and c. 10 m. No bedrock exposures have been found along the features and no trenching across them has been carried out. A series of glacial melt-water channels incised in one of the scarps end blindly at about the same level in the steep slope (forming small-scale hanging valleys), thus suggesting that the scarp developed as a result of fault movement during local deglaciation and afterwards (Lagerbäck 1994). Furthermore, beheaded streams and an anastomosing drainage pattern in the area (Fig. 42), otherwise completely atypical for the landscape, give support for a geologically recent crustal deformation of the area. Likewise, the presence of several landslides in the vicinity of the scarps (Fig. 2) supports the occurrence of seismogenic faulting during or after deglaciation. For these reasons, and because of their similarity to the true fault scarps elsewhere, the scarps are believed to represent late- to postglacially developed fault scarps.

MALÅ

Four very short (up to c. 1 km) but morphologically conspicuos escarpments were identified by means of air photograph interpretation in the vicinity of Malå in Västerbotten county (Ransed et al. 1994). The features have not been the subject of field investigations and their precise explanation is therefore unclear. According to Ransed et al. (1994) the escarpments may have other origins than faulting, but their alleged resemblance to fault scarps and their proximity to a major landslide developed in glacial till, has, with some hesitation, qualified them to be designated as possible late- or postglacial faults in Figure 2.

Fig. 31. The 4 m high fault scarp at Molberget after thorough cleaning and removal of all the loose matter that covered the bedrock. The person, excavator operator Erik Knutstedt, is c. 1.8 m tall. Cf. Figs. 30, 32. Photo: R. Lagerbäck.

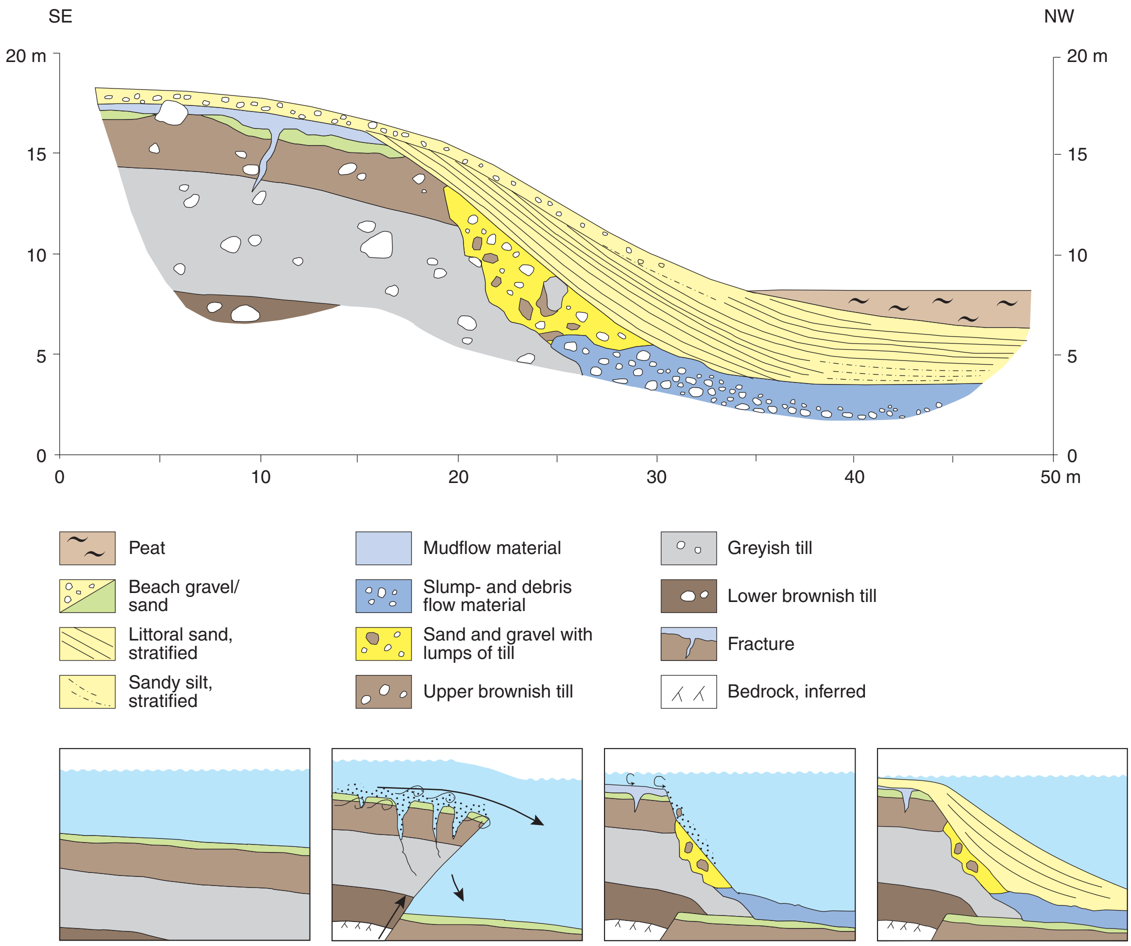


A. Previous to faulting. The recently deglaciated locality is covered by the postglacial sea, deposition of fairly fine-grained littoral sediments.

B. Faulting. Movement occurs in an existing, strongly weathered fracture zone. The fine-grained sediment on the lower block becomes covered by debris and mud from the collapsing overburden on the rim of the raised block.

C. Wave-erosion of the till on the raised block and deposition of beach gravel and sand on the lower block during the land upheaval masks the originally more marked fault-scarp.

Fig. 32. Simplified log of the trench excavated across the Lansjärv fault at Molberget. The site is located c. 175 m a.s.l. and only a few meters below the highest shoreline. Although only c. 1 m high and diffusely expressed in the ground surface, the scarp was identified in air photographs. Cf. Figs. 30–31. Redrawn after Lagerbäck (1988c).



A. The recently deglaciated locality is covered by shallow water and a thin cover of littoral sand is deposited.

B. Faulting, contemporaneous rupturing and collapse of the hanging-wall deposits. Water discharge and mud flowage from the raised block.

C. Stabilization of the fault scarp. Lumps of till become mixed with poorly sorted sand and gravel. These deposits probably formed more or less in direct connection to faulting.

D. The scarp becomes covered by littoral sand and beach gravel before the locality is raised above the sea.

Fig. 33. Simplified log of trench excavated across the Lansjärv fault at L. Telmträsket (site 2 in Fig. 49), c. 8 km north-east of Lansjärv. As with the Molberget site (Fig. 32) this site is located only a few meters below the highest shoreline and the impact of fault movement on the different stratigraphical units clearly dates faulting to have occurred shortly after deglaciation. Redrawn after Lagerbäck (1988c).

Fig. 34. The edge of the fractured and weathered hanging wall at Stupforsen (site 7 in Fig. 49), some 10 km south-west of Lansjärv. In contrast to most of the other fault segments belonging to the Lansjärv fault set, this fairly short (c. 5 km) scarp faces eastwards. Note that the outermost tip of the scarp appears to have been projected forward at the end of fault movement. At several sites a similar phenomenon is indicated by rock blocks that appear to have been thrown out from the fault scarp rather than just falling by gravity. 4 m long levelling rod for scale. Photo: R. Lagerbäck

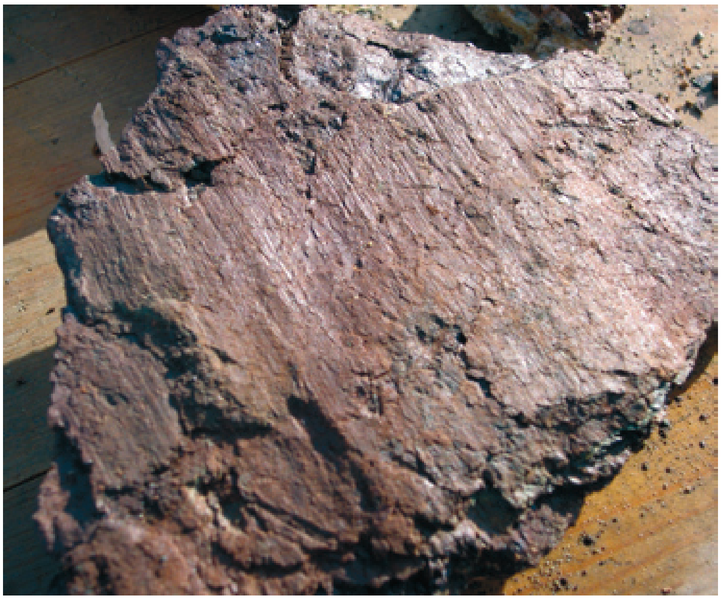


Fig. 35. A piece of slickensided, clayey fault gouge cut out from the fault scarp at Molberget (cf. Figs. 30–32). The specimen is desiccated and cracked after almost 20 years of storage. When fresh, the surficial clayey material could easily be smeared and the slickensides erased with fingers. The photograph is approximately 15 cm across. Photo: R. Lagerbäck.

Fig. 36. Part of the Röjnoret fault at Stensberget (site 2 in Fig. 62), some 40 km to the west of Skellefteå. The fault scarp, about 6–8 m high, runs diagonally across the photograph, from upper left to lower right. Cf. Fig. 17. The trench site shown in Figs. 37–40 is encircled. Photo: R. Lagerbäck.

Fig. 37. The 7 m high fault scarp at Stensberget before trenching. Cf. Fig. 36, 38–40. Photo: M. Sundh.

Fig. 38. At an early stage of trenching across the fault scarp at Stensberget. The upper frontal part of the hanging wall block is seen at the bend of the trench. The trench was later significantly widened and deepened, and the excavated masses were removed in order to keep the site available for future research. Cf. Figs. 37, 39–40. Photo: R. Lagerbäck.

Fig. 39. The northern, 12 m high trench wall at Stensberget. The 7 m high step in ground surface corresponds to a reverse bedrock fault scarp of the same height in the heavily weathered bedrock (orange colored). The foot-wall is seen at the bottom of the trench. Photo: R. Lagerbäck.

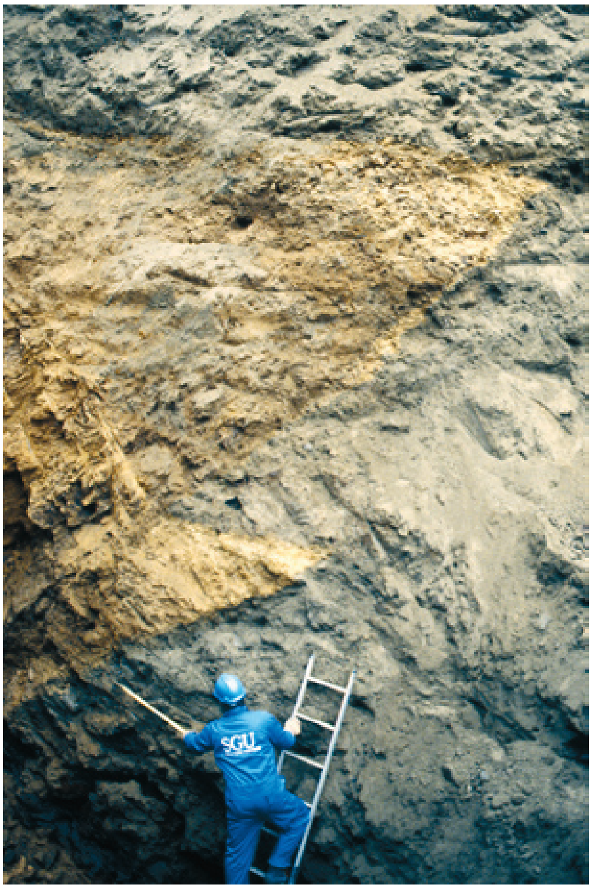


Fig. 40. Part of the fault zone in the southern trench wall at Stensberget. Note the well-expressed subsidiary thrust above the investigator (R. Lagerbäck) occupied with trimming the wall. Photo: M. Sundh.

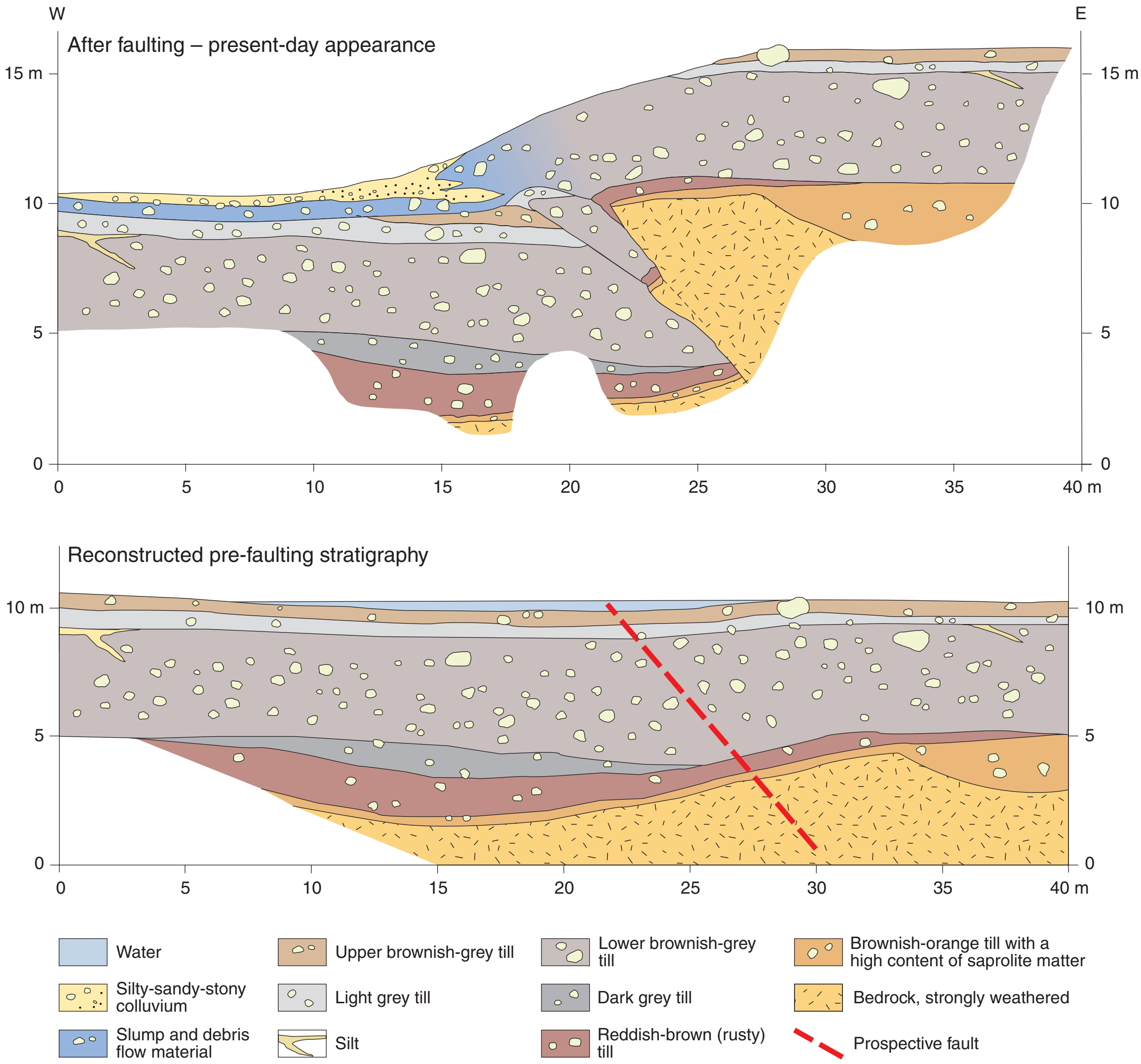


Fig. 41. Log of the trench excavated across the Röjnoret fault at Stensberget (cf. Figs. 37–40). The fact that all the till units are cut by the fault strongly indicates that faulting occurred after the deglaciation of the site.

ISMUNDEN

Two short but very conspicuous fault scarps were identified south of Lake Ismunden, some 25 km south-east of Östersund, by mineral hunter Bertil Strandberg, Frösön. The scarps, c. 1 and 2 km long respectively and located close to each other, both strike ENE–WSW and face SSE. Where bedrock is exposed along the 3–5 m high scarps, it forms overhanging (55–65°) cliffs, indicating reverse fault movements (Fig. 43). Since the last ice sheet most probably was actively flowing over the area (e.g. Lundqvist 1973), it is hard to imagine how the scarps could have remained uneroded and protrude so distinctly in the terrain if not late- or postglacially developed. However, as no excavations or other field-work supporting a young age of the features have been carried out, they are designated possible late- or postglacial fault scarps in Figure 2.

MINOR FAULT OFFSETS AND LARGE OPEN CREVASSES

Glacially polished and striated bedrock outcrops exhibiting minor (a few centimeters to a decimeter) offsets, single or in series, have locally been encountered in northern Sweden (Fig. 44). Because of the limited size of outcrops, it is generally not possible to trace such features over distances greater than a few tens of meters, and their significance as indicators of postglacial faulting is therefore not possible to estimate. It should be

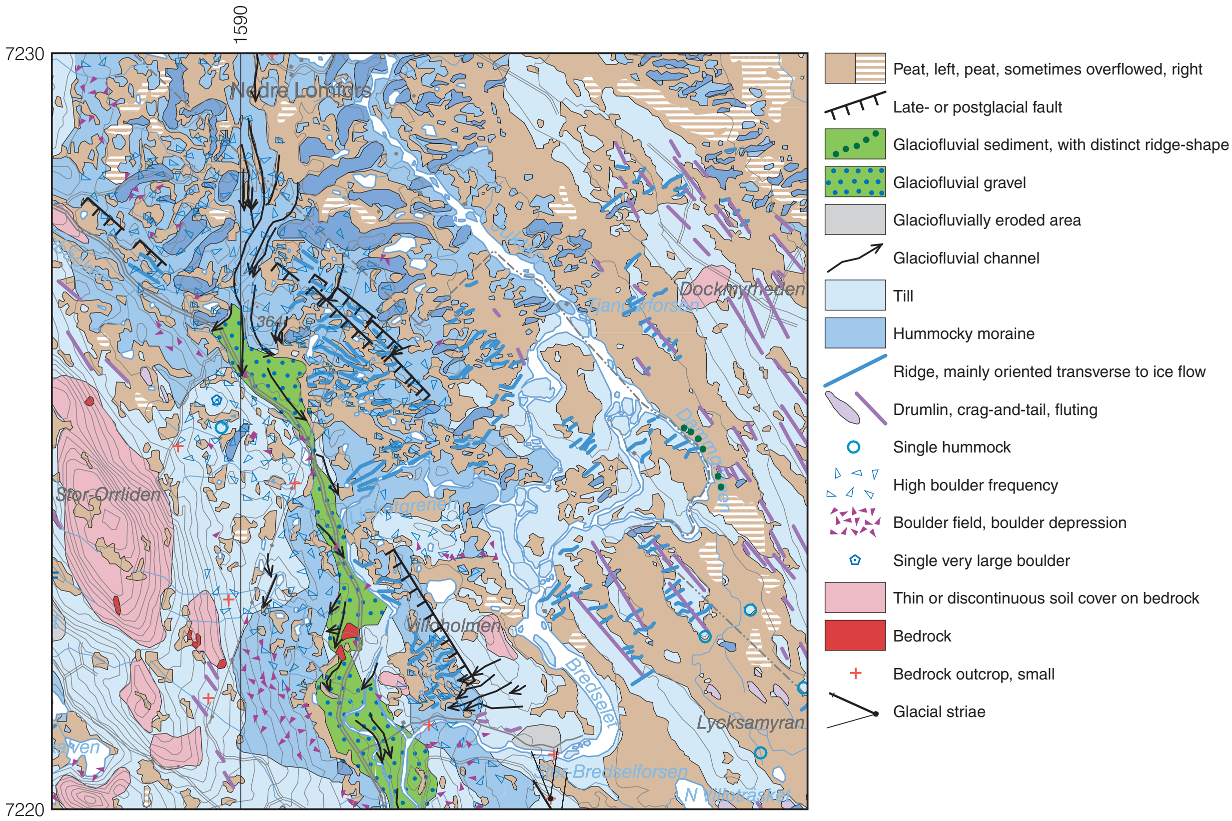


Fig. 42. Excerpt from the map of Quaternary deposits 23H Stensele (Johansson & Ransed 2003). Fault scarps are shown with black, hatched lines with hatches on the down-thrown block. Beheaded streams and an anastomosing drainage pattern are indicative of a geologically recent crustal deformation of the area.

Fig. 43. Part of a c. 4 m high fault scarp at Lake Ismunden, some 25 km south-east of Östersund. The discoverer of the feature, mineral hunter Bertil Strandberg, holds the hammer vertically to visualize the dip of the fault plane (some 60 degrees). Photo: R. Lagerbäck.

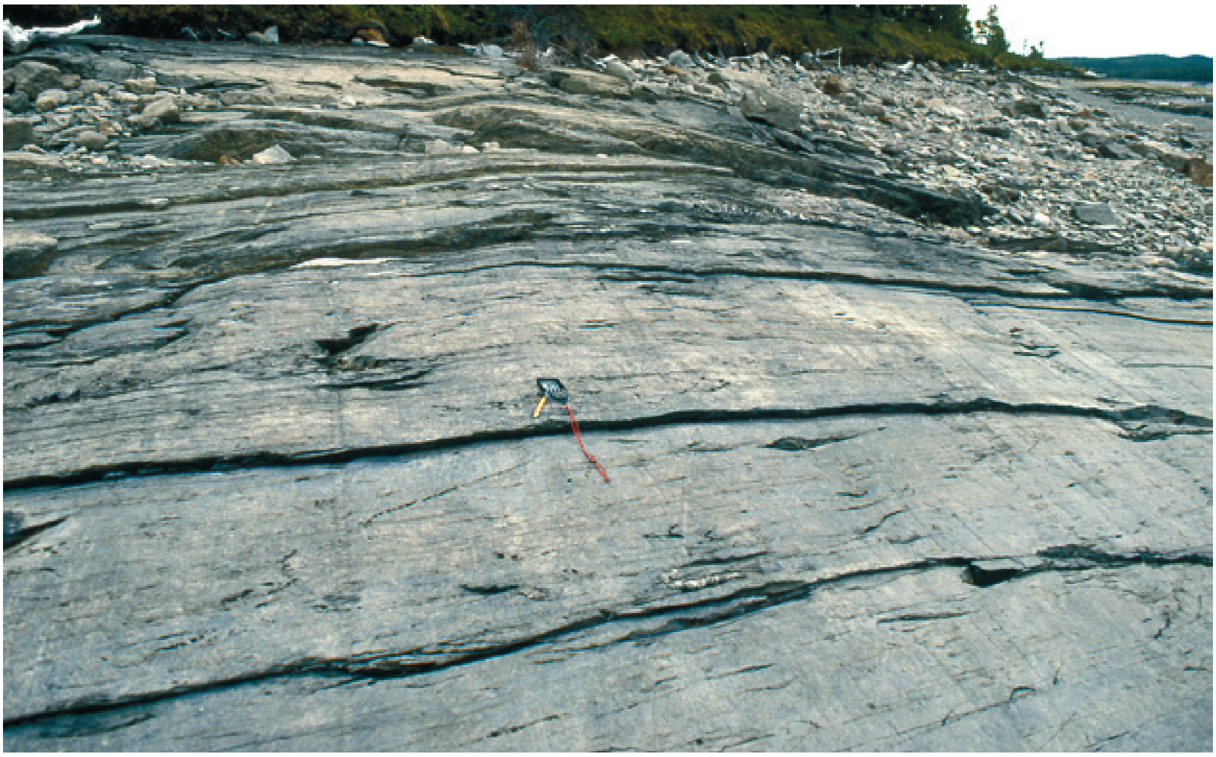


Fig. 44. A series of minor offsets in a glacially smoothed and striated outcrop of slaty rock at the southern shore of Lake Atjiken, c. 25 km south of Tärnaby in southern Lapland. The offsets are no more than a few centimetres high and the total amount of displacement measures only some 20 cm. The offsets clearly postdate the two most recent ice movements (see pencil and compass string respectively, ice movement away from the viewer). In this area, the most recent ice sheet is believed to have been actively flowing right until final deglaciation (Ulfstedt 1980), which most likely indicates that the offsets developed postglacially. In this special case it might be speculated that the dislocation could have been caused by the impounding of an artificial water reservoir located mainly downstream of the outcrop, i.e. on the "foot-wall" side of the offsets. Similar small-scale features have been encountered at a small number of other sites in northern Sweden, but because of their insignificant size they are not depicted in Figure 2. Photo: R. Lagerbäck.

Fig. 45. Parallel, open fractures in Caledonian rocks at Mount Nordhallsfjället, some 15 km north-west of Åre in Jämtland. The photograph to the right shows one of the c. 0.3 m wide fractures as seen from the ground. Photo: R. Lagerbäck.

observed, however, that such tiny features are not found more abundantly in areas adjacent to the major faults than elsewhere in northern Sweden.

Rather spectacular open crevasses, up to almost one meter wide and extending for hundreds of meters or even several kilometers, occur in the Caledonian rocks of the mountain range. An extensive (c. 5 km), north-southerly trending system of such features was encountered during geological reconnaissance at Mount Nordhallsfjället, some 15 km north-west of Åre in Jämtland (Fig. 45), and identical features are reported from the Vilhelmina mountains (Du Rietz 1937) and the Narvik district (Bargel et al. 1995) further to the north along the mountain range. The crevasses are fresh-looking and show no signs of glacial erosion or deposition after their formation. No significant vertical or lateral displacements were indicated along the features at Nordhallsfjället and the width of the single crevasses appeared to be rather consistent along their entire length. Although most likely late- or postglacially developed, the origin of the features is obscure. A tectonic origin cannot, perhaps, be excluded, but more likely they are the result of collapse of the nappe pile rather than faulting and, therefore, the features are not depicted in Figure 2. This explanation was favoured also by Du Rietz (1937).

Paleoseismic records

LANDSLIDES

Fault displacements of 5 m or greater along faults extending from 35 to 155 km must reflect significant earthquakes, and evidence for a coseismic origin of these fault scarps has increased over the years. Kujansuu (1972) intimated the possibility that earthquakes associated with the supposed Recent faulting in Finnish Lapland had triggered landslides in the vicinity of the fault scarps, and a causal relationship between faulting and landslides became even better established after the disclosure of similar features in adjacent parts of northernmost Sweden (e.g. Lagerbäck & Witschard 1983). The number of identified landslides has since increased significantly and the geographical concordance between landslides and faults has become even more marked (Fig. 2). In northern Sweden, a total of some two hundred and fifty landslide scars have been identified, of which the vast majority occur in the north-eastern part of Norrbotten county, adjacent to the border to Finland. Although most of the landslides identified in Sweden are concentrated in eastern Norrbotten, several similar landslides developed in glacial till have also been identified in the eastern and central parts of Västerbotten County (Fig. 2). As in Norrbotten, the majority of these slides occur adjacent to fault scarps inferred to be of late- or postglacial age.

The landslides appear in areas entirely dominated by glacial till. The tills in this part of Sweden generally have a sandy composition and excavations in the slided masses and at the margins of some of the slide scars have not revealed anything but till. Such tills are not expected to slide or flow under normal conditions, especially since most of them occur on very gentle slopes of only a few degrees (Figs. 6, 46). This strongly suggests that seismically induced liquefaction processes have contributed to failure. Most of the mobilized material appears to have moved in a liquefied state but carrying big chunks of more coherent, superficial parts of the overburden downslope to form hummocks and ridges (Fig. 47). Segments of the original till stratigraphy are identified in these hummocky deposits, while the most far-travelled portions of the mobilized masses have lost all primary till characteristics and are better described as debris-flow materials. The volume of mobilized masses in the slides range between c. 0.2 and 2 million cubic meters, but very likely a great number of smaller slides may have been overlooked due to difficulties in recognizing them in the low-resolution air photographs used for interpretation (chiefly IR-color images at 1:60 000, see Fig. 7).

According to Kujansuu (1972) a large proportion of the landslides in Finnish Lapland are situated on southern slopes and he suggests that an increased thawing of permafrost due to a higher degree of insolation may have promoted sliding in southerly directions. No clear preferred orientation has, however, been noticed on the Swedish side of the border where the slides appear to be more randomly oriented.

Almost all of the landslide scars identified in northern Sweden occur above the highest shoreline. Very likely also subaqueous slides may have been triggered below the highest shoreline but, due to longer travel distances and dispersal of slided masses as well as degrada-

Fig. 46. Landslide scar developed in glacial till at Elmaberget, some 20 km north-east of Lansjärv. The landslide developed in a slope of only 3–4 degrees and the volume of the slided masses is estimated to be c. 0,5 million cubic meters. Radiocarbon dating of the bottommost peat accumulated inside the scar gives the slide a minimum age of 8 140 ± 180 ^{14}C-years BP. Photo R. Lagerbäck.

tion of the landslide scars by erosional processes in the ancient sea, such slides have become more indistinctly expressed and, therefore, are not so easily identifiable in air photographs. Layers of coarse-grained diamict material, interpreted as subaqueous debris flow deposits, have also been found to intercalate varved glacial clay in several of the trenches excavated in the northern coastal areas (see further below). Parts of these deposits very likely originated in slided masses that were released in connection with major earthquakes. Furthermore, the absence of fresh looking (i.e. uneroded by littoral processes) landslide scars below the highest shoreline confirms that faulting occurred during or shortly after deglaciation.

Radiocarbon dating of the bottommost peat formed inside one of the landslide scars in the Lansjärv area yielded a ^{14}C-age of 8 140 ± 180 BP, which corresponds to a calendar age of c. 9 000 BP, i.e. a minimum age for the sliding (Fig. 46). Although not dated, thick deposits of peat formed inside many of the other landslide scars demonstrably show that the landslides are ancient features. Not far from the Burträsk fault in Västerbotten a landslide scar, located just below the highest shoreline, proved to be wavewashed, and thus demonstrates that sliding occurred shortly after deglaciation (Jan-Olov Svedlund, Geological Survey of Sweden, pers. comm. 2006). Likewise, based on radiocarbon dating and pollen analyses of peat accumulated inside the landslide scars, Kujansuu (1972) concluded that the sliding in Finnish Lapland took place shortly after local deglaciation.

Sutinen (2005) reports on a radiocarbon date of 8 720 ± 170 ^{14}C years BP for birch wood buried by landslide deposits in the vicinity of the Suasselkä fault in Finnish Lapland, and concludes that the pre-landslide presence of birch trees signifies that the slide event was not an ice-marginal feature at this site. Based on the fact that peat accumulated inside another landslide scar in the region yielded a significantly younger age (6 610 ± 175 ^{14}C years BP), Sutinen (2005) also claims that sliding must have continued for a long period of time after the disappearance of the ice sheet. However, dating of peat accumulated within a landslide scar yields merely minimum ages of sliding and, therefore, Sutinens dating of buried wood (8 720 ± 170 ^{14}C years BP) may so far be regarded the best constraint on the timing of landsliding in the region. If calibrated into calender years the dating indicates that the landsliding and, accordingly, faulting occurred almost 10 000 calender years ago in the area.

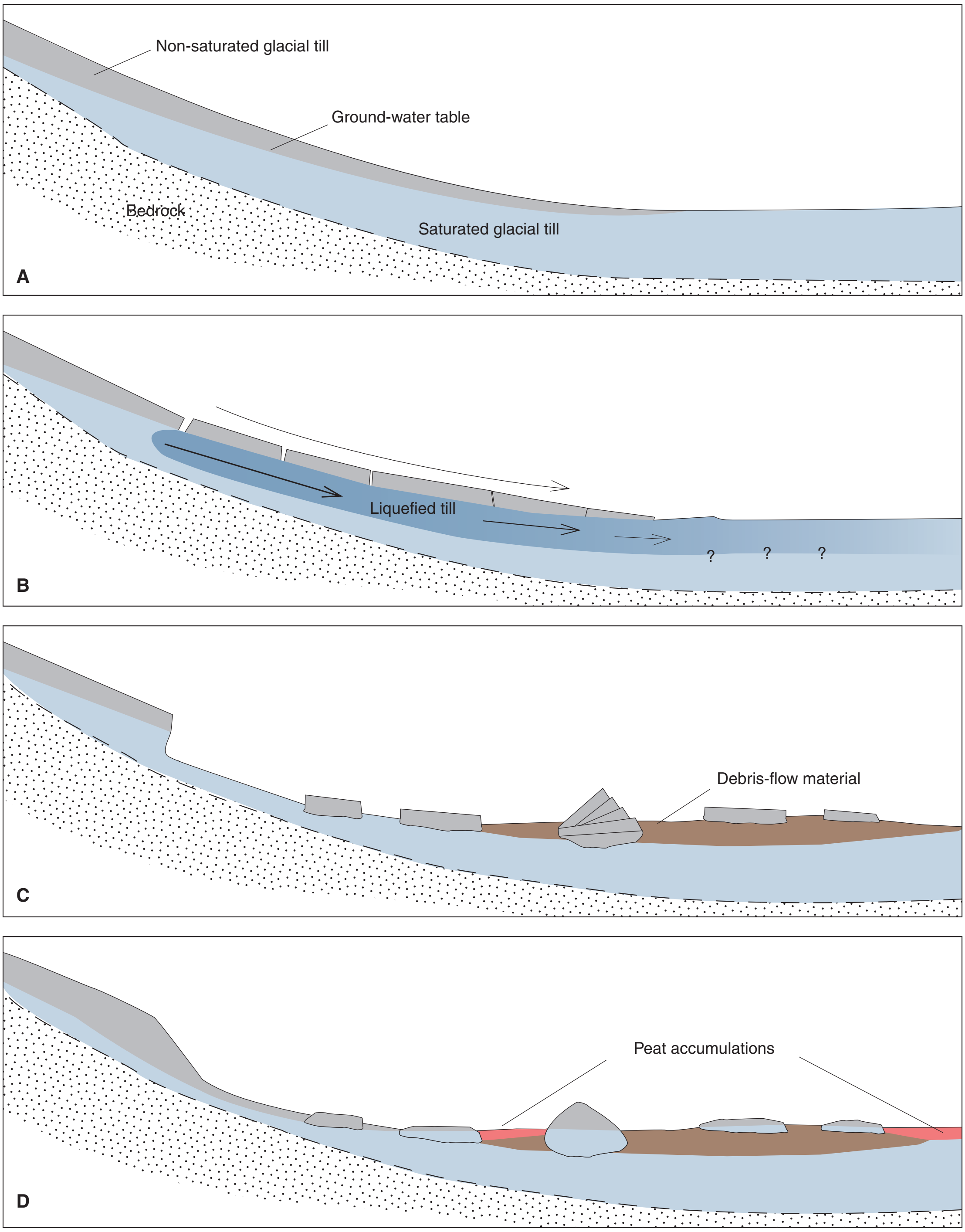


Fig. 47. Inferred sequence of events to cause landsliding in a gentle (exaggerated in the figure) slope of glacial till. The structure of the slide scar and mobilized masses is based on a number of trenches excavated in different parts of two slide scars in northernmost Sweden. **A.** Prior to sliding. **B.** Strong earthquake ground shaking causes the till beneath the groundwater table to liquefy and start to flow downslope. The more coherent (dry and, if during winter, perhaps to some extent frozen) upper part of the till is carried like rafts floating on the liquefied masses. **C.** The mobilized material comes to rest. Some of the till rafts become stranded and stacked to form ridges and hummocks. **D.** Present-day situation. The edges of precipices have become smoothed and peat has accumulated in waterlogged parts of the terrain. Cf. Fig. 46.

SOFT-SEDIMENT DEFORMATION STRUCTURES INTERPRETED AS SEISMITES

The term seismite was introduced by Seilacher (1969) to define a sedimentary sequence displaying deformational structures produced by seismic shaking ("fault-graded beds"), and is used here to denote various features interpreted to be the result of seismically induced alteration of the primary sedimentary structures. The stratigraphical information gained in the machine-cut trenches was assessed to determine if there had been evidence of strong ground shaking leading to earthquake-induced liquefaction and fluidization during the period when the sediments were saturated. If a loosely packed deposit of saturated, cohesionless soil is subjected to strong ground shaking, the grains of silt and sand may be re-arranged and consolidated, leading to an increase in trapped fluid pressures. As a result, the sediment loses its strength and can behave more or less as a liquid. The susceptibility for liquefaction varies greatly depending on the composition of a sediment and in a deposit composed of alternating layers of sand, silt and clay, the sand and coarse silt may liquefy while the stiffer fine silt and clay layers resist liquefaction and deform plastically, and a great variety of deformation features may occur.

Liquefaction will be prolonged where a cap of less permeable deposits prevents pressurized pore-water escaping from underlying deposits. This effect is clearly demonstrated at a great number of investigation sites in northern Sweden where sandy and coarse silty deposits covered by layers of fine silt or clay were intensely deformed although no more than one or a few decimeter thick. However, according to the experience gained during the investigations, a sealing cap is not an absolute prerequisite for the development of liquefaction. According to our field observations the composition of the sediment is the most critical factor and deposits composed of coarse silt or fine sand are the most sensitive to deformation, whether or not covered by more fine-grained sediments. Relatively small differences in grain size appear to determine whether or not liquefaction will occur.

As a consequence of liquefaction, the primary sedimentary structures are deformed or completely destroyed, the sediment particles become more tightly packed and excess pore-water is expelled to form fluid-escape features, commonly dykes or sills of sand that intrude into overlying deposits. The denser packing of a sediment that has undergone liquefaction is often very remarkable and such sediments are sometimes very hard to excavate. Gravitational sorting has proved to be a rather common phenomenon in the seismically deformed sediments in northern Sweden. A grain-size sorting has occurred in liquefied till deposits and elutriation processes during upward water-escape in waterlain sediments have at many sites resulted in a separation of heavy minerals from the lighter quartz and feldspar grains.

Earthquake-induced liquefaction is controlled by a number of factors. Except for variables such as grain size and packing of the sediment, also duration and intensity of shaking determines whether liquefaction will occur. It is commonly considered that liquefaction phenomena may develop in highly susceptible sediments in the vicinity of earthquakes with magnitudes as low as M5 but become more common at M6 or higher. A shallow-focus, M6 earthquake may cause liquefaction features at a distance of some 20 km from the epicentre, an M7 earthquake within some 100 km, while a great M8 earthquake may induce liquefaction as far away as 300 km (Obermeier 1996). For reasons given above (see Methods), seismites are expected to occur more frequently, and, in contrast to the landslide scars, to be more easily traced and investigated below the highest shoreline. Seismites may have formed in waterlogged ground above the highest shoreline as well, but such sites are commonly peaty in the present-day landscape and, therefore, near impossible to investigate by trenching.

The arguments for a seismic origin of the soft-sediment deformation structures found in the Lansjärv area (e.g. Lagerbäck 1990) are valid also for the deformational features found in Västerbotten and along the northern coastal area. These arguments are (here slightly modified):

- They occur in sediments with a grain size favourable for liquefaction if affected by strong and prolonged earthquake vibration.
- They occur in mainly grain-supported deposits, of a similar grain-size throughout the sections, not expected to develop soft-sediment deformation structures if not liquefied.
- They occur in flat-lying or very gently sloping terrain which tends to exclude the possibility that slumping or sliding was the driver of the deformation.
- They occur in sediments that were present during the deglaciation or early postglacial period, i.e. contemporaneous with major faulting, but have not been found in younger sediments of similar composition.
- On each site they appear to be developed at a certain stratigraphical level and at many sites they are covered by undisturbed sediments of a similar composition, indicating that deformation occurred

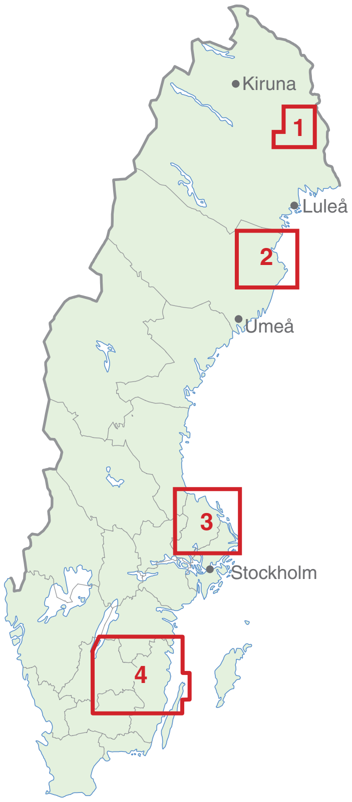


Fig. 48. The four main investigation areas that have been searched for seismically induced soft-sediment deformation structures. Sediment sequences have also been examined in sand and gravel pits as well as in specially cut trenches along the entire coastal area of northern and central Sweden (see Fig. 71). Investigation areas: 1. Lansjärv (see Fig. 49). 2. Eastern Västerbotten (see Fig. 62). 3. Uppland (see Fig. 77). 4. Eastern Småland.

syndepositionally and over a short interval of time before the sites were raised above the sea.

- The features corroborate a phase of fault rupturing, accompanied by large earthquakes triggering a great number of landslides in the late glacial to early postglacial period.

It may be added that after the investigations had been expanded to cover other parts of Sweden, such deformational features are encountered at almost every site in the vicinity of the Recent faults where contemporary liquefiable sediments were present, while in areas without evidence for such fault movements, similar deformation structures are much rarer and less extensive.

The search for seismites by means of trenching has been directed mainly to four different areas: the Lansjärv and eastern Västerbotten areas in northern Sweden and Uppland and eastern Småland in southern Sweden (Fig. 48), but in addition sandy–silty sediments in sand and gravel pits along the entire coastal area of northern and central Sweden have been examined. A brief account of the results of these investigations is given below.

The Lansjärv area

The Lansjärv area was for several reasons considered favourable for detailed paleoseismic investigations: 1) A complex till stratigraphy made it possible to date the faulting relative to several glaciations. 2) The presence of the landslide scars, some of them occupied by considerable accumulations of peat, indicated that co-seismic faulting occurred early in the postglacial period. 3) Parts of the fault were covered by the postglacial sea after deglaciation, allowing faulting to be dated relative to land upheaval. 4) Below the contemporary sea level freshly deposited sediments were entirely saturated and susceptible to liquefaction, but are presently available for excavation on dry land. 5) A fairly dense road network made the area accessible for transporting excavators.

With the aim to search for seismites something like 160–180 trenches of varying length were excavated at about 60 sites in the Lansjärv area during the years 1982 to 1993 (Fig. 49). Their total length measured several kilometers and most reached depths between 2.5 m and 4 m. The absolute majority of the trenches were excavated in a range of waterlain sediments (glaciofluvial sediments deposited during the latest deglaciation, till-covered glaciofluvial sediments deriving from a previous deglaciation, fine-grained marine sediments and sandy–silty fluvial sediments), but trenches were also cut in glacial till terrain that displayed certain surficial characteristics. In addition to the investigations carried out by trenching, a number of sediment sequences in sand and gravel pits and natural exposures along streams were also examined. Some of the results of these investigations were summarized in Lagerbäck (1990, 1991).

A great variety of deformation features, interpreted to be seismically induced, were encountered within the area, but only in deposits of glacial (till beds) or deglaciation (waterlain sediments) age. While practically all investigated sequences containing sandy–silty sediments deriving from the last deglaciation displayed deformation attributed to liquefaction or fluidization (Figs. 50–53), deltaic sediments deposited postglacially along the river valleys during land-upheaval, though tens of meters thick and of a similar composition to the deglaciation sediments, displayed no soft-sediment deformation structures whatsoever (Fig. 54). Neither were soft-sediment deformation structures of any significance encountered in till-covered, tectonized and rather dense sandy sediments deriving from a previous deglaciation. At several sites, some impact on these till-covered sandy sediments was, however, indicated in the form of water-escape features, emanating from the sediments and penetrating into and through the covering till bed.

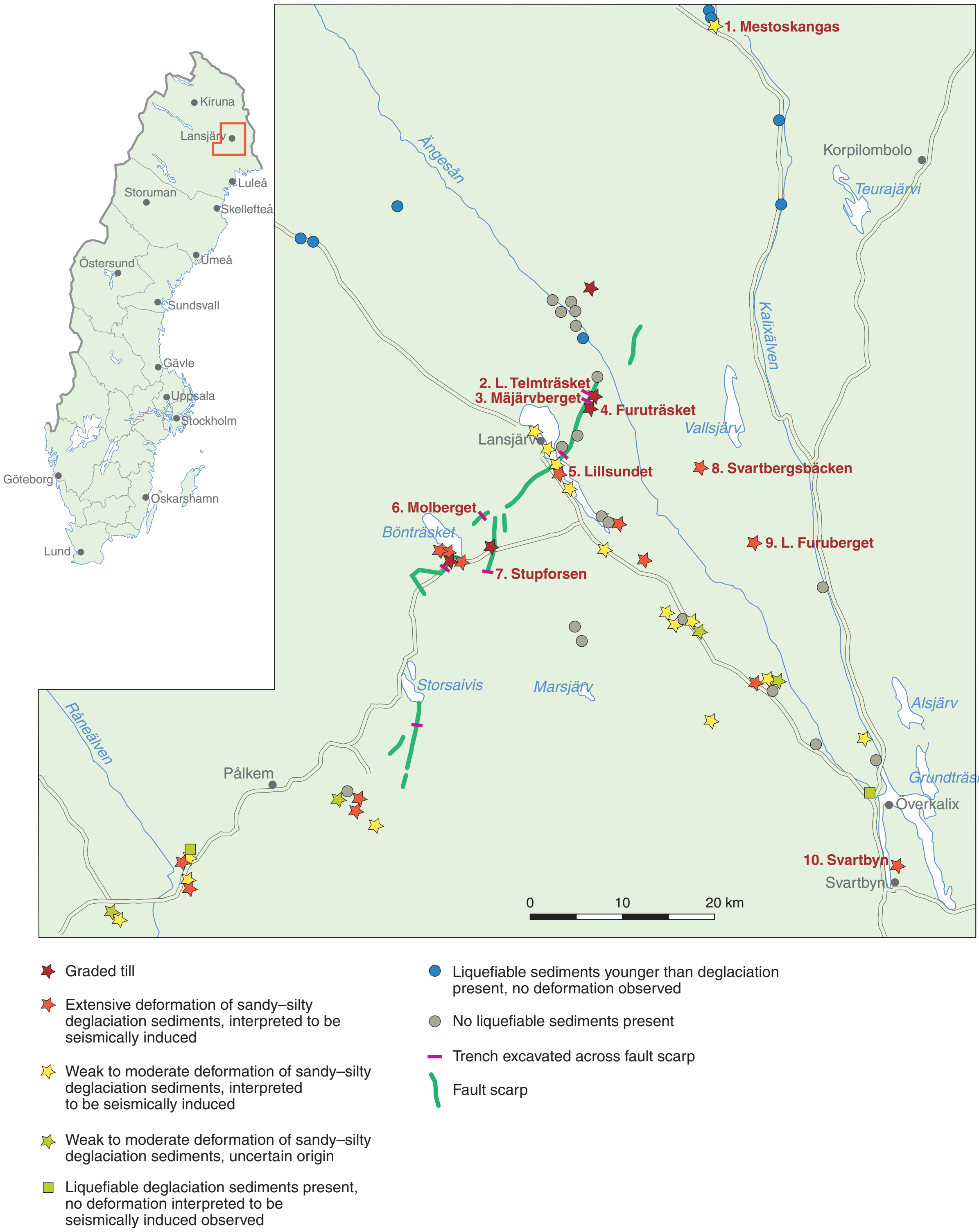


Fig. 49. The Lansjärv investigation area. Sites mentioned in the text or shown in photographs are marked with numbers and names.

While the deformation features occurring in the sandy–silty deglaciation sediments invariably persisted laterally along the whole length of the trenches, at several sites this deformation only reached up to a certain level in the stratigraphical sequence indicating that deformation took place during the build-up of the sediment piles shortly after local deglaciation (Fig. 53). Likewise, since several of the sites displaying liquefaction features are located only slighly below the highest shoreline, deformation must have taken place shortly

Fig. 50. Pseudo-nodules in strongly deformed and densely packed sandy–silty, sublittoral sediments (redeposited glaciofluvial deposits) at L. Furuberget, c. 20 km south-east of Lansjärv. Photo: R. Lagerbäck.

Fig. 51. Flame-like structures and density-driven deformation structures in fine sandy and coarse silty beds covered by a capping layer of silty clay. The deformed sequence is c. 0.4 m thick and extremely densely packed. In a saturated state, the bulk density of the upper, somewhat more fine-grained and mainly coarse silty sediment, was found to be slightly higher than that of the lower, mainly fine sandy sediment (both when loosely packed in a glass beaker and after packing by vibration). Lillsundet, 3 km south-east of Lansjärv and only 1 km away from the Lansjärv fault. 25 mm coin for scale. Photo: R. Lagerbäck.

Fig. 52. The same deposits as shown in Fig. 51 but a few meters away. Separation of heavy mineral grains from lighter quartz and feldspar grains due to gravitational sorting is indicative of a prolonged liquefied state and intense shaking. Note the minor faulting that has occurred after density fractionation and compaction. The deposits were extremely densely packed. 25 mm coin for scale. Photo: R. Lagerbäck.

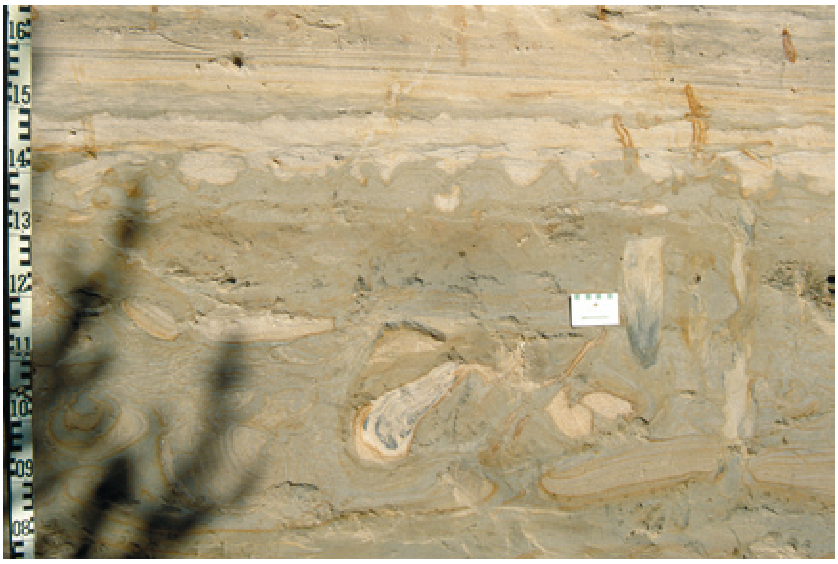


Fig. 53. Strongly deformed and densely packed silty and fine sandy sublittoral sediments (redeposited glaciofluvial deposits) at Svartbergsbäcken, c. 15 km east of Lansjärv. The original bedding is replaced by a chaotic mass of contorted and broken layers of coarse silt, sand pockets and water-escape features etc. Note gravitational sorting of heavy minerals in the sand pocket to the right of the scale. The deformed bed was laterally persistent along the whole length of the trench (several 10s of meters). Since the site is located c. 10 m below the highest shoreline and since the uppermost part of the sequence is totally unaffected by any disturbances along the trench, the deformation must have taken place during the build-up of the deposits and, thus, fairly shortly after deglaciation. Photo: R. Lagerbäck.

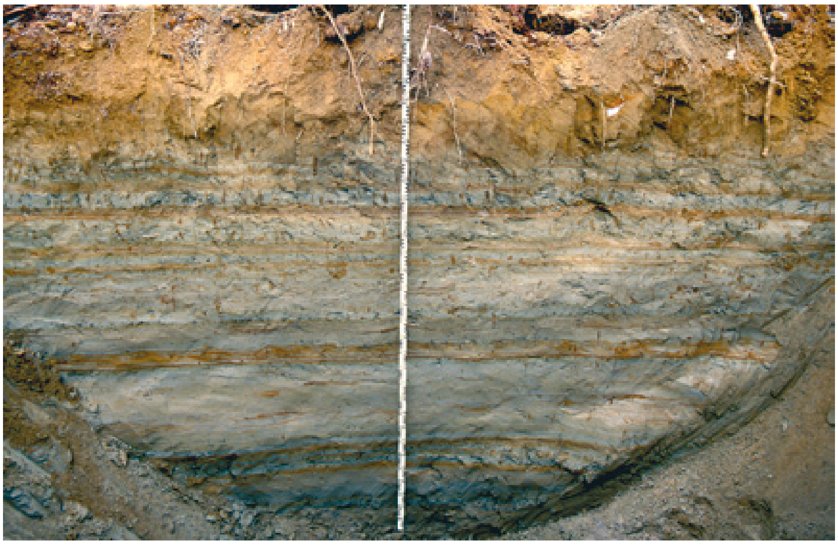


Fig. 54. In marked contrast to the sandy–silty sediments deposited during or shortly after the deglaciation of the area, and though at least 10–15 m thick, loosely packed and of a similar composition as the deglaciation sediments, the sandy–silty deltaic and fluvial sediments along River Kalixälven display no soft-sediment deformation structures whatsoever. Eight trenches, representing different stratigraphic levels from top to bottom of the thick deposits, were excavated at the site but, except for at the very bottom, the primary layering was perfectly intact without even the tiniest faults or water-escape features. In the bottommost part of the deposits, some deformation structures were found in a 0.5 m thick sandy–silty sequence resting on one meter of silty clay overlying glacial till. Since the deposition of the fluvial sediments most likely started fairly close in time to the deglaciation, and the deformed sediments were among the first deposited, these deformation structures may well have been caused by vibration from the rupturing of the Lansjärv fault. Mestoskangas (site 1 in Fig. 49), c. 40 km north-east of Lansjärv. Photo: R. Lagerbäck.

after local deglaciation while the deposits were submerged and saturated.

The most spectacular type of soft sediment deformation was found in glacial till. All primary sedimentary structures of the till were completely destroyed in these deformed sequences and, when fully developed, were replaced by a perfect size-sorting of clasts coarser than sand so that the coarseness of the ballast material regularly increased with depth (Figs. 55–58). Due to a significant compaction these *graded tills* reveal themselves by weak depressions in the ground and the graded material is often so well consolidated that it is extremely difficult to

Fig. 55. Graded till at Furuträsket, c. 6 km north-east of Lansjärv. The size of the clasts, from sand grains to boulders, successively increases downwards and the biggest boulders (>0.5 m) do not occur until a depth of about 3.5–4 m below ground surface. The primary stratigraphy (consisting of two different till beds) has been completely destroyed and the clasts from the till beds are totally mixed. See 1.2 m long spade for scale. Photo: R. Lagerbäck.

Fig. 56. Trench cut at the margin of a major depression with graded till at Furuträsket. The original stratigraphy, consisting of two different till beds, is abruptly replaced by graded till where the ground surface begins to decline towards the level bottom of the depression, situated almost one meter below the surroundings. Note the boulder-strewn ground surface in the foreground in contrast to the boulder-free surface in the depression. See 1.5 m long shaft for scale. Cf. Figs. 57–58. Photo: R. Lagerbäck.

Fig. 57. The distinct contact between the undeformed till stratigraphy and graded till in Figure 56. Photo: R. Lagerbäck.

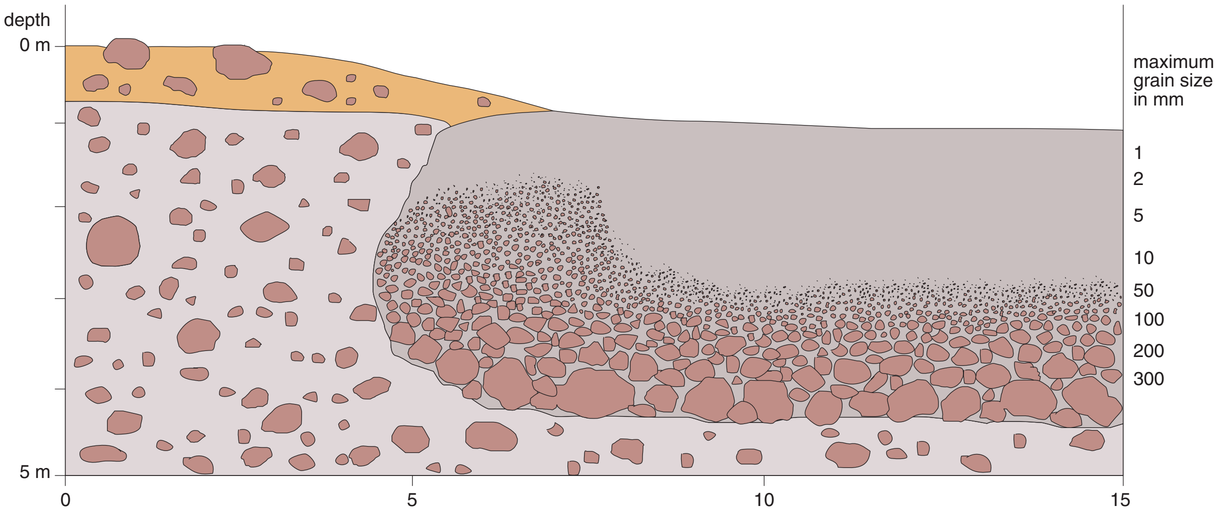


Fig. 58. Simplified log of the sequence shown in Figure 56. The "maximum grain size" scale refers to the right part of the figure, where the sorting of clasts is complete.

excavate. The ground surface within the depressions is smooth and free of stones and boulders, while the surrounding ordinary sandy till is covered with scattered boulders (Fig. 56). The deformed sequences may reach to depths of at least 5–6 m and two or more till beds may be involved in the deformation (Figs. 57–58). The process of deformation is similar to the segregation of ballast that may occur if wet concrete is overvibrated. Artificial graded till sequences can be readily produced by vibrating barrels filled with saturated sandy till on a shaking-table (Fig. 59). This type of seismite has not been found more than a few kilometers away from a prominent fault scarp, and is considered to reflect the strongest earthquake ground motion represented by the different paleoseismic sedimentary phenomena to be found in the Lansjärv area or elsewhere in northern Sweden.

Even if the most intensely developed and spectacular features were found closest to the earthquake fault, de-

Fig. 59 Although not as perfectly sorted and densely packed as in nature, an artificial graded till was produced by vibrating a barrel filled with saturated sandy till on a shaking table. In order to make the grading more apparent, the surface of the column has been flushed by water. More sophisticated experiments were planned for in a significantly larger (1 m^3) device (right), but unfortunately the project ran out of money before these plans could be realized. Photo: R. Lagerbäck.

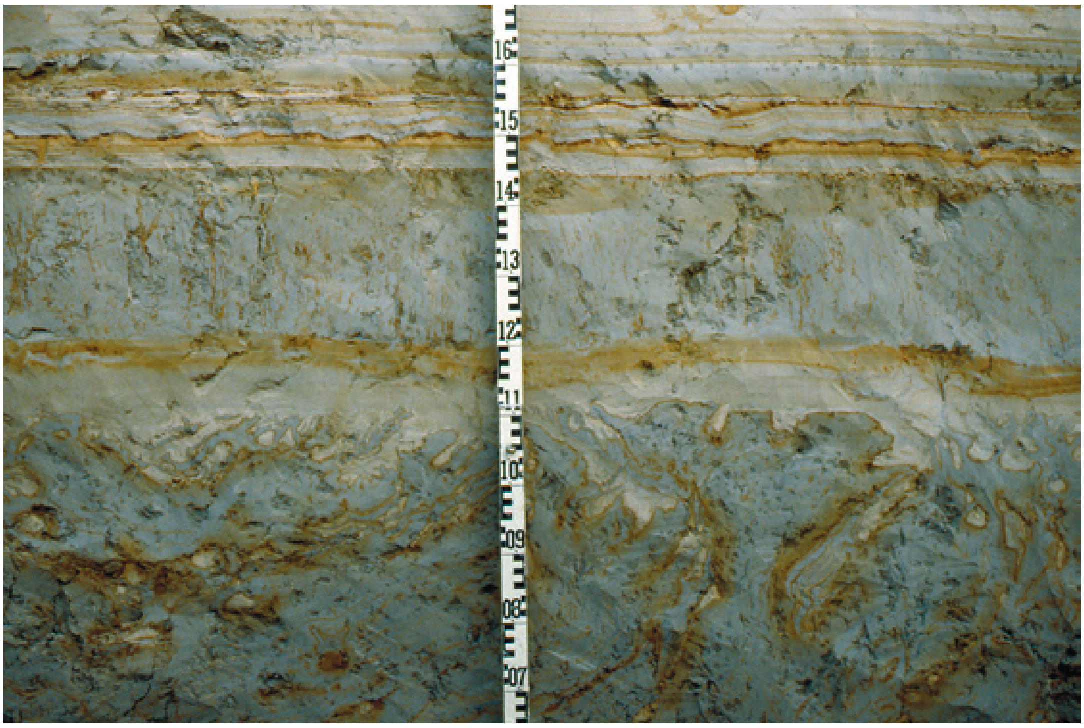


Fig. 60. Deformed and densely packed sandy and silty sediments at Svartbyn, some 60 km south-east of the Lansjärv Fault. The seemingly undeformed, mainly silty layer situated between 1.20 to 1.45 m on the levelling rod may have acted as a "straining-cloth" that constrained the upward escape of excess pore-water in connection with liquefaction of the deposits at depth. A closer look at the layer reveals that the primary layering is completely destroyed and replaced by small-scale dewatering features (Fig. 61). The deformed sequence was laterally persistent along the whole length of the trench (tens of meters). Photo: R. Lagerbäck.

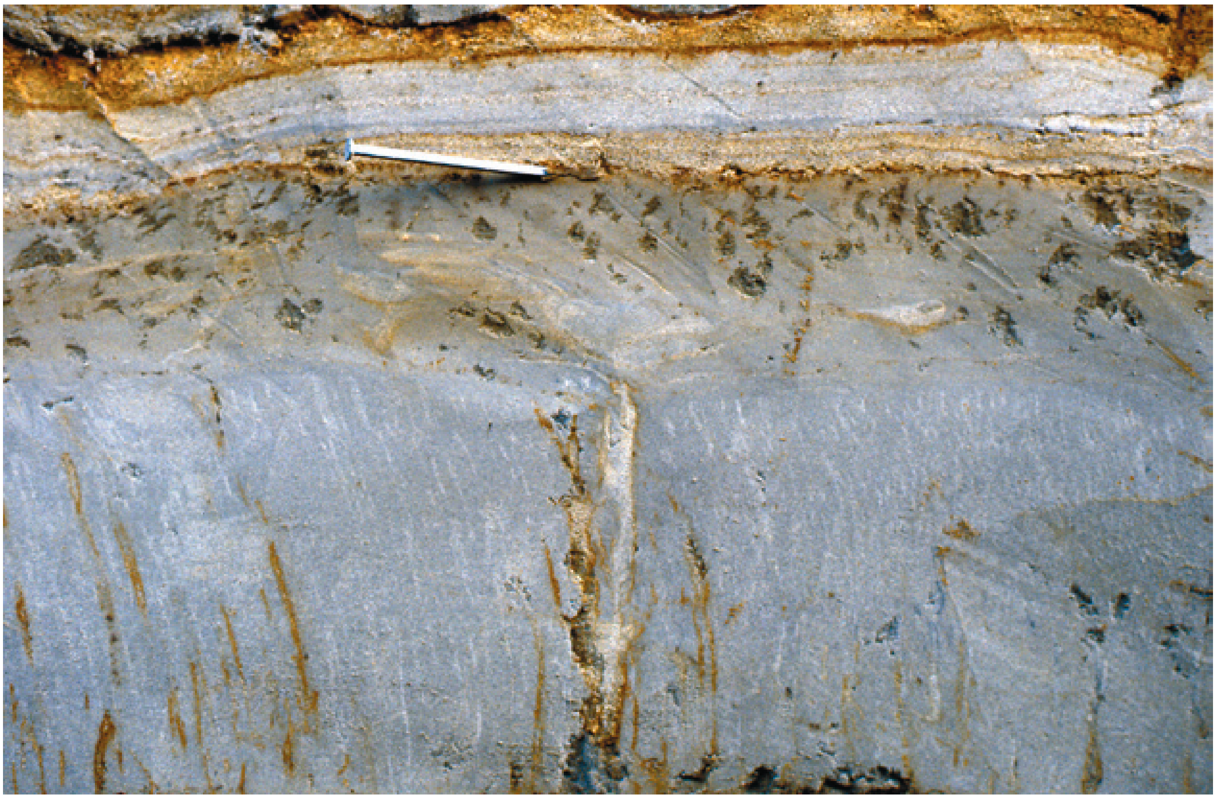


Fig. 61. Close-up of the sequence between 1.2 and 1.5 m in Figure 60. The lower part of the bed consists mainly of coarse silt, vertically striped by tiny dewatering features. The uppermost silty layer (up until the level of the nail) is interpreted to have been formed by sedimentation of fines that were elutriated from the underlying silty bed during the upward seepage of excess water from depth. Photo: R. Lagerbäck.

formational structures interpreted to be seismically induced are found at greater distances, in particular to the south-east of the fault (Figs. 60–61). Most of the paleoseismic phenomena at these more distant sites occurred in waterlain, sandy–silty sediments, but water escape structures were also found in glacial till overlying sandy deposits. At some sites these till beds were draped by thin layers of clay, penetrated by the water-escape features but overlain by sediments unaffected by the deformation, ranging from current-bedded sand to fine-grained, slurried beds containing pebbles and lumps of clay, inferred to have been deposited shortly after faulting by rapid currents and highly fluid debris flows.

Since the contemporary sea formed an inlet that reached into the Lansjärv area, the displacement of the sea bottom, with a corresponding displacement of the sea surface, must have forced large volumes of water to rush out through this inlet into the open Gulf of Bothnia. Traces of this tsunamigenic behavior are likely to have left both a depositioning signature as sediments mobilised by the strong currents resedimented on the sea floor and erosional effects along the shoreline. Much of the terrain below the highest shoreline in the Lansjärv area appears to be intensely wave-washed, although this is surprising with respect to the limited wave fetch of this relatively sheltered coastline. Instead this erosion could be attributed to the sudden, fault-generated nearfield tsunami activity associated with the profound changes in seafloor topography associated with faulting.

Eastern Västerbotten

The easternmost part of the Västerbotten county is the second most thoroughly investigated area (Fig. 62). During the years 1990 to 1992 some 70 trenches with a total length of almost 2 km were excavated at 35 different sites, all within c. 30 km from either of the Burträsk and Röjnoret faults. In addition, sediment sequences in some 15 sand and gravel pits in the area were examined. Contorted sandy–silty sediments and water-escape features were encountered throughout the investigation area and at almost all sites where liquefiable deglaciation sediments were present (Figs. 63–67). However, in contrast to the Lansjärv area, with a few exceptions, it was not possible to identify any obvious regional relationship between the intensity of the deformation and proximity to recognised fault scarps. Both small-scale and more extensive deformation structures were encountered close to the faults as well as at more distant sites. Therefore, it was in most cases

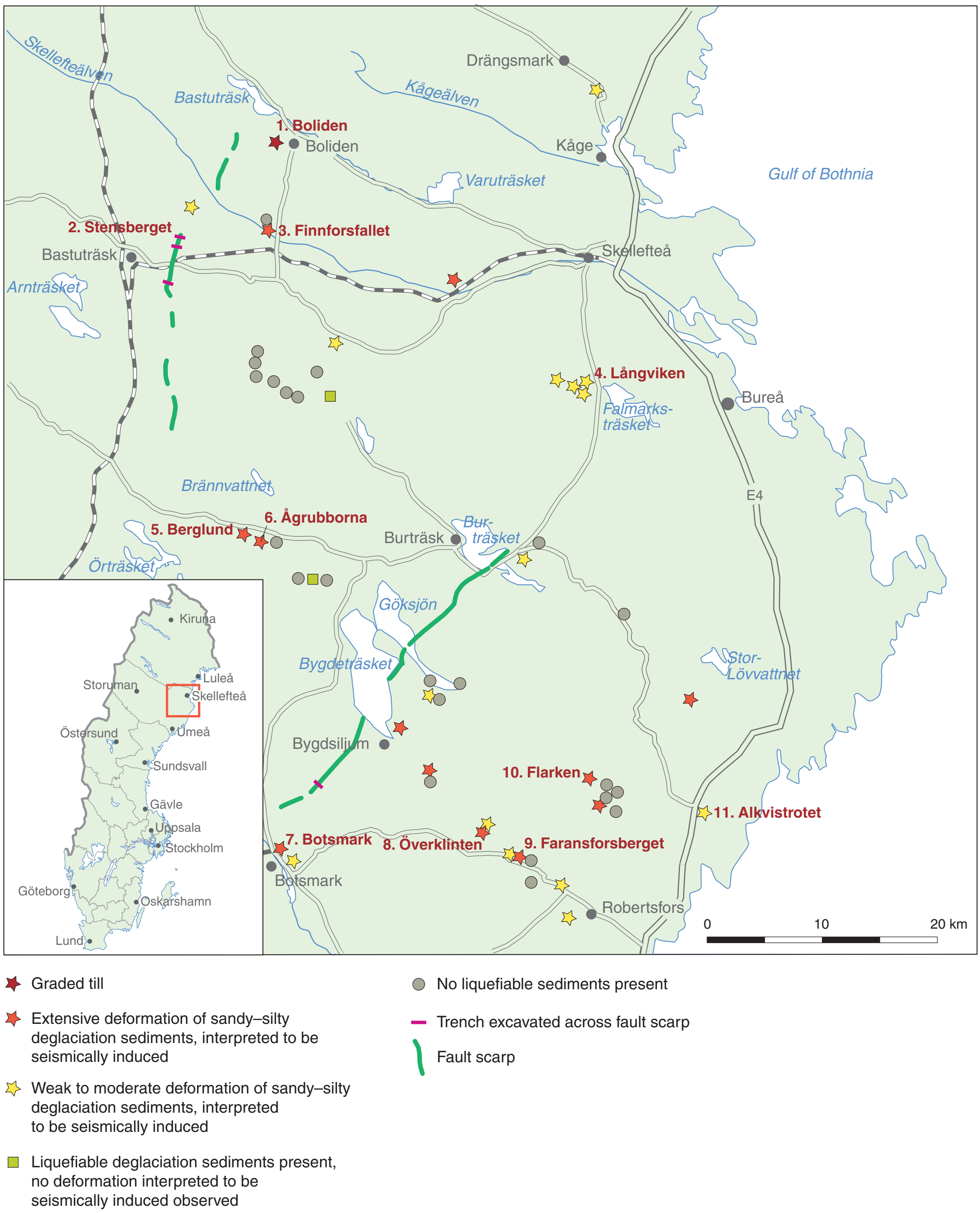


Fig. 62. The eastern Västerbotten investigation area. Sites mentioned in the text or shown in photographs are marked with numbers and names.

not possible to attribute which of the two faults that was responsible for a certain deformation. At a few sites, two contorted sandy–silty beds, separated by undisturbed sediments in between, tentatively indicated two episodes of ground shaking. However, this may be illusory, since at several sites deformation was strictly confined to specific layers of a certain granular composition (e.g. Figs. 66a, 67a).

The graded tills encountered in the vicinity of the Lansjärv fault were not specifically searched for in this area but one occurrence had already been identified (see Lagerbäck 1990). Although not identified as a seismite, Lundqvist (1946) described a section of graded till at Boliden, very similar to those found close to the Lansjärv fault. The site is located some 4 km to the east of the northern end of the Röjnoret fault and gives sup-

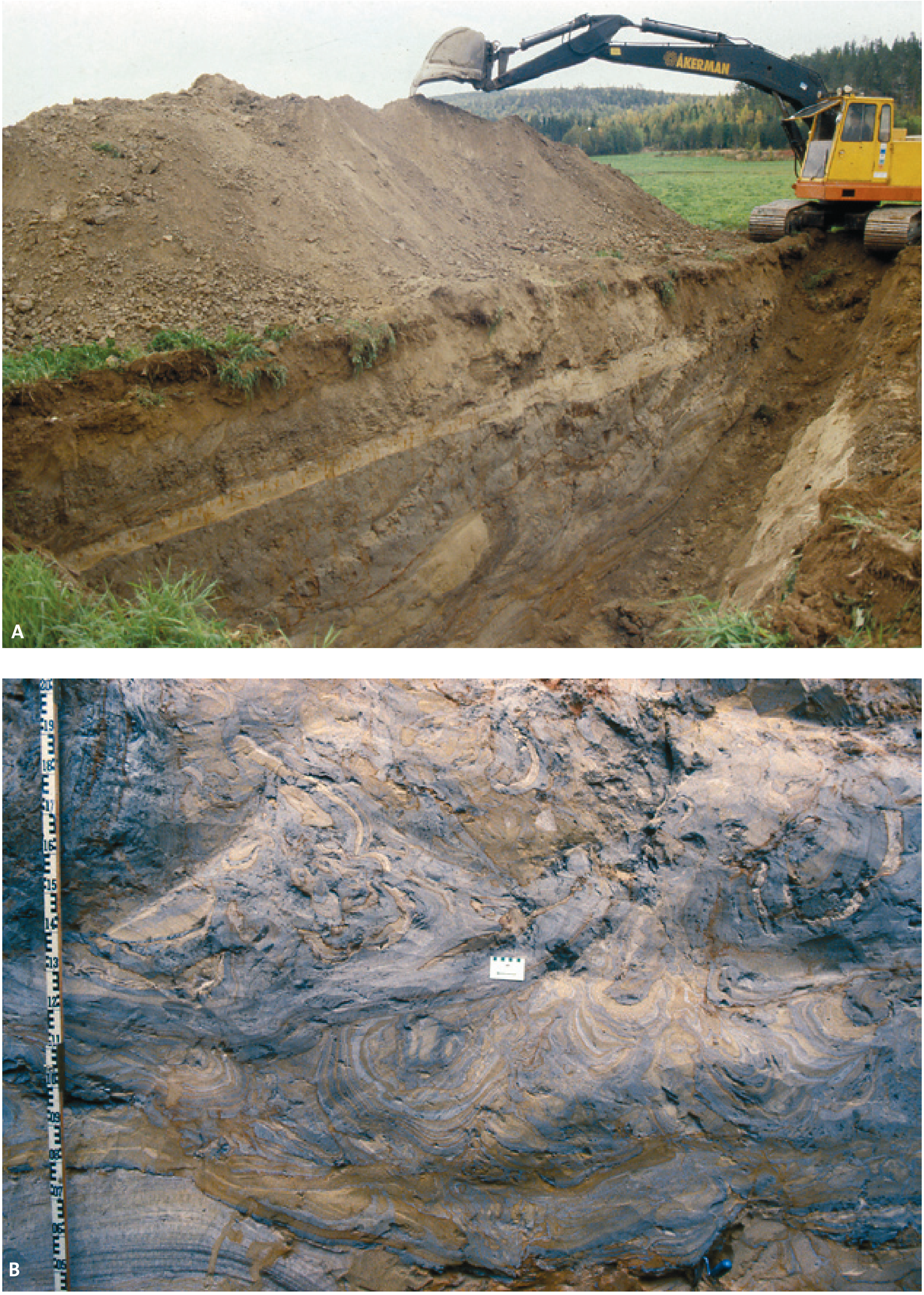


Fig. 63. Intensely deformed and densely packed sandy and silty deglaciation sediments at Botsmark. **A.** An erosional surface, accompanied by a c. 0.3 m thick layer of fine sand containing clods of glacial clay, is cut into the deformed sediments. The sand layer is overlain by undeformed glacial clay, indicating that deformation and erosion occurred fairly soon after deglaciation. **B.** Close-up of the strongly contorted sandy and silty sediments. Photo: R. Lagerbäck.

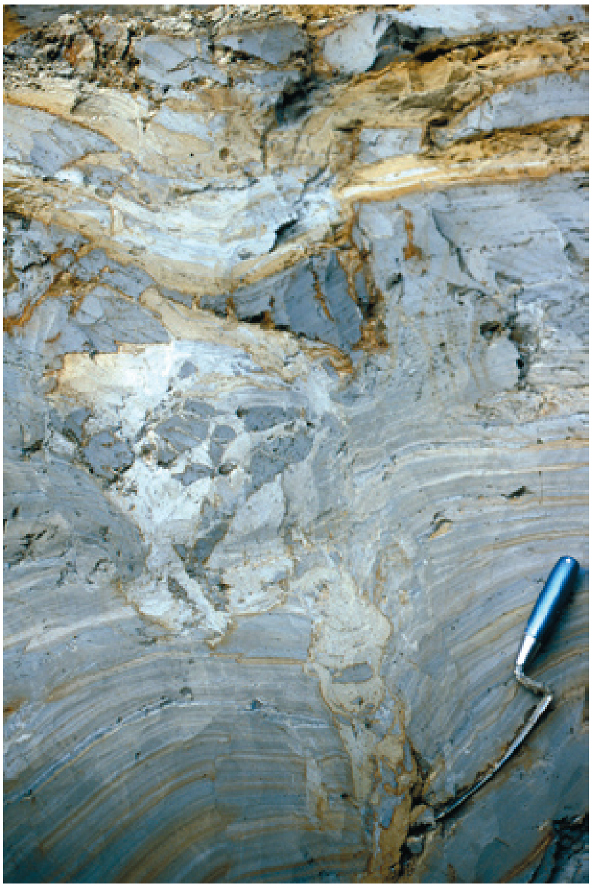


Fig. 64. Minor sand-filled water-escape feature, emanating from heavily deformed sediments at depth and penetrating into covering silty–clayey strata to form sand-filled sills, governed by the stratification of the fine-grained sediments. Överklinten, some 10 km south-east of Bygdsiljum. 30 cm trowel for scale. Photo: R. Lagerbäck.

Fig. 65. Deformation of the primary bedding was seen at practically all sites displaying sandy–silty glaciofluvial sediments in the eastern Västerbotten investigation area. The deformed sediments at this site are densely compacted and provide the swallows with good conditions for nesting burrows. Gravel pit at Långviken, some 10 km south of Skellefteå. Photo: M. Sundh.

port to the previous conclusion that the Röjnoret fault ruptured after or very shortly before local deglaciation. Another odd sequence, in coarse sandy glaciofluvial sediments, was found in a sand pit at Finnforsfallet some 10 km south of Boliden. Although the primary layering appeared to be more or less intact, the entire sand sequence was strongly compacted and displayed a great number of spherical "bulbs" protruding out of the steep pit wall (Fig. 68). Nothing resembling these features has been observed by us in the region (or elsewhere in Sweden). Not far from these bulbs, in the same sand pit, alternating sandy and silty layers were found to be heavily contorted.

The graded till at Boliden as well as heavily deformed sandy–silty glaciofluvial sediments at two sites (Ågrubborna and Berglund in Fig. 62) 10–15 km south-east of the Röjnoret fault, are located less than 20, 30 and 10 m respectively below the highest shoreline. As saturation of deposits is a prerequisite for the development of such features, and when considering the rapid land-upheaval following deglaciation, this means that the earthquake that caused these deformation structures must have occurred fairly soon after deglaciation. Since the graded till at Boliden most likely formed due to the strong shaking from the rupturing of the Röjnoret fault (in the Lansjärv area analogous features were not found more than a few kilometers away from the fault), it can also be concluded that the rupturing of this fault occurred contemporaneously with local deglaciation.

On the assumption that the rather extensive deformation structures in the southernmost part of the investigation area were caused by shaking from the rupture of the Burträsk fault, this fault also must have moved during local deglaciation. At several of these sites, varved glacial clay was involved in the deformation. At Flarken, c. 20 km east of the Burträsk fault, the deformed clay contained at least 100 varves, representing an equal number of years (Fig. 67d). With an inferred north-westerly ice recession of some 30 km/100 years (Lundqvist 1998), this implies that the area around the Burträsk fault most likely was ice-free when the fault ruptured.

The search for seismites in the area was concentrated on sandy–silty deglaciation sediments, but, due to difficulties with getting access to favourable excavation sites, a considerable number of the trenches exhibited mainly varved (anually laminated) glacial clay. Except for water-escape features emanating from more coarse-grained sediments at depth, no deformation features attributed to seismic shaking were found in these stiff, non-liquefiable sediments, but at several sites a layer of poorly sorted and non-stratified sediments, composed of anything from clay to pebble and cobble-sized clasts, was encountered (Fig. 69). This type of sediment is quite abnormal for what would be expected in a glacial clay sequence and indicates that the quiet sedimentological regime that generally prevailed beneath the sea at the margin of the melting ice sheet was interrupted by some kind of high-energy event. Since the diamict layer intercalated with or was overlain by varved glacial clay, this event must have taken place early during the postglacial period and, thus, at a significant water depth.

The number of varves that were covered by the diamict layer varied between about 10 at a site located c. 5 km to the east of the Burträsk fault and 40–50 at a site located c. 15 km to the east of the fault. Provided the layer was associated with the rupturing of the Burträsk fault, and since the contact with the underlying clay was erosive (i.e. the deposition of the layer may have occurred more than 10 and 40–50 years respectively after local deglaciation), these conditions imply that the fault most likely ruptured after the area was deglaciated.

The origin of the diamict layer is not clear but very likely it was deposited by high density bottom currents or highly fluid debris-flows, supplied with minerogenic matter eroded or slumped from the sea-floor as well as vented from deposits below the sea-bed. An inferred causal relationship with an earthquake is supported by the occurrence of sand dykes reaching up to, but not through, the diamict layer at some of the sites and by the presence of erosional surfaces cutting deformed sandy–silty deposits, e.g. at Flarken (Figs. 67c–e) and Botsmark. At Botsmark (Fig. 63) an erosional surface was accompanied by a sandy layer containing clods of glacial clay. Since the sandy layer was covered by undisturbed glacial clay, the current that eroded the deformed sandy–silty deposits and subsequently deposited the sand, must have occurred early in the postglacial period.

Layers of sand or silt intercalating with varved glacial clay were observed in many of the trenches. At several sites it was evident that the sand was vented from liquefied deposits at depth to form sills governed by the stratification of the clay (e.g. Fig. 64). However, for sandy layers of a uniform thickness, displaying graded bedding and extending laterally for tens of meters along the whole length of the trenches (e.g. Fig. 63a), such an origin cannot be supported. One such layer occurred at several sites and is considered to correspond with the sand layer at Botsmark, but tentatively also with the diamict layer at Alkvistrotet (Fig. 69) and several other sites. Major disturbances in the water body accompanying slumping, and land-level changes, i.e. similar to the inferred scenario in the Lansjärv area, may explain the erosion as well as the deposition of the coarse-grained sediments.

At a few sites, an erosional unconformity associated with a sandy–gravelly layer was also found to separate

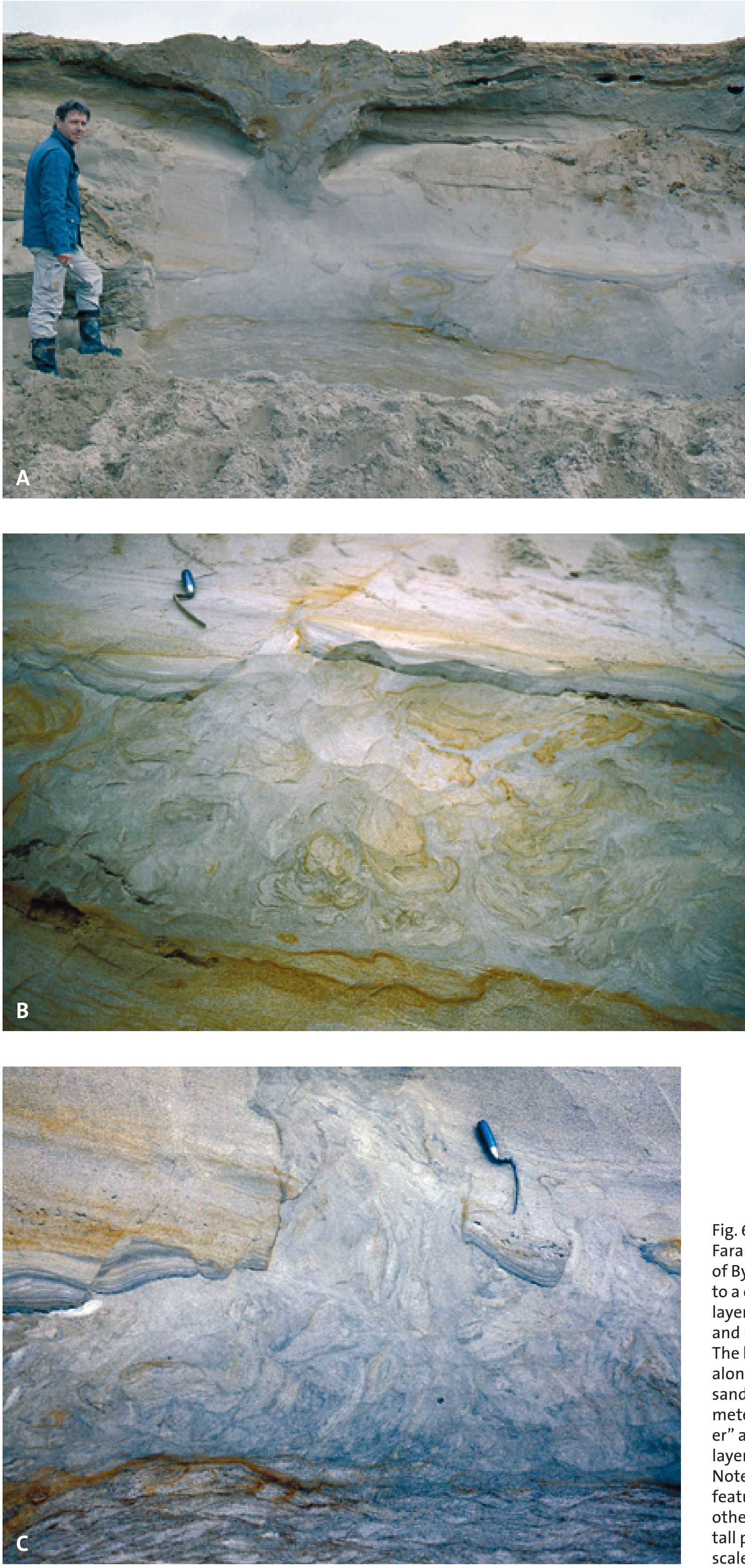


Fig. 66. **A.** One of several sand-blows at Faransforsberget, some 15 km south-east of Bygdsiljum. Liquefaction was confined to a c. 0.3–0.7 m thick, sandy–silty "feeder" layer, capped by a thin silty-clayey layer and underlain by undisturbed coarse sand. The liquefied layer was laterally persistent along the entire exposed section in the sand pit (extending over several tens of meters). **B–C.** Close-ups of the "feeder layer" and the conjuction between the "feeder layer" and the vertical dyke respectively. Note the similarity of the deformation features with those occurring at several other sites, e.g. at Flarken (Fig. 67a). 1.8 m tall person (M. Sundh) and 30 cm trowel for scale. Photo: R. Lagerbäck.

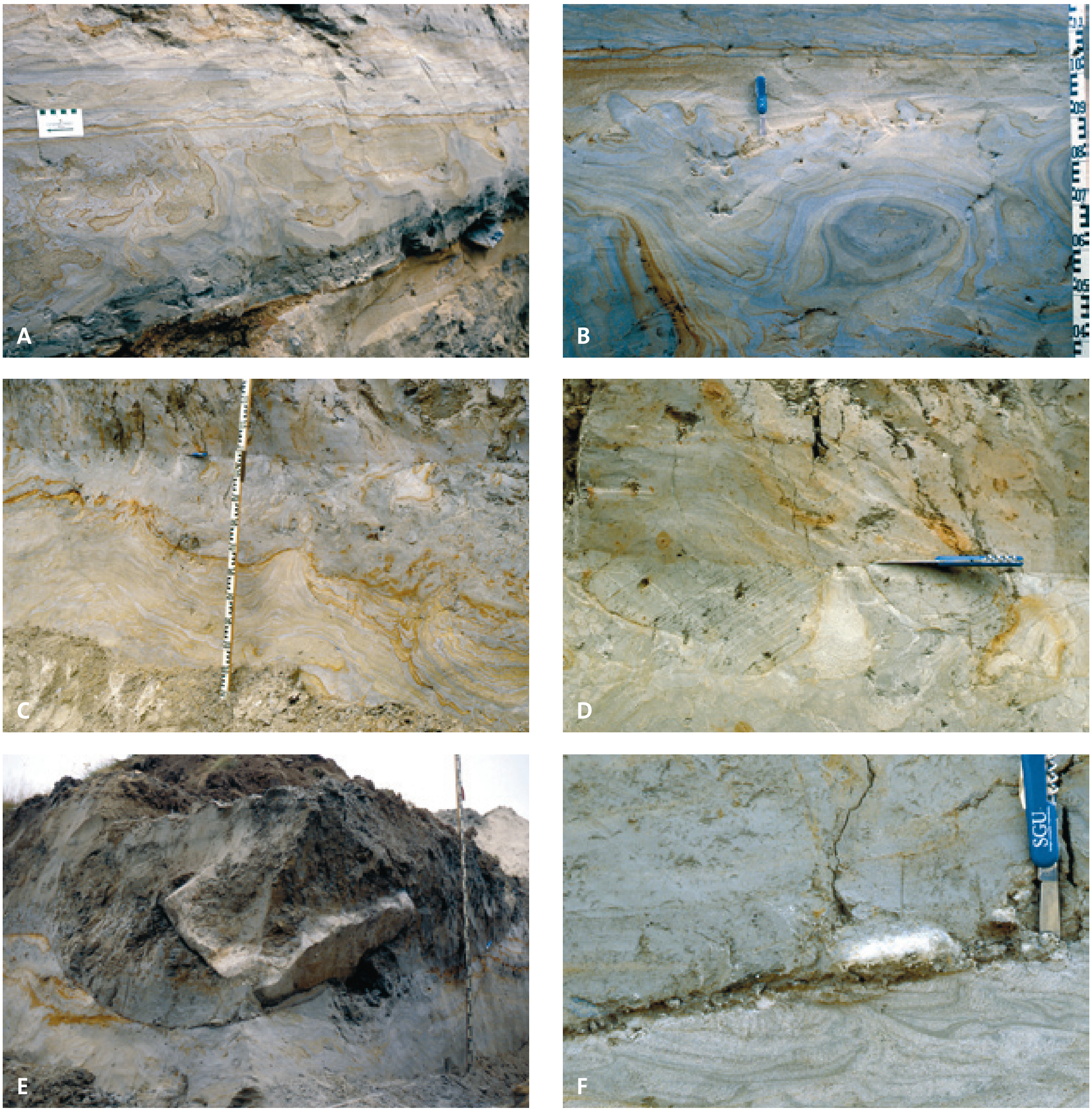


Fig. 67. At Flarken, some 50 km south of Skellefteå, deformation of sandy and silty deglaciation sediments seemingly appeared to have occurred at two different occasions. In parts of the extensive excavation site deformation was restricted to the bottommost and uppermost parts of the sandy–silty sequence, while close by the entire sequence as well as lumps of glacial clay were involved in the deformation. As at Botsmark (Fig. 63), the deformed sediments were subsequently eroded by a highly erosive bottom current. **A–B.** Deformed sandy–silty, glaciofluvial sediments directly overlying glacial till. The uppermost parts of the sections appear to be unaffected by the deformation. **C.** Intensely deformed sandy, silty and clayey sediments cut by an erosional unconformity and covered by a diffusely stratified, slightly sandy silt, grading upwards into a clayey silt. The covering sediment is assumed to be the result of fall-out of suspended matter following the erosional event. **D.** Close-up of the erosional unconformity in C. The erosional surface cuts as if by a knife through the sand and silt as well as through lumps of stiff glacial clay. Since these lumps of clay display some 100 annually laminated varves, the inferred earthquake and subsequent erosion must have occurred at least 100 years after local deglaciation. **E.** Enhanced erosion at a big boulder. The otherwise quite level and straight erosional contact (cf. C) dips to form a bowl-shaped depression, probably due to turbulent flow and eddy currents around the boulder. **F.** The occurrence of scattered pebbles and cobbles along the erosional contact is indicative of a coarse-grained bedload transport. Photo: R. Lagerbäck.

underlying glacial clay from covering postglacial clay (Fig. 70). This phenomenon was also encountered at many sites in the Uppland investigation area and was there interpreted to have been caused by strong bottom currents immediately before local upheaval above sea level (e.g. Lagerbäck et al. 2005b).

The northern coastal area

In the years 1993–94 some 30 trenches were dug at 14 different sites in the coastal areas between the Lansjärv and eastern Västerbotten investigation areas (Fig. 71), and in addition sediment sequences in a dozen sand

Fig. 68. Spherical "bulbs" protruding out of a steep sandpit wall at Finnforsfallet, some 10 km south of Boliden. Although strongly compacted, the coarse sand displays no significant deformation of the primary sedimentary layering. The section is c. 6 m high. Photo: R. Lagerbäck.

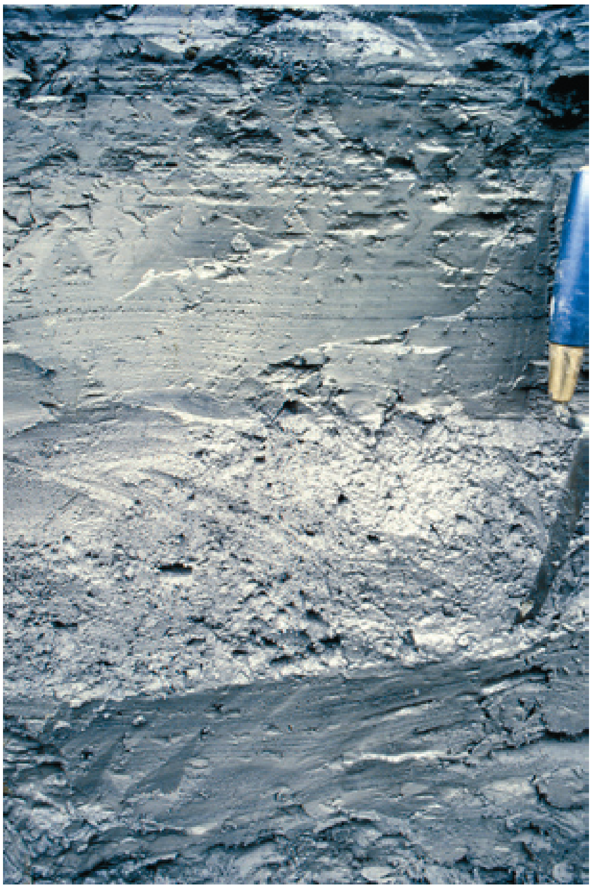


Fig. 69. Layers of poorly sorted, non-stratified sediments, composed of anything from clay to pebbles, were found to intercalate with varved glacial clay at several sites, here at Alviksrotet. Photo: R. Lagerbäck.

and gravel pits were examined. Deglaciation sediments potentially susceptible to liquefaction were present in the majority of the trenches and in a few sand and gravel pits. Fairly intense soft-sediment deformation features, water-escape features and layers of sand, coarse silt or diamict material intercalating with or covered by varved glacial clay, i.e. similar to those found in the eastern Västerbotten area, were found at several sites.

When considering that the distance from most of the investigated sites to the nearest known faults (Röjnoret, Burträsk and Lansjärv) is about 100 km or more, some of the deformation structures encountered were surprisingly intense. At Kallaxheden, a major delta-like glaciofluvial accumulation to the south of Luleå, extensive deformation of sandy and silty glaciofluvial deposits was encountered in several sand and gravel pits. At the largest extraction site, a several meter thick bed of intensely deformed sand and silt persisted laterally along several hundreds of meters of exposed section (Fig. 72). The deformation was confined to one and the same horizon of fine sandy and silty sediments and appeared not to have affected overlying coarse sandy deposits. Very likely the absence of deformation in overlying deposits can be explained by their coarseness and low susceptibility to liquefaction, but at the same time it may be considered notable that no water-escape features emanating from the deformed sediments at depth were found in the covering sand layers. If, tentatively, deformation occurred during the build-up of the glaciofluvial deposits,

Fig. 70. An erosional unconformity, accompanied by a layer of gravelly sand containing cobble-sized clasts, separates varved glacial clay from overlying postglacial clay at Alviksrotet. The erosion is believed to have been caused by strong bottom currents occurring fairly shortly before local upheaval above the sea level. Cf. Fig. 81. Photo: M. Sundh.

an inferred north-westerly ice recession of the area (e.g. Lundqvist 1998) excludes faulting in the Lansjärv area as a cause of deformation, while rupturing of either of the Röjnoret or Burträsk faults appears to be a more likely alternative.

However, it cannot be excluded that the extensive deformation occurring at Kallaxheden and several other sites in the northern coastal area was induced by an unidentified, more closely located source. Possibly, seismogenic faulting may have occurred in the eastern vicinity, i.e. below the surface of the present Gulf of Bothnia. Late Pleistocene and even postglacial movements along pre-existing, north-east-striking fault zones at the bottom of the Gulf of Bothnia, as well as intensely disturbed glacial clay along one of these fault zones, have actually been indicated by Andrén (1990), but as long as more manifest evidence for such fault movements are missing, a causal relationship with the deformational features in the coastal area is merely speculative.

The southern coastal area

The investigations along the coastal area between eastern Västerbotten and Uppland (Fig. 71) have mainly been restricted to reconnaissance of about 20 sand and gravel pits, but rather extensive excavations were also carried out at a site located some 25 km south of Söderhamn. Sandy–silty sediments, interpreted to be susceptible to liquefaction if saturated, were found at almost all of the extraction sites, but coarse sandy and gravelly glaciofluvial sediments were the dominating deposits in most of them. Water-escape features (Fig. 73) and sandy–silty beds with deformed bedding (Fig. 74), tentatively caused by seismic shaking, were found at some of the sites, but these were nowhere as extensive as those encountered at numerous sites in the northern areas. An erosional unconformity separating deformed sandy–silty sediments from overlying, undeformed sand and silt was found at one site, but since all the sediments were of glaciofluvial origin, the deformation and erosion were tentatively interpreted to be related to the local melt-water discharge (Fig. 75).

Since strongly deformed sediments had been observed in a gravel pit cut into a glaciofluvial esker at Själstuga (site 5 in Fig. 71), it was decided to execute a minor excavation program at the site. Six trenches in a row and perpendicular to the esker were excavated. The ground was markedly inclined nearest to the esker while at the most distant trenches the ground was more or less level. Sandy, silty and clayey deposits proved to have slided down the flank of the esker and become chaotically mixed. The slided sediments were covered by undisturbed glacial clay, clearly indicating that sliding had occurred soon after deglaciation (Fig. 76). At this time, the sliding was interpreted as a possible result of one or two (the slide deposits were divided by a sandy layer containing clods of glacial clay) earthquakes shortly after deglaciation, but this opinion had later to be revised in the light of extensive sliding in almost level ground in the Uppland investigation area, where nothing else indicated any significant Holocene paleoseismicity.

Uppland

Investigations in Uppland (Fig. 77) were carried out in 1997 within the frame of a research project funded by the Geological Survey of Sweden and in 2002–2004 at the request of SKB (e.g. Lagerbäck et al. 2005b). By means of air photograph interpretation a major part of the area was searched for morphologically conspicuous lineaments that might be late- or postglacial fault candidates. A number of fairly prominent but short escarpments were noted, but when field-checked these features

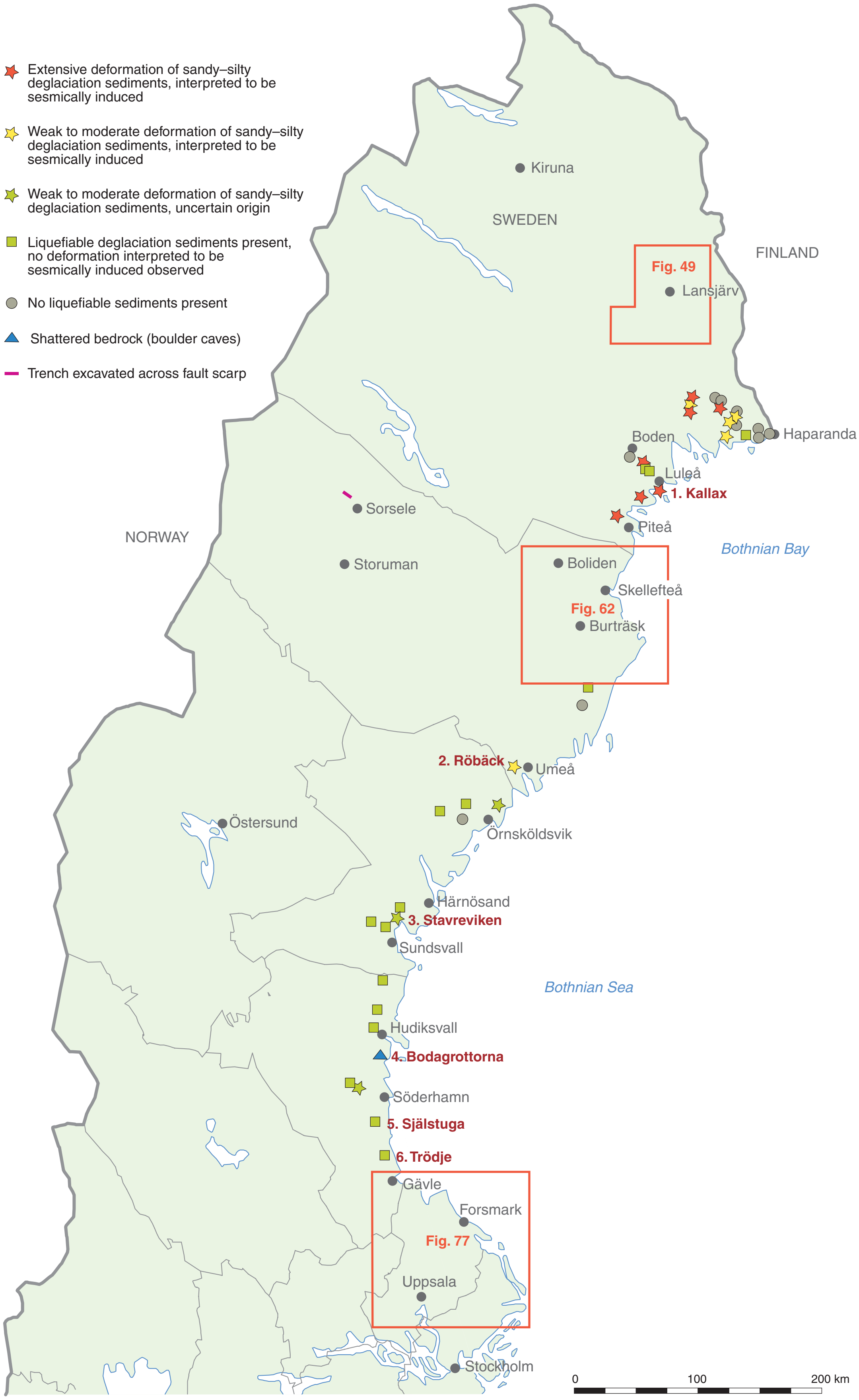


Fig. 71. Investigation sites along the coastal areas of northern and central Sweden.
Sites mentioned in the text or shown in photographs are marked with numbers and names.

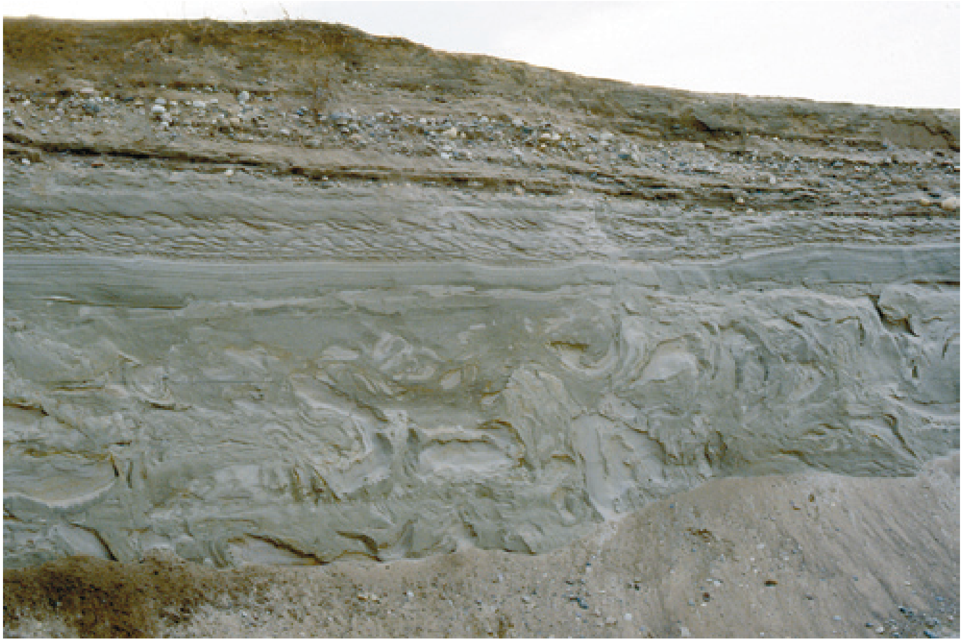


Fig. 72. Soft-sediment deformation structures were encountered in several sand and gravel pits at Kallaxheden, a few kilometers to the south of Luleå and about 100 km from the nearest identified late- or postglacial fault. At this site, a several meter thick bed of intensely deformed glaciofluvial sand and coarse silt persisted laterally along the whole length of the exposed section (hundreds of meters). The deformation appears to be confined to the most easily liquefied, sandy–silty sediments while the covering, somewhat coarser sand is almost unaffected. The gravelly sediment in the uppermost part of the section is interpreted to be beach deposits. Photo: R. Lagerbäck.

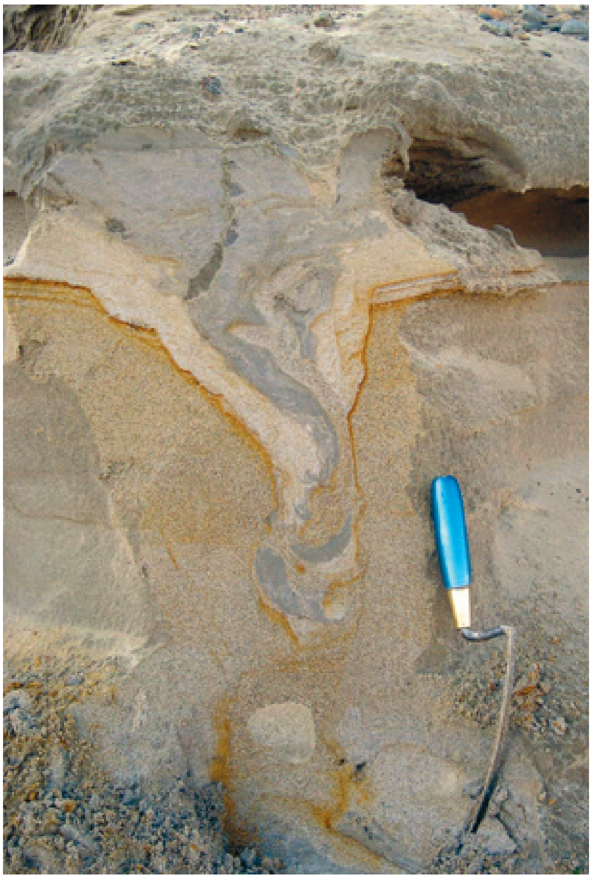


Fig. 73. Water-escape feature in sandy glaciofluvial deposits in a sandpit at Röbäck, a few kilometers west of Umeå. The upper part of the feature is partly infilled with silt from overlying beds. About 30 cm long trowel for scale. Photo: R. Lagerbäck.

Fig. 74. Deformed sandy and silty glaciofluvial sediments at Trödje, some 25 km north of Gävle. The deformation appears to be restricted to the bottommost one or two very thick annual “varves” and, thus, probably occurred in close connection to local deglaciation. Photo: R. Lagerbäck.

Fig. 75. At Stavreviken, about 20 km north of Sundsvall, an erosional unconformity with scattered pebbles and cobbles separates undisturbed glaciofluvial sand from underlying sandy–silty sediments with completely destroyed primary bedding replaced by flame structures. The deformed sequence is no more than c. 0.4 m thick and is underlain by undeformed sediments of a similar composition. The origin of deformation is uncertain, but liquefaction of the uppermost part of the former seabed induced by the eroding melt-water stream may perhaps be considered. Wave-induced liquefaction is excluded as a cause of deformation since the sediments are glaciofluvial in origin and, thus, deposited in connection with local deglaciation and at a significant water depth (c. 200 m or more). Photo: R. Lagerbäck.

Fig. 76. Slided sandy–silty deposits covered by undisturbed glacial clay at Själstuga, some 25 km south of Söderhamn. Photo: M. Sundh.

proved to be more or less strongly glacially abraded, i.e. formed prior to the last deglaciation.

In order to search for seismically induced distortions some 70 trenches with a total length of c. 1.3 km were excavated at about 25 sites, with a concentration in the vicinity of the proposed repository for nuclear waste at Forsmark in the north-eastern part of the area. The majority of the trenches were excavated in sandy–silty deglaciation sediments, considered to be highly susceptible to liquefaction if saturated (Fig. 78). In addition, some 40 sand and gravel pits were visited and examined for any features indicating seismically induced distortions of the primary layering. Of these, about 10 displayed considerable amounts of sandy–silty deposits regarded as susceptible to liquefaction if saturated. Deformational features (Fig. 79) and water-

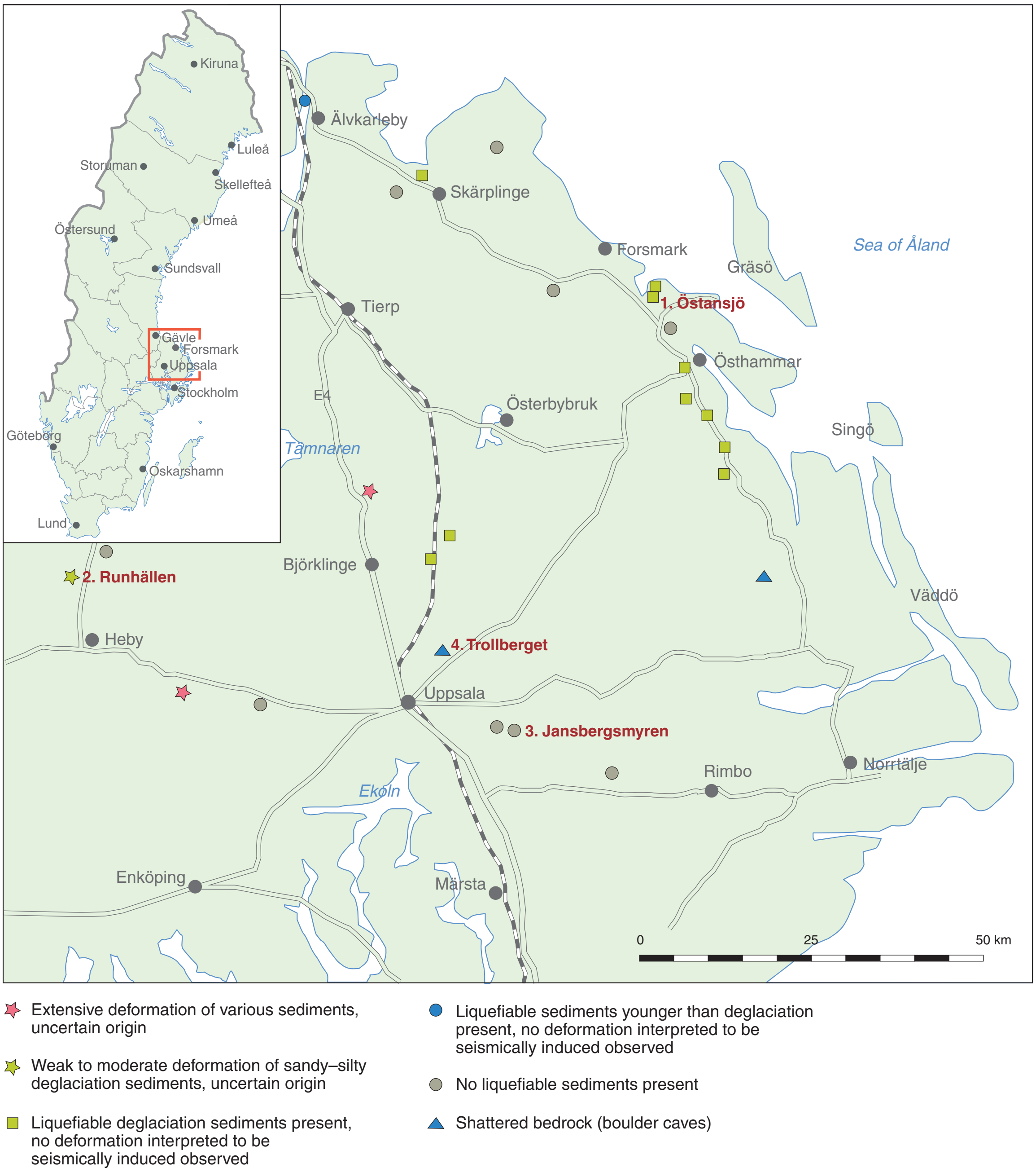


Fig. 77. The Uppland investigation area. In addition to the excavation sites depicted on the map, a number of sand and gravel pits were visited and examined as well. Sites mentioned in the text or shown in photographs are marked with numbers and names.

escape features, tentatively caused by seismic shaking, were encountered at a few sites, but the features were generally laterally very restricted and nowhere as extensive as those occurring at numerous sites in northern Sweden. Although containing sandy–silty deposits considered as highly sensitive to liquefaction if saturated, the majority of the trenches did not exhibit any deformational features or only minor water-escape features. A major water-escape structure was encountered at one site along the Uppsala esker but the feature was interpreted to be due to local hydrological conditions rather than seismically induced liquefaction (Lagerbäck et al. 2005b).

Two remarkable phenomena, potentially indicative of paleoearthquakes and fault movements respectively, were noticed in the area. It soon became evident that a surprisingly extensive, subaqueous sliding and folding of chiefly clayey deposits had occurred at many of the sites though the trenches were excavated in level or only very slightly inclined ground (Fig. 80). Hypothetically, this sliding may have been triggered by earthquakes but the absence of any soft-sediment deformation features

Fig. 78. Typical for the stratigraphy along the Börstil esker south of Forsmark in Uppland, this trench section at Östansjö shows a bed of loosely packed fine sand and coarse silt covered by a bed of clay-laminated silt. Extended excavation revealed loosely packed and saturated glaciofluvial sand to a depth of at least 5 m. In a saturated state, the stratigraphy in the trench is considered to be highly susceptible to liquefaction, but no deformation structures related to seismically induced liquefaction were found here or elsewhere along the esker. From Lagerbäck et al. (2005b).

Fig. 79. Pseudo-nodules in a pillow-like structure and otherwise deformed sandy–silty glaciofluvial sediments at Runhällen, some 10 km north of Heby. An erosional contact (not visible in this photograph) to overlying glaciofluvial deposits indicated that the deformation is synsedimentary, i.e. occurred in close vicinity to the receding ice sheet. From Lagerbäck et al. (2005b).

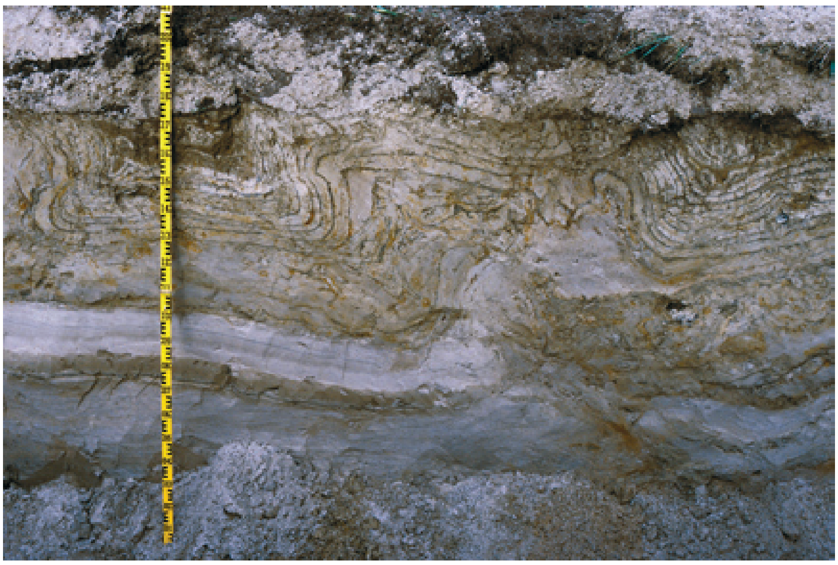


Fig. 80. Although most trenching was carried out in almost level ground, folding and sliding proved to occur very frequently in Uppland. Gently folded silt and fine sand at Östansjö, some 7 km south-east of Forsmark. From Lagerbäck et al. (2005b).

Fig. 81. A layer of gravel containing large clasts (up to 0.3 m in diameter) separates eroded glacial clay from covering postglacial clay at Jansbergsmyren, some 15 km south-east of Uppsala. Cf. Fig. 70. Photo: R. Lagerbäck.

in the easternmost part of the investigation area, where sliding occurred most frequently, speaks against this alternative. Moreover, in spite of strong evidence for paleoearthquakes, clayey sediments involved in slides were only rarely met with in northern Sweden.

Furthermore, an erosional unconformity, accompanied by a laterally persistent layer of sandy or gravelly sediments and separating glacial clay from covering postglacial clay, was present in many of the investigated trenches within the entire investigation area (Fig. 81). The erosional unconformity and associated sediment layers in this area are supposed to correspond to the upper erosional unconformity that separated glacial clay from covering postglacial clay in eastern Västerbotten (cf. Fig. 70) and were interpreted to have occurred in shallow water fairly shortly before local upheaval above the sea level (see Lagerbäck et al. 2005b and references therein). The phenomenon is indicative of extremely strong and erosive bottom currents in the ancient sea, but their origin is elusive since currents capable of transporting cobbles 0.3 m in size appear to be an unexpected phenomenon in this type of environment (e.g. Brydsten 1999). A hypothetical dislocation of the sea-floor is not a credible explanation of the phenomenon since at each site, irrespective of elevation above the sea, the layer was formed fairly shortly before local upheaval above sea level and, thus, not synchronously in the area.

Eastern Småland

In 2003–2005 an investigation programme similar to that in Uppland was carried out at the request of SKB in a fairly large area in eastern Småland in southern Sweden (Fig. 48, Lagerbäck et al. 2004, 2005a, 2006). By means of air photograph interpretation the entire area was searched for morphologically conspicuous lineaments and landslides. A number of fairly prominent escarpments were noted, but when field-checked they proved to be either glacially eroded or strongly weathered, i.e. most likely formed prior to the last deglaciation, and no indications whatsoever on late- or postglacial fault movements along the features were found. On the island of Öland, a c. 7 km long north-striking fault-like lineament was identified in air photographs. When field-checked, the feature was found to correspond to a 0–1.5 m high step in ground surface or to a very distinct vegetational boundary due to different soil depths on each side of the lineament. It was concluded that the step in the ground surface derived from a bedrock scarp but conclusive evidence for a fault origin was not found.

A few landslide scars and rockfall deposits, hypothetically indicative of paleoearthquakes, were noticed during the air photograph interpretation. When field-checked, at least one of the slides appeared to have developed in glacial till, but possibly the slide was triggered by undermining of the slope foot by glaciofluvial erosion rather than by an earthquake.

In the easternmost part of the area, which is mainly located below the highest shoreline, some 50 trenches, with an overall length of some 750 m, were excavated at 14 sites, and in addition a great number of sand and gravel pits were visited. The majority of the pits were, however, out of operation and "restored", and of the remaining ones only some fifteen displayed minor deposits of coarse silt or sand. What is more, the Quaternary stratigraphy within the area afforded a great surprise. A literature review performed before

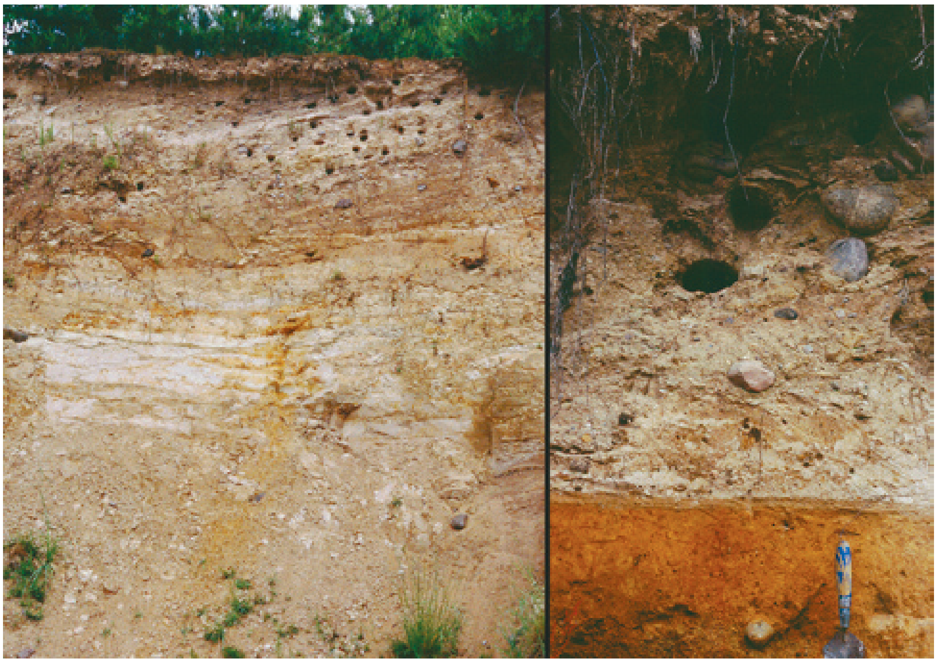


Fig. 82. Glaciofluvial sand and coarse silt covered by a bed of diamicton, most likely glacial till, at Hälgsjö some 10 km north-west of Västervik in south-eastern Sweden. The upper part of the glaciofluvial sand is tectonized and contains incorporated pebbles. Well-rounded clasts in the diamicton indicate reworked glaciofluvium of local origin. From Lagerbäck et al. (2004).

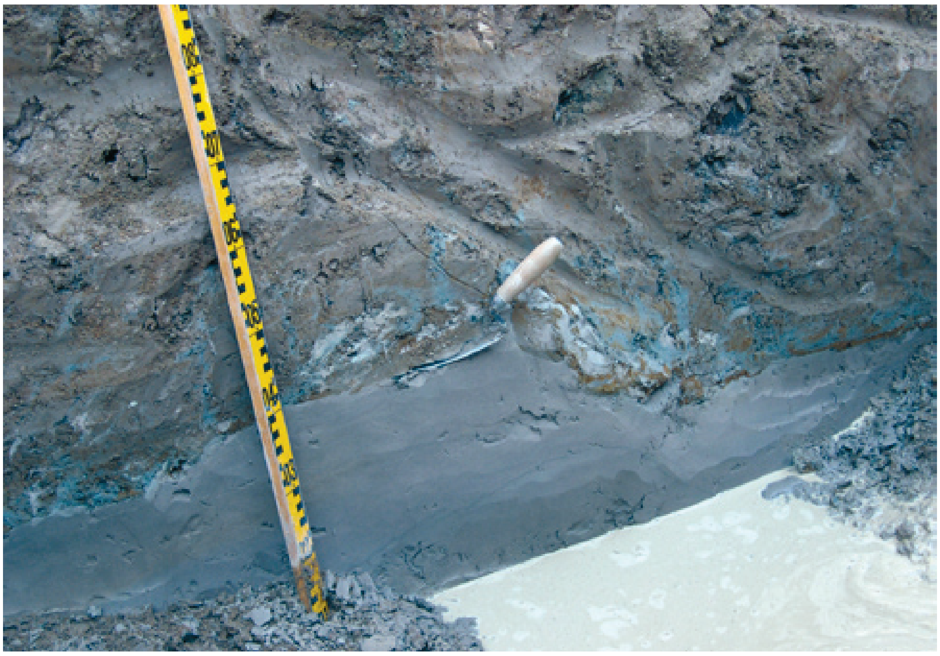


Fig. 83. A bed of clayey diamicton covers intensely deformed and densely compacted glacial silt at Mistekärr, some 20 km north of Västervik in southern Sweden. The diamicton is interpreted as a basal till and the deformation and compaction of the underlying silt is believed to be glaciotectonically induced. From Lagerbäck et al. (2006).

the investigations started did not indicate any complicated geological development during the deglaciation of the area. Accordingly, the glaciofluvial deposits were generally expected to derive from the last deglaciation and loosely packed sandy–silty deposits were anticipated along the flanks of the eskers in the same way as in the previously investigated areas. However, it soon became apparent that the glaciofluvial deposits in the region were to a large extent covered by a layer of till-like diamicton and superficial boulders, indicating

Fig. 84. To avoid falling over, this boulder seemingly appears to be supported by the tree. However, as the boulder is situated above the highest shoreline it has probably, without any support, remained in the same position since it was carefully laid down by the inland ice sheet. Boulders in unstable positions occur rather frequently in parts of southern Sweden, and preferably above the highest shoreline, where they have escaped the impact of waves and sea ice. From Lagerbäck et al. (2004).

Fig. 85. A perched erratic boulder is precariously balanced on the edge of another major boulder not far from Örneström, some 10 km west of Kisa in southern Sweden. The finder of the boulder (Harald Agrell, Geological Survey of Sweden, to the left in picture) appears to feel comfortable with the situation. Photo: R. Lagerbäck

that the glaciofluvium was overridden by an ice sheet (Figs. 82–83).

This was totally unexpected and it proved quite difficult to find suitable deposits for investigation. Not only glaciofluvial sandy–gravelly sediments, but at several sites also glacial clay and silt, were covered by, and even incorporated in, the diamict deposits. Although it was never elucidated whether these sequences were the result of oscillations of the ice sheet during the last deglaciation or represented deposits from two separate glaciations, glaciotectonics had to be considered a cause for deformational features in the water-lain sediments. Moreover, if overridden by a thick ice sheet, the water-lain deposits might have been consolidated and become less susceptible to liquefaction.

Nevertheless, thick beds of loosely packed sand and coarse silt were present at a number of sites along some of the eskers and at a few sites these sediments were also covered by a cap of glacial clay or fine silt and, thus, may have provided favourable conditions for development of liquefaction in a saturated state. However, no deformational features supposedly related to seismic shaking were noted in any of these trenches. Water-escape features were found in one trench and soft-sediment deformation structures tentatively caused by seismic shaking were encountered at two of the gravel pits, but the nature of the deformational processes was not considered clear.

If it was difficult to find adequate sediments for tracing soft-sediment deformation, a richness of superficial boulders in parts of the investigation area provided a complementary possibility for assessment of the postglacial paleoseismic history of the area. A great many of the boulders found within the investigation area were considered fairly susceptible to strong seismic acceleration, but without estimates of how much earthquake-induced ground motion these boulders could withstand before they are toppled, it was difficult to judge their significance as paleoearthquake indicators (cf. Brune et al. 1996). However, some of these boulders proved to be situated in such unstable positions, e.g. on steeply sloping bedrock surfaces, that they could hardly remain unaffected if subjected to strong ground shaking (Figs. 84–85).

Discussion

REGIONAL DISTRIBUTION OF FAULT SCARPS

Although over thirty years have passed since the major fault traces in northern Sweden were identified and first mapped (Lagerbäck 1977, 1979, Lagerbäck & Henkel 1977), the overall pattern of late- and post-glacial fault scarps in northern Sweden has not changed to any significant degree. Some details of the traces of the major fault scarps have been modified and a few relatively short or less conspicuous fault scarps have been added to the picture. During the last thirty years, the geology of most of central Sweden as well as great parts of southern Sweden has been mapped by the Geological Survey of Sweden, with air photograph interpretation as an important tool, but no major, previously unidentified, fault scarps of this type have been recognized. Therefore, it is not considered likely that any faults of similar magnitudes and character to the Pärvie, Lainio–Suijavaara, Lansjärv, Röjnoret or Burträsk faults would have remained undetected if they did exist in more southern parts of Sweden and, accordingly, it is strongly indicated that this type of faulting was concentrated to the northern parts of the country. The situation appears to be similar in Finland (Kuivamäki et al. 1998) and Norway (Olesen et al. 2004) where the late- or postglacial faults so far identified are also concentrated to the northern parts of these countries (Fig. 2).

However, over these same decades, other claims have been published for presumed late- or postglacial fault movements in more southern parts of Sweden (e.g. Lagerlund 1977, Mörner et al. 1981, Mörner 2003, Tirén et al. 2001). Yet, as far as is known to the authors, no conclusive evidence for such faulting has been presented and, therefore, these claims must be considered uncertain. While it is impossible to discount the existence of minor or less conspicuous late- or postglacially developed fault scarps in more southern parts of Sweden, it is not considered likely that the general regionalisation of the area of known major fault scarps will change in any significant way in the future. It should be stressed, however, that the conditions for identifying morphological expressions of any low-angle normal or strike-slip fault movements by means of air photograph interpretation are much less favourable, but these styles of faulting are not expected to develop in the stress regime that prevailed during deglaciation, at least over the site of the main ice sheet (Muir-Wood 1989, Johnston et al. 1998).

PALEOSEISMIC RECORDS

A concentration of the late- to postglacial faulting to northern Sweden is also strongly supported by the regional distribution of the paleoseismic records, landslides as well as soft-sediment deformation features. While hundreds of landslides developed in glacial till occur in the vicinity of the faults in northern Sweden, only a few such landslides have been identified in the more southern parts of the country – including two landslide scars, both probably developed in glacial till, which were identified in connection with the investigations in eastern Småland (Lagerbäck et al. 2004) and a major slide (c. 1.5 million cubic meters) developed in thick till deposits at Kallhem, some 40 km west of Säffle, which was discovered in connection with mapping of Quaternary deposits (Arne Hilldén, Geological Survey of Sweden, pers. comm. 2006). It is true that apart from in eastern Småland no systematic search for this type of landslides has been carried out in southern Sweden, but if such slides were widespread, it is considered unlikely that they would have escaped detection since, over the past couple of decades, large areas in most of the country have been geologically mapped by means of air photograph interpretation.

There is a strong spatial relation between landslides and faults in north-eastern Norrbotten and adjacent parts of Finland, as well as in eastern Västerbotten and in the Storuman area in central Västerbotten (Fig. 2). The apparent absence of landslides in the vicinity of the Pärvie, Lainio–Suijavaara and Merasjärvi faults is, however, somewhat obscure. Whereas additional landslides in the area might become identified in connection with more detailed mapping, the overall distribution pattern is unlikely to change in any significant way in this part of Sweden. There may be several explanations for the scarcity of landslides in the vicinity of these faults. The continued cover of the inland ice sheet during faulting appears the most likely explanation for the absence of widespread landsliding in these areas, although the precise regional distribution of remaining inland ice during rupturing of the different faults remains poorly known. A generally rather thin regolith cover in the north-western areas may also have hampered the triggering of landslides in the surroundings of the Pärvie fault, and if the faulting occurred in late winter the ground could also have been deeply frozen. Remaining permafrost might be an explanation for the lack of landslides around the Merasjärvi fault, but if so, permafrost would just as well have prevented sliding at the northern end of the Lansjärv fault, where landslides do occur in abundance. There is good evidence that cold-based ice conditions and permafrost have prevailed until the final deglaciation in wide areas of northern Sweden, but the degree of degradation of the permafrost after deglaciation might certainly have varied from area to area when faulting occurred. Kujansuu (1972) suggested that the slip plane of the landslides may have coincided with the boundary between frozen and thawed-out ground. The predominant southward orientation of the Finnish slides, tentatively indicating a deeper thawing of the permafrost due to a higher insolation, was taken as support for this interpretation. However, as was mentioned above, no such preferred orientation has been recognized on the Swedish side of the border where the landslides appear to be more randomly oriented.

The very marked concentration of landslides to the area around the Finnish–Swedish border could also reflect the magnitude and duration of earthquake ground motion in this region. Because of its dimensions and based on the assumption that the fault ruptured during a single event, the Pärvie fault is considered to have produced the greatest earthquake of all (e.g. Muir-Wood 1989, 1993, Arvidsson 1996, Johnston 1996). While stratigraphic evidence of a single episode of fault rupture is only available for the Lansjärv and Röjnoret faults, even if some of the fault scarps were a product of more than one episode of displacement, the associated earthquakes (of at least $M_W 7$) would probably have been large enough to each generate regional liquefaction. The Pärvie and, less likely (see the appearance of the fault scarp at Pyhävaara), the Lainio–Suijavaara fault scarps could possibly have been the product of more than one episode of displacement, and a two-step origin is indicated for the short fault scarps at Storuman. However, repeated fault displacement does not provide a reasonable explanation for the absence of landslides in the north-western areas.

The abundance of landslides in densely packed glacial till, which is not easy to liquefy, in the entire area between the Lansjärv and Suasselkä faults suggests very high levels of prolonged ground shaking in this region. The magnitude of the earthquake associated with the rupturing of the Lansjärv fault on its own has been estimated to c. M 7.8 (Muir Wood 1993, Arvidsson 1996). The Suasselkä fault lies along strike from the Lansjärv fault and, although they are a large distance apart and only a few short surface fault ruptures have been identified between them (Fig. 2), it might be speculated that the fault ruptures are in fact connected at depth. This speculation finds some support in the existence of the 4 km long surface rupture of the Pasmajärvi fault, with an extraordinary height of 12 m, located in between the Suasselkä and Lansjärv faults.

In this context it may be stressed that the strike direction and height of the fault scarps generally appears to be strongly governed by the properties of the local surficial bedrock and that fairly long gaps in the scarp traces occur along several of the other faults. Furthermore, the hypothesis that the fault remained blind without surface outcrop between the Suasselkä and Lansjärv faults gains some support from the drainage pattern in the area north-west of the tentative deep-seated deformation (warping) of the crust. At least on the Swedish side of the border, widespread mires and apparently altered stream courses, including one of the largest bifurcations in the world, river Tärendöälven, may be indicative of a geologically recent deformation and tilting of the land surface.

A key feature of the faults of northern Sweden is that there appear to have been a relatively small number of very long and large rupture earthquakes in the region. This implies that the conditions of earthquake initiation were difficult to attain, but once a rupture had begun on a fault at depth it was able to propagate through the prevailing stress field for long distances. The large rupture dimensions imply very high deviatoric stresses requiring to be relieved through shear strain on the fault.

It is not only the landslides but also the soft-sediment deformation interpreted to be seismically induced which appears to be almost entirely limited to northern Sweden. While it is true that the detailed search for such features has been concentrated in only four areas (Fig. 48), reconnaissance was also carried out in sand and gravel pits along the entire coastal areas of northern and central Sweden, and less systematically in various parts of southern Sweden. Although there were relatively few observations in appropriate liquefiable deposits in the coastal area, deformation features interpreted to be due to seismically induced liquefaction or fluidization diminish drastically south of Västerbot-

Fig. 86. Heavily disrupted bedrock at Bodagrottorna (site 4 in Fig. 71), some 10 km to the south of Hudiksvall. An interstitial network of cavities in the mass of angular blocks forms the "boulder caves". Photo: R. Lagerbäck.

ten county. While in the northern areas almost every deposit composed of sandy–silty deglaciation sediments displayed various soft-sediment deformation structures, equivalent sediment sequences in the Uppland and eastern Småland investigation areas were practically devoid of such features. Tentatively, the widespread sliding of clayey and silty deposits met with in Uppland, and to some extent also in eastern Småland, may have been triggered by earthquakes, but this explanation is not consistent with the scarcity of soft-sediment deformation structures in these areas.

According to our own observations as well as literature reports (e.g. Tröften 1997, Lindén 2002, Mörner 2003), there is no doubt that soft-sediment deformation structures occur here and there in central and southern Sweden, but as long as the observations of such features are isolated in areas where deposits of similar age and composition remain largely undeformed, the seismic origin of the deformation structures must be considered uncertain. Accordingly, although it has not been possible to convincingly connect these deformational features to any mapped fault scarps it can by no means be excluded that they have a local seismic origin. However, it is inconceivable that postglacial earthquakes of comparable magnitudes to those accompanying the creation of the Lansjärv, Röjnoret and Burträsk fault scarps have occurred in more southern parts of Sweden.

However, in a number of papers by Mörner, conveniently summarized in Mörner (2003), a great number of paleoseismic events have been claimed to have occurred in more southern parts of Sweden, of which some are suggested to represent great earthquakes with "estimated magnitudes >>8". Various phenomena are suggested to support these putative cataclysms, but no conclusive evidence for corresponding fault movements is presented. It is not possible here to comment on all of the paleoseismic claims presented by Mörner but one phenomenon, namely a massive disruption of bedrock outcrops, that is thoroughly dealt with in Mörner (2003) and has been considered a paleoseismic record by others as well (e.g. Sjöberg 1994), will be briefly reviewed.

Intensely disrupted bedrock outcrops, forming masses of angular blocks with interstitial cavities, so-called "boulder caves", occur rather frequently in the eastern

Fig. 87. A disrupted bedrock outcrop hosting a "boulder cave" at Trollberget (site 4 in Fig. 77), some 10 km to the north-east of Uppsala. The rock fragments appear in an "imbricated" manner, something that was found to be typical of many of the heavily broken bedrock outcrops hosting "bedrock caves" in southern Sweden. Similar to the "bedrock caves" at Boda (Figs. 86 and 88) this site is located in an area of very few outcrops but with a strongly increased boulder frequency in the surrounding area. The consistent inclination of the glacially abraded block surfaces is interpreted to reflect the impact of ice flow from right to left. From Lagerbäck et al. (2005b).

parts of southern and central Sweden (Sjöberg 1994). Bodagrottorna, located some 15 km to the south of Hudiksvall (see Fig. 71), is the most impressive of the Swedish boulder caves (Fig. 86). According to Mörner (2003) the bedrock fracturing at Boda reflects a major paleoseismic event in year 9663 BP according to the applied clay-varve chronology, i.e. well after local deglaciation. According to Mörner (2003) the deformation of the bedrock at Boda and other sites is attributed to the interaction of "shaking, rise and fall of the ground at the passing of seismic waves and methane venting", and the epicentre of this assumed and exceptionally devastating earthquake "seems to have been located just west of Hornslandet along a major NW–SE trending fault", i.e. some 15 km to the east of the disrupted outcrop. In addition to this extraordinary earthquake another six paleoseismic events were inferred to have occurred in the Hudiksvall area, of which the last one, believed to have occurred about 2000 years ago, "seems to represent a methane venting event" (Mörner 2003).

According to our knowledge, these imaginative processes of massive seismic bedrock disruption is not demonstrated from other contemporary earthquakes around the world and one may find it strange that the phenomenon should be restricted to Sweden. It may also be observed that such outcrops of disrupted bedrock are common in parts of southern Sweden but are not found in the vicinity of the faults in northern Sweden, where more manifest evidence for major earthquakes is present. During a short inspection of the boulder cave area at Boda it readily became evident that the mass of angular boulders was slightly displaced in the ice flow direction and, thus, the disruption must have occurred prior to the deglaciation of the site (Lagerbäck et al. 2005b), i.e. in contrast to what was claimed by Mörner (2003). The impact of ice flow on the rock mass at Boda was indicated also by an "imbricated" appearance of several of the big angular boulders and this feature proved to be characteristic also for other heavily disrupted bedrock occurrences, in the Uppland investigation area (Fig. 87) as well as at several sites in eastern Småland.

At Bodagrottorna as well as at many other occurrences of disrupted bedrock outcrops (several of them considered as "boulder caves" hypothesized by Sjöberg (1994) to have a seismic origin), there is a significantly raised boulder frequency in the surrounding till terrain (Fig. 88). Furthermore, a brief look at the map of Quaternary deposits in the Boda area reveals an inverse relationship between the frequency of boulders on the ground surface and the occurrence of bedrock outcrops (Fig. 88). Since the situation is similar in many other areas it seems evident that former bedrock knobs, and probably much of the superficial parts of the bedrock, are disrupted and spread over the terrain to create fields of angular boulders. It was concluded by Lagerbäck et al. (2005b) that the intense disruption of bedrock at Boda and many other similar sites was indicative of a massive detachment of boulders during a very short and late phase of the deglaciation and that the main factors responsible for the fracturing should be sought for 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. Accordingly, the "boulder caves" at Boda and many other sites are not considered to be the result of earthquakes after local deglaciation but rather related to an intense glacial quarrying during a late stage of deglaciation.

The concept of seismic disruption of bedrock was originally introduced by De Geer (e.g. 1938, 1940) who

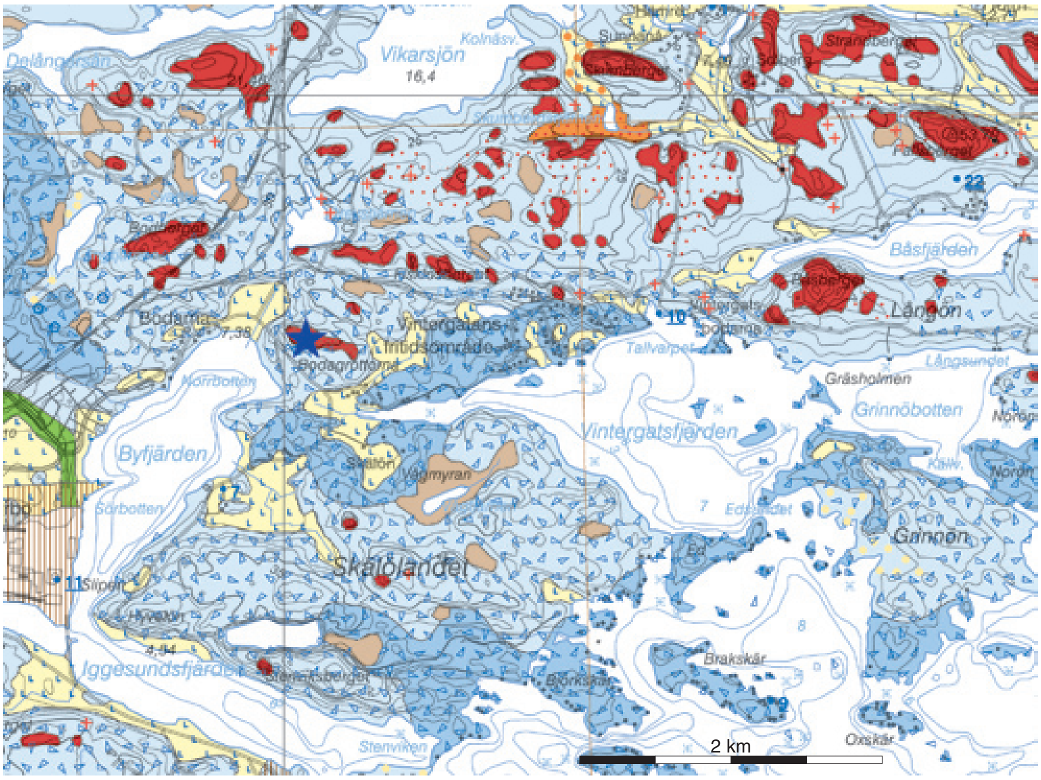


Fig. 88. Excerpt from Quaternary map 15H Hudiksvall NV (Svedlund 2002). The intensely disrupted bedrock outcrop at Bodagrottorna, marked by a blue star, is located in an area of very few outcrops but with a strongly increased boulder frequency in the till surface. Outcrops in red, till in blue, peat deposits in brown and clay in yellow. A high frequency of boulders is depicted by blue triangles.

suggested that this process of massive boulder production was the only reasonable explanation for the abundance of big, angular boulders associated with some small moraine ridges, so-called De Geer moraines, that occur in swarms below the highest shoreline in parts of central and northern Sweden. In De Geer's main investigation area close to Stockholm, some of these ridges displayed an irregular pattern, deviating from the prevailing trend parallel to the ice-margin, and De Geer concluded that "if the bed-rocks here splitted by an earthquake this must also have been the case with the superjacent part of the land-ice". This hypothesis is more recently discussed by Lundqvist (2000) who suggests that a geographical concordance between the current seismicity and the De Geer moraines, as well as fresh-looking bedrock scarps and a raised frequency of angular boulders in certain De Geer moraine areas, may indicate a paleoseismic origin of the features, beneath the ice-sheet. However, Lundqvist emphasizes that there are alternative mechanisms for the formation of the crevasses in the ice sheet and that conclusive evidence for late-glacial or Holocene fault movements along the bedrock scarps is lacking.

SEDIMENTARY EVIDENCE FOR FAULT-INDUCED DISPLACEMENTS OF THE ANCIENT SEA FLOOR?

The most puzzling features met with during the excavation work were the erosional unconformities and associated layers of various, mostly coarse-grained, sediments. An erosional unconformity separating varved glacial clay from overlying postglacial clay was found to be very common both along the northern coastal areas and in Uppland (Figs. 70, 81). This erosion is interpreted to have been caused by surprisingly strong currents fairly shortly before local land upheaval and is not to be confused with the erosional surfaces and layers of coarse-grained (sandy, gravelly or diamictic) sediments, intercalating with or underlying glacial clay along the coastal area of northern Sweden.

One, or locally two or more, such layers of coarse-grained sediments or erosional unconformities intercalating with glacial clay were encountered at a number of sites along the northern coastal areas, from south-east of the Lansjärv fault in the north to eastern Västerbotten in the south. The stratigraphic relationship between the features and varved glacial clay clearly indicates that erosion as well as deposition must have taken place fairly soon after deglaciation and, thus, at fairly great (over 150–200 m) water depth in the ancient sea. The origin of the features is not fully understood, but since strong erosion and coarse-grained sediments are atypical for any normal sediment sequence deposited in the low-energy environment at the bottom of the ancient sea, they must represent abnormal episodes in the early postglacial period. Since the trenches were excavated in level ground, the layers of coarse-grained sediment are interpreted to have been deposited by strong currents or by highly fluid debris-flows. These flows are believed to have been caused and fed by minerogenic matter from gravitational mass flows (subaqueous analogues to the landslides), or matter eroded from the sea-floor by currents. Sand extruded from liquefied deposits beneath the sea floor may also have contributed. At several sites, sand vents reached up to, but not through, laterally persistent sandy layers, indicating that the deposition of sand occurred subsequent to liquefaction of sandy sediments at depth.

Extensive sandy or coarse silty layers intercalating with glacial clay have traditionally been designated "drainage varves", interpreted to reflect a significant increase in sediment supply to the ancient sea in connection with the drainage of major ice-dammed lakes and often considered to be correlated between widely separated sites. When considering the supposed very extensive lateral distribution (hundreds or even thousands of square kilometers) of these "drainage varves", an origin in an increased discharge of water by rivers, whether caused by ice-lake drainage or by a climate shift, seems not to be a credible explanation, as streams carrying sand and silt will build deltas when entering the sea, unless the sediment supply is great enough to genererate a density-driven underflow. Given that there is no significant bottom slope gradient to promote any extensive gravity flows or turbidity currents loaded with sand in the shallow Gulf of Bothnia, a purely sedimentological explanation appears unrealistic.

However, in the northern Gulf of Bothnia, massive displacement of water caused by sudden vertical displacement of the sea-floor in connection with movements along the Lansjärv, Burträsk and Röjnoret faults would most certainly have resulted in a significant erosion and redeposition of sediments over large areas. The subsequent sedimentation of a fairly consistent layer of sand or silt may indicate that the level of disturbance, submarine flows and erosion was such as to create a suspension that then was redeposited over the whole sea floor.

Similar sandy or silty layers intercalating with glacial clay have been found to occur also in the coastal areas of southern Västerbotten (Bergström 1968). Based on the fact that at least one of these layers appeared to be synchronous over several sedimentation areas, i.e. associated with different river valleys, Bergström considered it unlikely that it could be explained by the drainage of an ice-dammed lake and suggested a climatically induced increase of river discharge to be more likely.

In the southern part of the Gulf of Bothnia, Mörner (2003) identified that one "drainage varve" (varve -424 in the applied clay varve chronology) cuts across at least 8 different drainage patterns (recorded as esker systems) and extends laterally from Sundsvall in the north to Uppland in the south. Since Mörner considers it unlikely that there were any substantial ice-dammed lakes to drain in the area, he concludes that the "drainage" origin of the features should be dismissed. Instead, Mörner argues for a seismic origin of the enthickened varve -424 and concludes that a major turbidite flow crossed the sea bed over an area of c. 210 × 80 km and, accordingly, the deposits should be considered turbidites. If the inferred extent of a continuous sandy–silty layer of a fairly uniform thickness really is c. 210 × 80 km, we agree with Mörner (though based on other arguments) that the phenomenon must be explained by a process other than drainage of an ice-dammed lake. However, the proof that these episodes of sedimentation reflect single events across wide areas and can, at least in part, be linked to submarine sliding and tsunamic activity in the Gulf of Bothnia, awaits further research.

TIMING OF FAULTING

The original opinion that the fault scarps in northern Sweden formed in close connection with the deglaciation of the region (e.g. Lundqvist & Lagerbäck 1976, Lagerbäck 1979) is supported by more recent investigations (e.g. Lagerbäck 1992). Based on morphological evidence, it was suggested by Lagerbäck (1979) that the Röjnoret and possibly also the Burträsk faults probably predated the deglaciation of the area, but the information gained during the excavation programme in the area clearly indicates that they ruptured fairly shortly after local deglaciation. However, due to an imperfectly known deglaciation history it is neither possible to settle the absolute age of the single ruptures, nor to determine with any certainty the temporal relationship between the different faulting events. Assuming that the coastal areas of northern Sweden became ice-free at about 10 500–10 000 years BP (Lundqvist 1998, Lindén et al. 2006) and the inland areas a few hundred years later (Lundqvist 1998), the age of faulting can be set to some 10 000–9 500 years BP, which is in accordance with the dating of wood buried below landslide deposits in Finnish Lapland by Sutinen (2005). Furthermore, if Lundqvist's (1998) tentative model of deglaciation is broadly correct, it implies that the faults developed successively during the vanishing of the ice sheet.

ARE THERE ANY RECENT MOVEMENTS ALONG THE FAULTS?

With the exception of the fault scarps at Storuman, field evidence gave little or no support for any on-going or repeated movements along the fault scarps since they were formed around the time of deglaciation. On the contrary, the results from the stratigraphical investigations in trenches excavated across the Lansjärv and Röjnoret faults clearly indicate that faulting occurred as single episodes and that the loose deposits affected by the collapse of the fault scarps were stabilized shortly after. Minor displacements (cm- or, at most, dm-scale) in the fault zones after the main rupturing cannot be completely ruled out, but more significant movements appear to be excluded at the investigated sites. With the exception of a dubious observation (fig. 89), the deposits that were involved in the rupturing along the fault scarps appear generally to be well stabilized and no curved trees or the like indicate any recent slope processes. A spectacular phenomenon, possibly indicative of a minor fault movement, was observed along the Lansjärv fault (Fig. 90), but in this case the tentative fault movement is believed to be artificially induced.

However, even if insignificant when compared with that of the deglaciation phase, recent seismicity indicates that minor movements occur in the vicinity of the late- to postglacially active fault zones. A tentative relationship between the current seismicity and the major faults in northern Sweden was indicated by Lagerbäck (1977, 1979) and, by means of more accurate data, Arvidsson (1996) showed that about 50% of the recent earthquakes in the region appeared to be associated with these faults. More recently the Swedish National Seismic Network (SNSN, Bödvarsson & Lund 2003) has operated eight new permanent seismic stations in northernmost Sweden since April 2004, and the strong correlation between the current seismicity and faults in northern Sweden was confirmed with the new SNSN data by Lund et al. (2004). The seismicity of northern Sweden, as recorded by the SNSN, from April 2004 to October 2007, is shown along with the Recent faults in Fig. 91. The earthquakes are concentrated along the coast of the Gulf of Bothnia, but north of 66 deg. latitude there is a very strong spatial correlation between the earthquake activity and the faults. There appears also to be a possible association between the very high activity in the Skellefteå area and the northeasterly striking Burträsk fault. It should also be noted that the majority of the earthquakes are located to the east of the faults, i.e. in concordance with the easterly dip of the fault zones at surface, suggesting that seismicity continues in the vicinity of the fault ruptures at seismogenic depths. Furthermore, it also appears that the possible postglacial faults at the bottom of the Gulf of Bothnia (Andrén 1990) and at lake Ismunden to the east of Östersund, may be associated with somewhat raised seismicity.

The coseismic strain-rates associated with the low level of seismicity in the region are very small and unsurprisingly it has not been possible to detect (detection level 0.3 mm per year) any fault related deformation of the land surface along the Pärvie fault by means of satellite interferometry (InSAR) investigations (Högrelius 2005). In order to trace any recent movements along the Pärvie fault, repeated high-precision levelling at two sites across the fault was planned for by the National Land Survey of Sweden, but unfortunately the figures from the first levellings in 1976 and 1979 appear to have been lost (Per-Ola Eriksson, National Land Survey of Sweden, pers. comm. 2005).

A RECURRENT PHENOMENON OR UNIQUE EVENTS?

The temporal relationship between faulting and deglaciation clearly indicates a causal relationship. The loading and subsequent unloading of the crust obviously created levels of crustal stress that exceeded the strength of pre-existing fault systems to cause very long high displacement reverse fault movements during the most recent deglaciation of northern Fennoscandia. However, although searched for, no evidence has been found for any equivalent major late- or postglacial faulting after the Wisconsin glaciation in North America (e.g. Fenton & Adams 1993, Adams 1996). This circumstance indicates that this phenomenon is not simply a consequence of the overall ice-sheet loading and unloading, but either reflects some derivative of unloading, such as the rate of unloading or the geographical variation of unloading (as around pre-existing topography) or reflects some specific accumulated tectonic stress state of the particular region where the ice sheet was situated.

It is generally believed that in northern Europe at least two or three previous ice sheets had a similar extent as (and hence it is assumed comparable thickness to) the Weichselian and that in addition to these a number of minor ice sheets have repeatedly covered parts of Sweden. However, although the Weichselian ice sheets appear to have remoulded much of the older Quaternary deposits in northern Sweden (Nordkalott Project 1986a,

Fig. 89. Judging from the pattern of lichens (lichen-covered parts of the boulder were turned downwards), the >1 m large boulder had fairly recently (photograph from 1975) tumbled down the slope. Whether this was caused by frost processes, soil creep, a minor movement in the fault zone or something else is not known. The Pärvie fault at the western foot of Mt Tsåktso, some 70 km north of Kiruna. Photo: R. Lagerbäck.

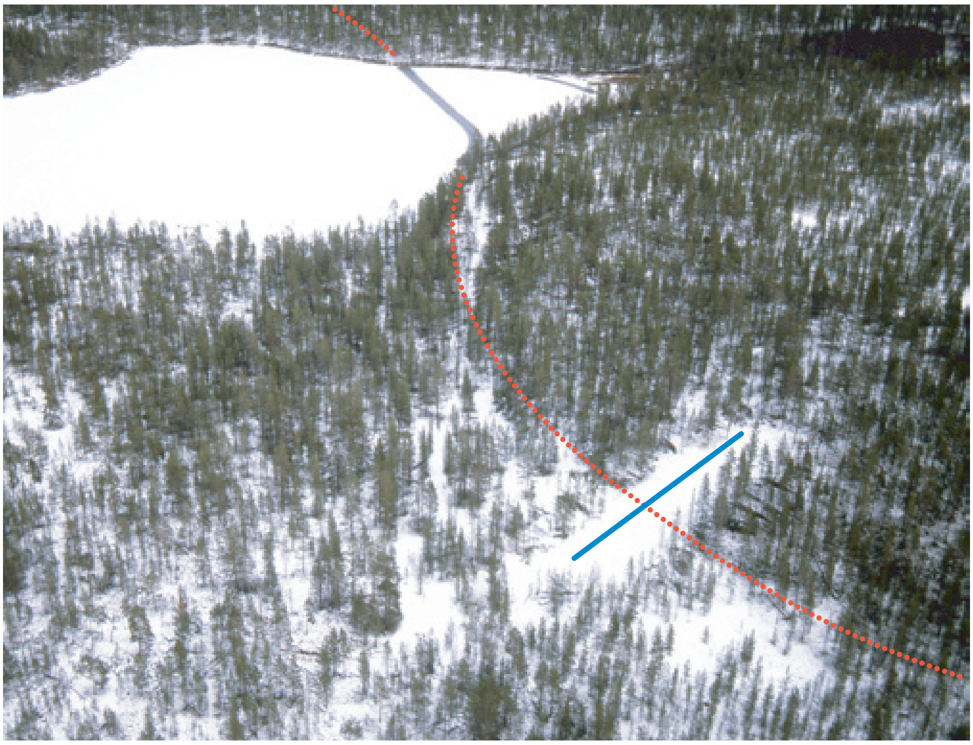


Fig. 90. In the photograph the trace of the Lansjärv fault is mirrored by a narrow fracture (cm-wide) in the thin ice of the small lake in the background. The fracture is accompanied by seeping water that wets the thin snow cover in a c. 2 m wide zone. A second fracture is seen some 50 m to the right and a fracture pattern occurred also in the ice of the nearby lake St. Mäjärvträsket that likewise is crossed by the fault trace. The fault scarp is dotted in red and the location of the Mäjärvberget trench shown in Fig. 29 is marked with a blue line. Hydrofracturing stress measurements performed in a 500 m deep borehole drilled c. 1 km away in the hanging wall yielded a highly anomalous stress pattern, including very low horizontal stress conditions and a rapid change in orientation of the maximum horizontal stress with depth, i.e. most likely influenced by the vicinity of the fault zone (Bjarnason 2008). The depth to the groundwater table in two percussion boreholes, drilled only a few tens of meters to the east of the fault zone, was surprisingly great, 55 and 65 m respectively below ground surface (Hansson 2008). Intrusion of water into the fault zone, by puncturing of an upper aquifer in contact with the lake in connection with the drilling of the percussion boreholes a few months before the photo was taken, may have increased the hydrostatic head in the fault zone and thereby reduced the effective stress in the zone (cf. e.g. Pakiser et al. 1969). The stress conditions in the local bedrock in combination with a temporary reduction of the frictional strength in the fault zone may hypothetically have promoted a minor (normal dip-slip) movement in the fault zone, manifested by the cracks in the thin ice covering the lakes. Photo: R. Lagerbäck.

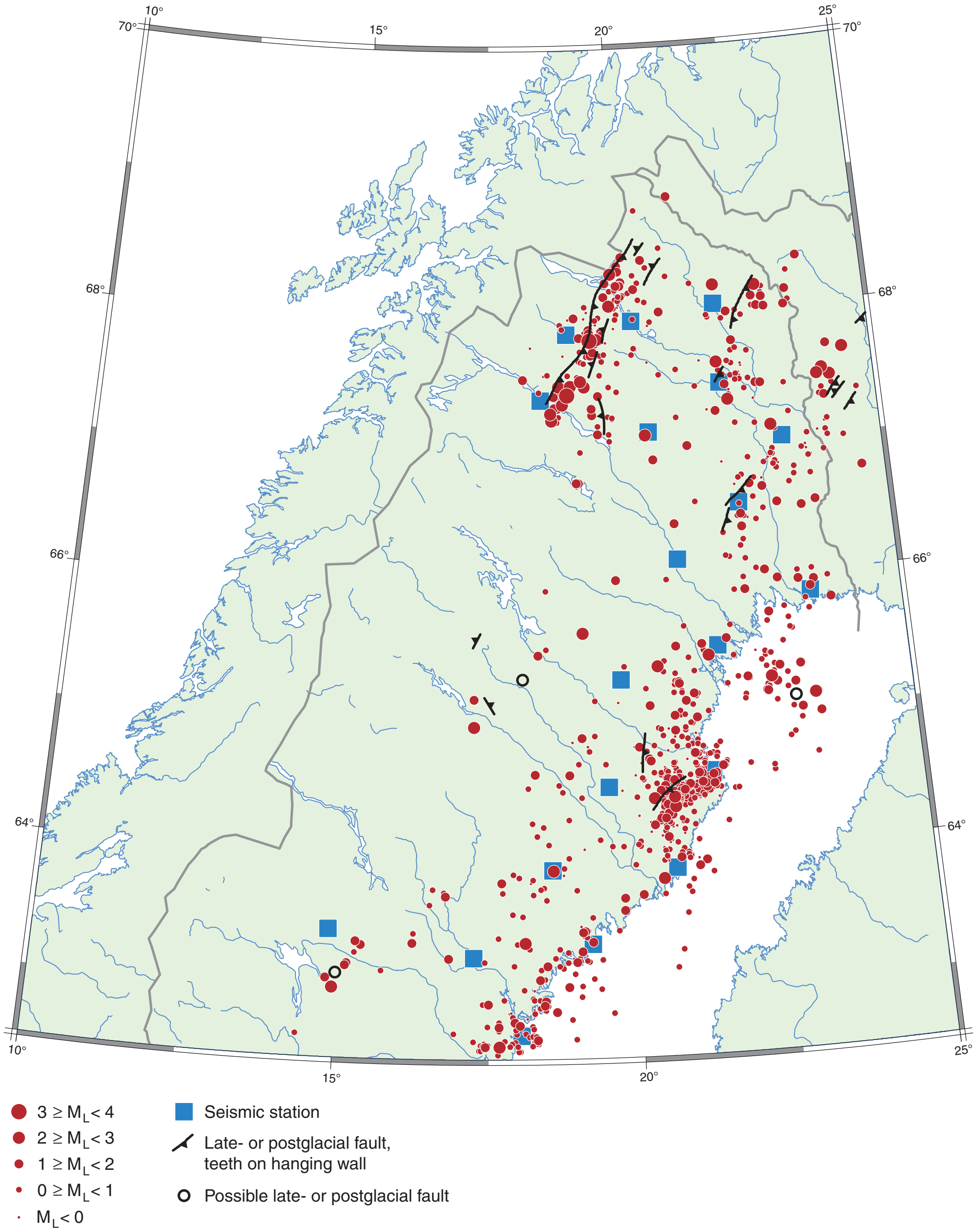


Fig. 91. The figure shows the faults of inferred late- or postglacial age along with the seismicity of northern Sweden and adjacent parts of northern Finland as recorded by the Swedish National Seismic Network (SNSN, Bödvarsson & Lund 2003), from April 2004 to October 2007. The SNSN has operated eight new permanent seismic stations in northernmost Sweden since April 2004. During this time period 1194 earthquakes were recorded north of latitude 62.5. Within the network, the magnitude of completeness is approximately M_L 0.5. Note that the earthquake detection capability is reduced in areas distant from the seismic stations.

Bargel et al. 1999b), the wide-spread occurrence of pre-Quaternary saprolites below the Weichselian deposits in the inland areas (Fig. 3) as well as relict preglacial land surface remnants in parts of the mountain range (Kleman & Stroeven 1997) still indicate that, except for in parts of the mountain and pre-mountain areas, the accumulated glacial erosion during the Quaternary was generally not sufficient for any significant reshaping of the pre-Quaternary relief.

This implies that if any major fault scarps had formed in connection with previous deglaciations, they most likely would not have become completely obliterated

Fig. 92. Wind-abraded boulders and outcrops, ventifacts, occur frequently in wide areas of northern and central Sweden (Lagerbäck 1988b, 2007). These ventifacts arose during severe climatic conditions in the Weichselian Tärendö interstadial and their presence in the present-day landscape is indicative of an insignificant erosional impact of the last ice sheet. Where found in their original positions, ventifacted boulders indicate that the last ice sheet was cold-based during its entire existence and left the interstadial ground surface intact. Ventifacted outcrop at mount Kabla in the eastern part of the mountain range, some 20 km east of Kvikkjokk in northern Sweden. Photo: R. Lagerbäck.

by the Quaternary ice sheets but should be possible to trace in the present-day landscape. No such earlier fault scarps have, however, been identified. There is nothing like the situation in areas of active tectonic deformation where sucessively less distinct fault scarps can be identified and there are even very few and rather insignificant candidate older pre-Weichselian fault escarpments. Furthermore, morphological as well as stratigraphical evidence indicate that no significant pre-Weichselian fault movements had contributed to the formation of the fault scarps discussed in this paper. Although all the fault scarps appeared to have formed on pre-existing old fault zones, no evidence was found to suggest any fault movements in these zones previously during the Quaternary. Except for a very uncertain indication of a minor fault movement during an earlier phase of the Weichselian glaciation, observed in the trench at Mäjärvberget along the Lansjärv fault (Fig. 3, Lagerbäck 1988c, 1990), the stratigraphy in the trenches dug across the Lansjärv or Röjnoret faults give no support for recurrent movements during the Quaternary.

Therefore, if, as it appears, previous deglaciations did not generate analogous faulting in northern Sweden, the question of what was atypical for the most recent ice sheet and its deglaciation remains the principal scientific question awaiting a solution. However, since not much is known about the accumulation of ice mass and the rate of deglaciation during the Saalian and previous glaciations in northern Sweden, it is not possible to give a decisive answer to this problem and the door remains open for speculation. A circumstance that, tentatively, may be of some interest in this context is that the last ice sheet apparently was cold-based throughout its entire existence in wide areas of northern and central Sweden (Lagerbäck 1988b, 2007, Kleman & Hättestrand 1999). The ice sheet most likely accumulated over a deeply fro-

Fig. 93. Ice-wedge casts and parts of tundra polygons developed in richly organic, silty sand deriving from the Tärendö interstadial. The features were revealed below a cover of several meters of deglaciation silt. That the wedges are infilled by this silt clearly demonstrates that the ground remained frozen through the entire latest glaciation. See 1.2 m long spade for scale. Riipiharju, some 25 km north-east of Kangos in northern Sweden. Photo: R. Lagerbäck.

zen landscape and in wide areas the permafrost persisted to the very deglaciation (Figs. 92, 93).

This raises the possibility that the development of residual fluid overpressures may have been a contributory factor in triggering this phase of faulting. The role of pore water pressure for reducing the effective stress in the upper part of the crust during deglaciation was pointed out by Muir Wood (1989) who emphasized the significance of an assumed, residual and hydrostatically derived, overpressuring of pore water for the formation of the faults. Beneath a cold-based ice sheet resting on a deeply frozen ground it can be surmised that as the crust was loaded, during ice sheet accumulation cracks would have undergone compression, raising fluid pressures to become close to lithostatic, and that these raised fluid pressures would not have a chance to be released through the overlying permafrost even as the ice sheet load was being removed during deglaciation. Fault stability margins would be significantly reduced under conditions of raised fluid pressures. This could tentatively explain what was unique both about the Weichselian deglaciation, and the particular circumstances of northern Fennoscandia, for the generation of this extraordinary episode of faulting.

Conclusions

The temporal relationship between the faulting and the latest deglaciation clearly indicates that there is a close causal relationship between these phenomena. The loading and subsequent unloading of the crust created a stress concentration (involving the compression locked in through ice-sheet loading, coinciding with the direction of the principal horizontal tectonic stress found across North-west Europe) that promoted a series of en echelon reverse fault movements. The association with the deglaciation is clearly demonstrated by the results of the stratigraphical investigations in trenches cut across fault scarps, but also by the spatial and temporal relationship to widespread seismically triggered landslides and soft sediment deformation features occurring in the vicinity of the faults.

It seems highly likely that the rupturing of the Lansjärv, Burträsk and Röjnoret faults resulted in extensive displacements of water in the ancient Gulf of Bothnia, which in its turn, and in combination with seismically triggered slumping and extrusion of liquefied sediments, led to the deposition of anomalous sequences in the subaquatic sediments.

Since no conclusive evidence for late or postglacial faulting has been found in the central or southern parts of Sweden and since soft-sediment deformation structures, tentatively interpreted to be seismically induced, are far less common there, it is evident that faulting and associated paleoseismicity were principally concentrated to the northern parts of the country. While it is not possible to exclude the possibility that moderate sized earthquakes may have occurred in more southern parts of Sweden, we find it very unlikely that major earthquakes of magnitudes comparable with those in the north (high M_W 7s or even over M_W 8) occurred south of Västerbotten county.

The limited erosional impact of the Quaternary glaciations in northern Sweden implies that any comparable tens of kilometer long and several metre high fault scarps, developed prior to the last glaciation, would not have become completely obliterated but should be possible to trace morphologically in the present day-landscape. The absence of any such features strongly indicates that the faulting that occurred in northern Sweden during the last deglaciation was not typical for each of the previous glaciations and it is considered highly unlikely that fault movements of comparable magnitude had occurred previously during the Quaternary in the area. This suggests that the crustal stress state, and associated fluid pressures, determining fault rupture at the end of the last glaciation beneath northern Sweden were unprecedented relative to previous deglaciations.

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