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Postglacial faulting and paleoseismicity in the Lansjärv area, northern Sweden

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ABSTRACT

Post-glacial fault scarps, up to about 20 m in height and forming a 50 km long fault set with a SSW-NNE orientation, occur in the Lansjärv area in northern Sweden. By trenching across the fault scarps it has been possible to date fault movement relative to the Quaternary stratigraphy. It is concluded that the fault scarps generally developed as single-event movements shortly after the deglaciation about 9000 years ago. At one location there are indications that minor fault movements may have occurred earlier during a previous glaciation but this is uncertain. The fault scarps are, at least partially, developed in strongly fractured and chemically weathered zones of presumed pre-Quaternary age. To judge from the appearance of the bedrock fault scarps, and the deformation of the Quaternary deposits, the faults are reverse and have dips between some $40\text{-}50^{\circ}$ and the vertical.

The faulting was co-seismic and earthquakes in the order of M 6.5-7.0, or higher, are inferred from fault dimensions and the distribution of seismically triggered landslides in a wider region. Distortions in different types of sediment, interpreted as caused by the influence of seismic shock, occur frequently in the area. Examples of these are briefly described.

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SUMMARY

Conspicuous fault scarps, interpreted to be late or post-glacial in age, are described from different parts of northern Fennoscandia. In the Lansjärv area, in northeastern Norrbotten, four major and several minor fault-scarp segments together form a 50 km long fault set with NNE-SSW orientation. Previous investigations in this area indicate that the fault scarps developed shortly after the deglaciation and that the faulting generated strong earthquakes.

The aim of the present study was to carry out a more thorough investigation of the relationship between faulting and Quaternary stratigraphy but also to elucidate the geographical extent and characteristics of fault induced, seismic distortions in sediments of the area. A complex till stratigraphy provides reference horizons for dating of fault movement relative to the latest three or four glaciations. The location of the faults, largely below the highest coastline, offer theoretically a potentially good means of dating fault movement relative to deglaciation and land upheaval.

Six machine excavated trenches were dug across the fault scarps. One trench investigated previously has also been included in the study. For economical reasons the excavations had to be made close to roads and at localities with little or no forest. This was not always at the most favourable spots from a geological point of view. The Quaternary stratigraphy and the bedrock, where present, is documented by drawings and photographs and the sections are interpreted in terms of timing and mode of fault movement.

Compared with the original plans the problems concerning timing of fault movement were stressed at the expense of the paleoseismic aspects. Therefore, it was not possible to do any systematical investigations of such paleoseismic records. Even so, ten trenches were dug and investigated. A naturally exposed section with extensive distortions of sandy sediments was also examined. The distortions found are documented mainly by photographs. A number of pits were also dug in connection with landslide scars in the area.

The excavators theoretically reached depths of c. 5.5 and 6.5 m but these depths were often not reached due to wet, unstable soils caused by a rainy weather during the summer and large amounts of water pouring out of the fractured bedrock in the fault scarps. Where bedrock was met with in the trenches across the scarps, it displayed heavily fractured and chemically weathered fault zones. The post-glacial faulting is obviously, at least in some places, located to older, presumably pre-Quaternary zones of weakness.

The faults are reverse and fault planes appear to dip between the vertical and some 40^{o}-50^{o}. Exclusively dip-slip movement is inferred in the majority of cases but minor dextral strike-slip is indicated at one site. Neither the observed bedrock fault scarps, the geometry of the scarps developed in the

overburden, nor the dislocations in the Quaternary stratigraphical sequences, give support to the interpretation of the faults as generally being very gently dipping thrusts which has been suggested.

The Quaternary sequences in the fault scarp trenches demonstrate that fault movement occurred within a very limited period of time in direct connection with, or shortly after, local deglaciation. There are no indications of fault movements after that time. The different segments of the fault scarp set most probably developed simultaneously or at least in close conjunction with each other. The scarps generally developed as single-event movements but it cannot be overlooked that some of them may have developed partially prior to, or developed in connection with, an earlier glaciation.

The faulting generated strong seismic activity. Earthquakes of high magnitudes, M 6.5-7.0 or higher, triggered landslides and produced extensive deformation of sandy and silty sediments by liquefaction within vast areas.

1 INTRODUCTION

Fault scarps, interpreted as post- or late-glacial, occur in northern Sweden (Lundqvist & Lagerbäck 1976, Lagerbäck 1979, Lagerbäck & Witschard 1983) and adjacent parts of Finland (Kujansuu 1964) and Norway (Olesen 1984). Supposedly Holocene fault-movements are also reported from the Fiskarhalvön peninsula in the north-westernmost part of Russia (Tanner 1930). The location of these presumed Late-Quaternary faults is shown in Fig. 1. The faults in Finland, Norway and Sweden are morphologically identified by a conspicuous step in the till cover, which can be traced over long distances.

In Sweden the faults have a total length of more than 300 km and the longest, single fault line, 155 km in length, is the so called Pärvie fault. The faults, all of which are developed in the Precambrian shield area, have a general NNE-SSW trend and show a vertical displacement of up to approximately 30 m.

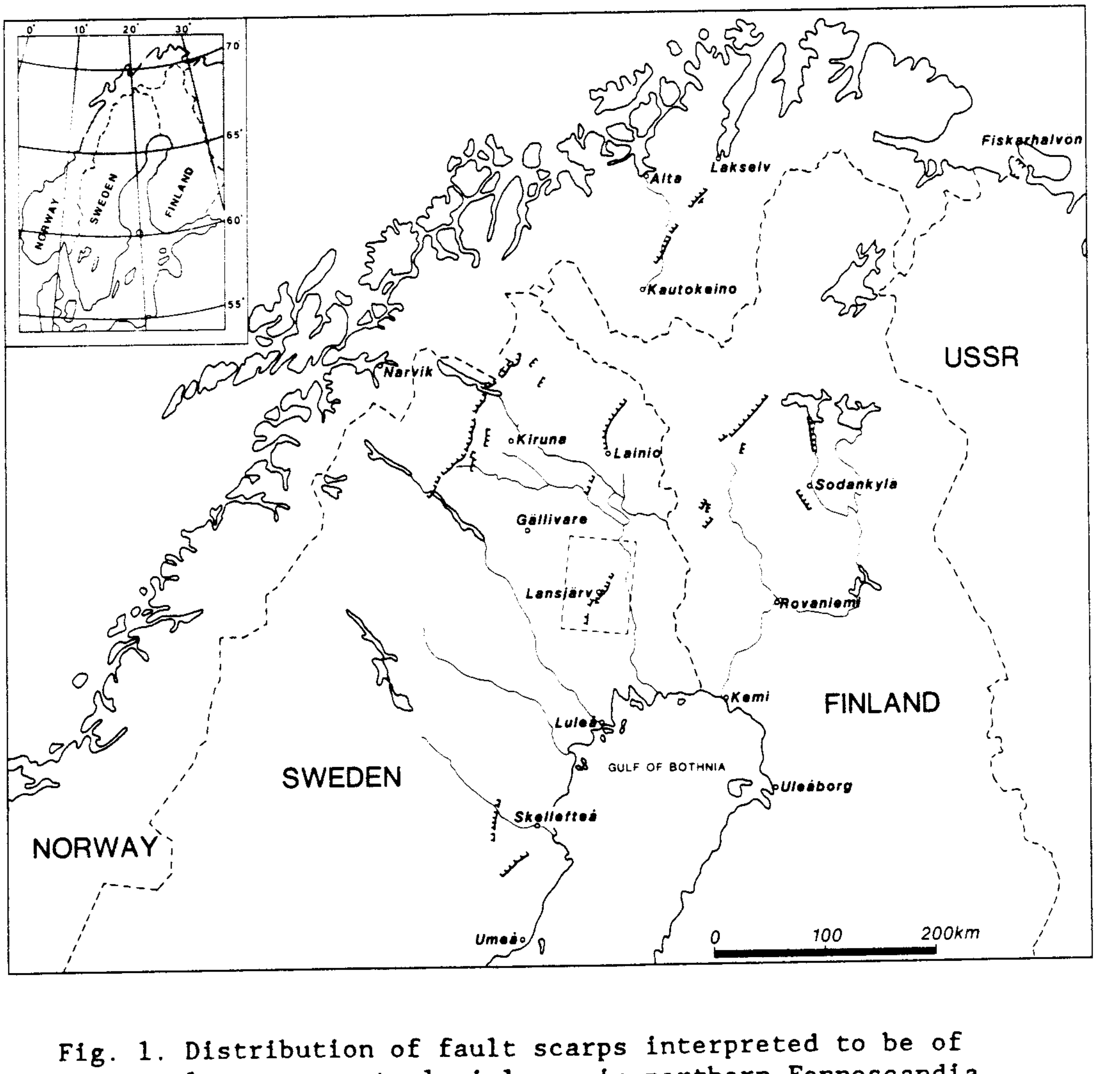


Fig. 1. Distribution of fault scarps interpreted to be of late- or post-glacial age in northern Fennoscandia. Barbs are turned towards the lower block. After Tanner 1930 (Fiskarhalvön), Kujansuu 1964 and pers. comm. (Finland), Lagerbäck 1979 (Sweden) and Olesen 1984 (Norway). The Lansjärv area is framed.

The relationship between the faults and different late-glacial features, e.g. eskers, melt-water channels and shore-lines, suggest faulting in close connection with local deglaciation. Locally it has also been possible to date fault displacement relative to the glacial and post-glacial stratigraphy (Lagerbäck 1988b, in manuscript).

The faulting obviously generated strong seismicity. Secondary, seismically induced phenomena including landslides and different types of seismites occur frequently (Lagerbäck 1988b, in manuscript).

These unexpected, young faults attracted attention in connection with the debate on nuclear-waste storage, and several studies, with the purpose of elucidating this manifestation of neotectonic activity, have been carried out by commision of KBS (Nuclear-fuel Safety Project) and SKB (Swedish Nuclear Fuel and Waste Management Co).

The present study constitutes a minor part of a research programme, located to the Lansjärv-area in the east of the County of Norrbotten (Fig. 1), and it belongs to the SKB-project of "Bedrock stability". The study includes excavations across till-covered fault scarps and brief investigations of seismic impact on the unconsolidated Quaternary overburden.

The aim of the study was;

- To attempt to elucidate when the different major fault scarps developed in relation to the melt-away of the most recent ice-sheet and to the postglacial land-upheaval.

- To attempt to determine whether the morphologically identifiable fault scarps developed as a rapid single event, step by step or by creeping over a long period of time.

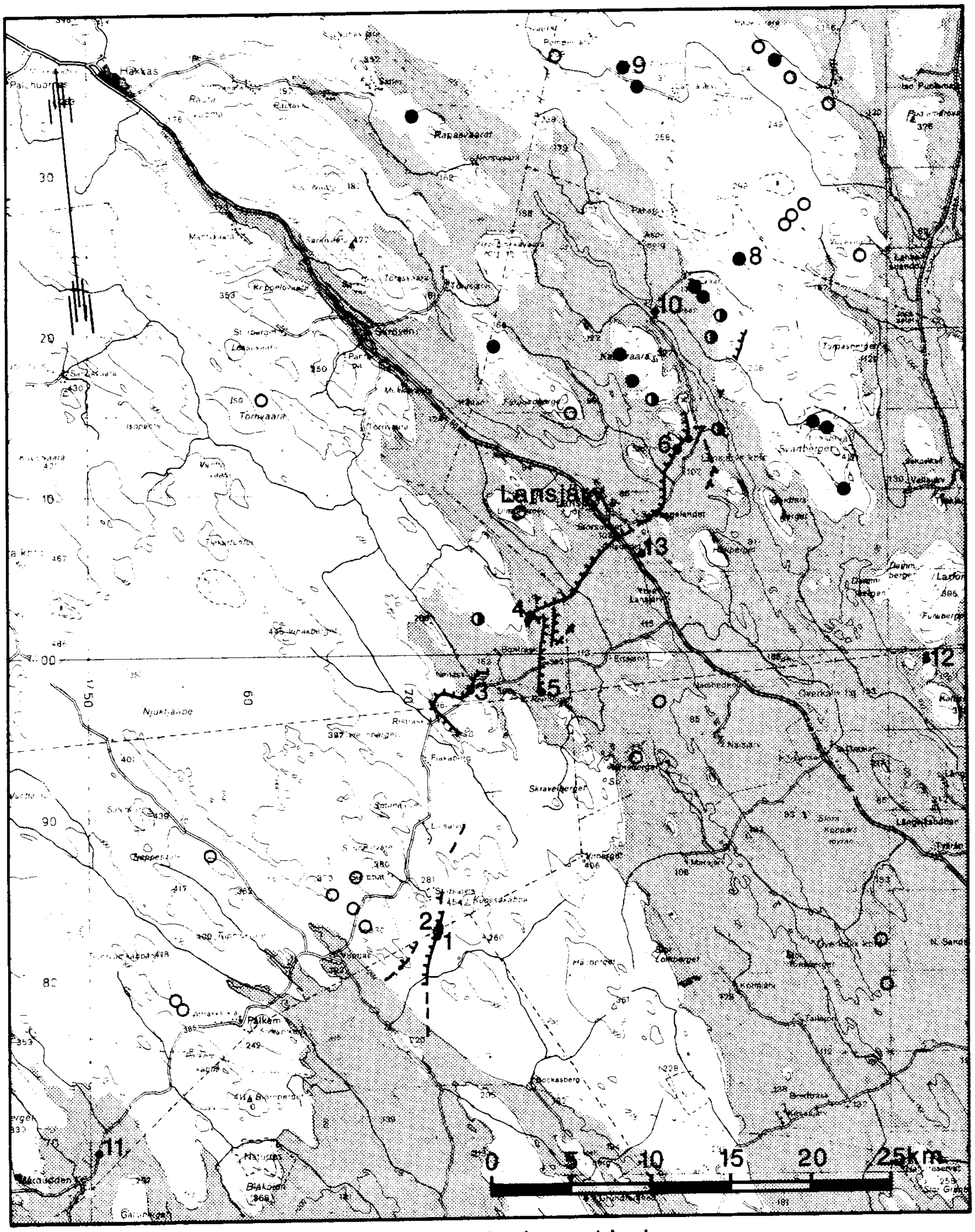
- To investigate the geographical extent and characteristics of secondary, fault-induced seismic distortions in different types of glacial and postglacial sediments.

Compared with the original plans, and in agreement with the commissioner, the problems concerning timing of fault movements were stressed at the expense of the paleoseismic aspects. The field work was carried out between Sept. 26 and Nov. 4, 1987

2 THE LANSJÄRV AREA

2.1 TOPOGRAPHY, HIGHEST COASTLINE

The Lansjärv area, as defined in Fig. 2, covers some 4 500 km^2. It is situated in the forested area of northernmost Sweden and is crossed by the Arctic Circle. Topographically it is a weakly undulating terrain with scattered hills and it is cut through by the valleys of Skrövån and Ängesån. The area is situated between about 50 and 470 m above sea level but altitudes between 100 and 300 m are most common. The terrain generally rises from the east towards the west.



Fault scarp, barbs turned towards the lower block

● Landslide

◐ Landslide, somewhat uncertain

○ Landslide, uncertain

Area below the highest coastline

•3 Site mentioned in the text

Fig. 2. Post-glacial fault scarps, landslides, areas below the highest coastline and investigated sites in the Lansjärv area. Sites: 1. Mainekjaure 2. Storsaiviskölen 3. Neitaskaite 4. Molberget 5. Stupforsen 6. Mäjärvberget 7. L. Telmträsket 8. Elmaberget 9. Repovaara 10. Ängeså 11. Slättheden 12. L. Furuberget.

The southern, eastern and central parts of the area are largely located below the Holocene, highest coastline (Fig. 2), which varies between about 205 m in the south-eastern part and 175 m in the north-west. The Late-Quaternary fault set is largely situated at, or below, the highest postglacial coastline, a fact which theoretically offers a good opportunity for dating the fault movements in relation to early postglacial land-upheaval.

2.2 BEDROCK GEOLOGY

The bedrock (see Nordkalott Project 1987) is dominated by granites of which the late orogenic Svekocarelian Lina Granite (c. 1800-1750 Ma) is the most common. The Lina Granite varies in texture/structure from aplitic to pegmatitic and it is generally reddish or pinkish in colour. These granites are in a macroscopic (regional) scale generally undeformed and therefore well suited to acting as indicators of postorogenic deformation. However major dislocation zones, mainly running NW-SE and N-S (Henkel et al. 1983) are an exception. Strongly fractured and chemically altered bedrock is also found along the Late Quaternary fault scarps (see further below).

Sometimes an older, characteristically well foliated, granite is met with. This granite occur as large xenolites floating in the "sea" of Lina Granitoids. Also greyish, granodioritic to dioritic, early orogenic granitoids, belonging to the Haparanda suite (c. 1900-1860 Ma) are frequently found as xenolites or as more continuous areas. Further, various gneissose and migmatitic rocks, probably representing various metasupracrustal rocks, occur in the area.

Exposed bedrock constitutes only a few per cent of the area and generally the outcrops are extensively frost-shattered. This shattering dates from an Early Weichselian interstadial characterized by strong periglacial conditions (Lagerbäck 1988a) and is indicative of an extremely sluggish Middle and Late Weichselian ice-sheet. Talbot (1986) suggested that this widespread shattering had a seismic origin and was related to the postglacial fault movements in the Lansjärv area (Talbots so-called "Jericho syndrome").

2.3 QUATERNARY DEPOSITS, GEOMORPHOLOGY AND STRATIGRAPHY

Glacial till is the predominant Quaternary deposit in the Lansjärv area. The tills in general have a sandy composition (Fig. 23) and often constitute morphologically prominent features such as hummocky moraines and drumlins. The drumlinoid features mainly belong to a north-westerly directed ice-flow system deriving from the first Weichselian glaciation (Lagerbäck & Robertsson 1988). Features belonging to this system are spread over the entire area and they are generally very well preserved despite being exposed to younger glaciations.

Younger glacial stades left few tracks within the area. Faint drumlinoid features, oriented in SSW-NNE and representing ice-movement during the Middle and Late Weichselian glaciation, occur sporadically. Glacial striations deriving from this ice-sheet are locally found but in general the bedrock outcrops, when not frost-shattered, display a massive, north-westerly striation.

In addition to these two systems there are scattered drumlinoid features lying in a more westerly direction. These features represent a glacial phase which is younger than the north-westerly ice-flow but probably pre-dates the south-westerly.

Glaciofluvial deposits occur as eskers and as different types of marginal and extramarginal outwash deposits. The glaciofluvial deposits mainly belong to the north-westerly glacial system and are frequently till-covered. Glaciofluvial deposits associated with the younger, south-westerly directed ice-flow are few and generally of moderate size.

The Quaternary stratigraphy is complex. Two or more till beds, often intercalated with water-laid sediments, appear to be the rule rather than the exception down to 4-6 m below ground surface. The typical sequence is one (or occasionally two) brown or greyish brown, fairly thin till bed(s), often no more than 0,5 m thick, resting on a thick, grey till. Fabric analyses of the upper brown till(s), generally suggest an ice-flow from south-west, west or west-north-west, that is, corresponding to the faint drumlinoid features and striations in these directions.

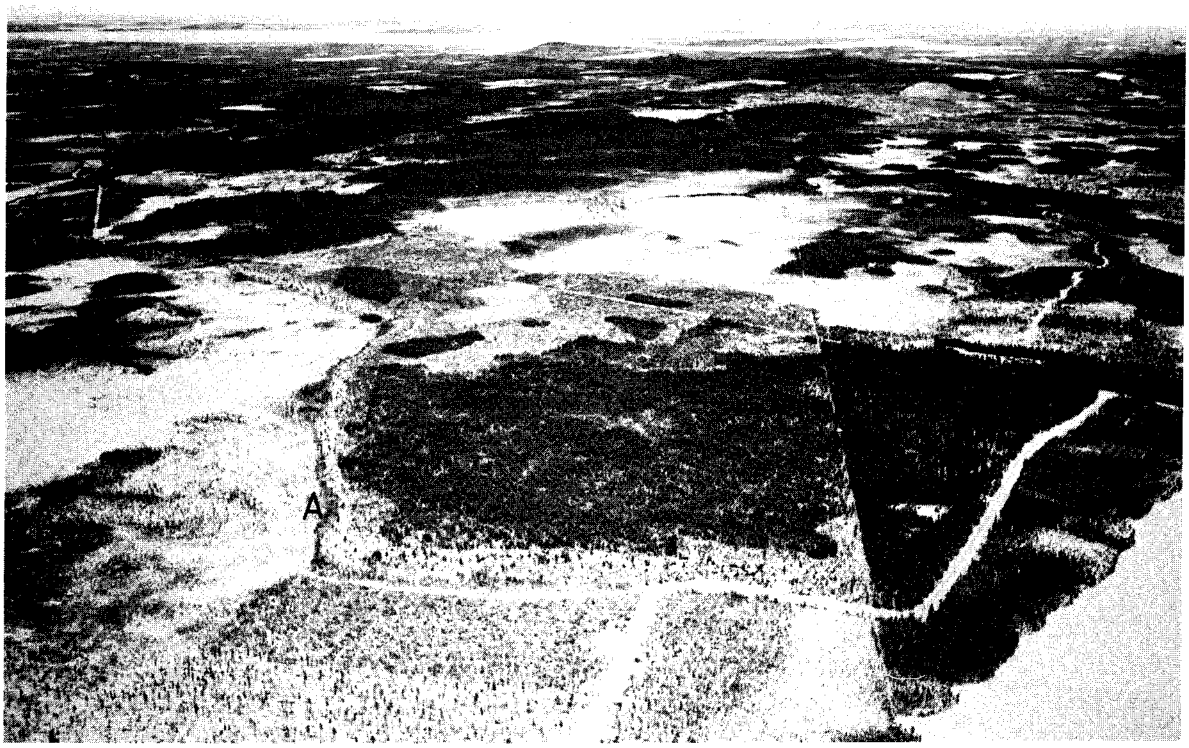
In the lower, grey till, which builds up the north-westerly drumlins, fabric analyses generally indicate a north-westerly ice-flow. This till normally reaches to the bottom of machine-made pits (4-6 m deep), but sometimes a brown, very compact till bed is encountered. This till is difficult to correlate to any certain system of glacial striations but it is thought to represent a northerly ice-flow and to be of Saalian age. The correlation to Saale is based on the till stratigraphy established for northernmost Finland by Hirvas (e. g. Hirvas et al. 1981).

The complex stratigraphy in the Lansjärv area, offers excellent reference structures for dating of fault movement relative to the Late Quaternary glacial and non-glacial stages.

2.4 FAULT SCARPS

The Late Quaternary fault complex in the area is composed of four major and several minor fault scarps (Fig. 2), together forming a 50 km long fault set with a SSW-NNE orientation. The longest continuous fault-scarp segment is 17 km. The scarps are identified by means of air-photo interpretation on the basis of their conspicuous morphology, a pronounced step in the Quaternary overburden. The identified fault scarps generally range in height from between 5 to 10 m, with slightly more than 20 m as a single exception. Most of the scarps downthrow to the west but some segments in the central and northern parts of the fault set show an eastward downthrow. Fault-scarp repose angles generally vary between 20 to 30 degrees.

The different fault segments generally have a straight or gently winding course, but one segment is strongly angled (Fig. 3). At some places the scarps appear to bend as a response to differences in topographic level, indicating a shallow easterly dip (c.f. Talbot 1986). However, at other places the tendency is the opposite or there appears to be no response at all to changes in elevation and some segments obviously bend independently of topography (Fig. 3). Highly varying dips and a strong influence of local bedrock properties on the configuration of the fault surfaces appear likely if judging from the course of the scarps.



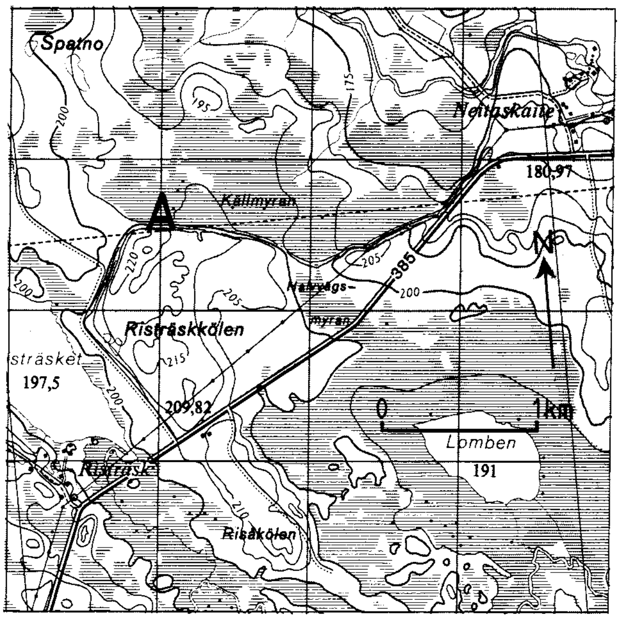


Fig. 3. a. The strongly angled postglacial fault scarp at the Risträskkölen plateau. The scarp in the foreground is about 20 m high. Bedrock outcrops occur at A. Photograph looking east.
Photo: R. Lagerbäck 1976.
Approved for publication.
b. Map of the area shown in the photo.

The bedrock along the scarps is generally covered by Quaternary deposits. Exposed bedrock in direct connection to the scarps is observed only at two localities. At one of these localities, situated at the edge of the strongly angled scarp in the central part of the fault set (Figs. 2, 3), the bedrock is strongly fractured and shattered and it is difficult to define which fault surface was active during the Late Quaternary movement. The repose angle (about 30^{o}) of the till covering the bedrock, the configuration of the outcrops and the relation between the outcropping bedrock, shatter debris and overburden indicate a moderately steep, reverse fault. Large quantities of ground water leaking from the scarp suggest an extensive system of open fractures in the fault zone and adjacent parts of the bedrock.

Exposed bedrock in the fault scarp occur also at the northernmost-fault scarp segment (Fig. 4). Here, bedrock outcrops occur along a several hundred meter long section. The bedrock in the hanging wall forms vertical or steeply, overhanging cliffs, also perpendicular to the main fault scarp, indicating steeply dipping fault planes and block movements.

Fig. 4. Exposed bedrock at the fault scarp east of Karhuvaara 13 km NE of Lansjärv. Photo: R. Lagerbäck 1987.

Excavations across fault scarps within the area have previously been carried out at two localities (5 and 7 in Fig. 2). At one of these sites (5), fault movement was demonstrated to have occurred sometime between the deposition of a till bed dating from the last glaciation and the rising of the locality above the postglacial sea. At the other site (7 in Fig. 2) it was possible to date fault movement to within a very short period of time immediately subsequent to local deglaciation (see further below and Lagerbäck 1988b, in manuscript).

2.5 EVIDENCE OF PALEOSEISMICITY

There are strong indications that the Late-Quaternary faulting was associated with intense seismic activity. In Sweden (Lagerbäck & Witschard 1983) as well as in Finland (Kujansuu 1972) a large number of landslides have occured in the same region as the fault scarps. In the Lansjärv area there are some ten well identified landslide scars representing major (> c.100 000 - 200 000 m^3) slides and in addition to these there are some thirty somewhat uncertain scars (Fig. 2). The landslides, like the fault scarps, are identified in aerial photographs.

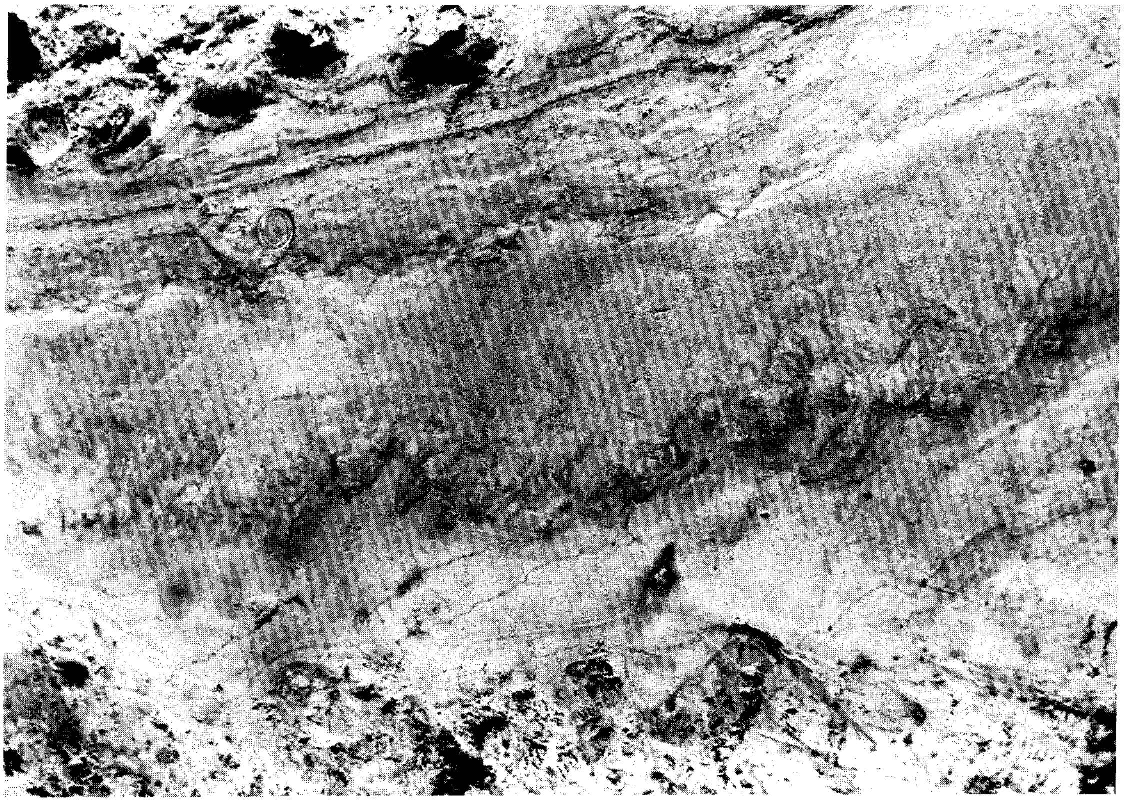


Fig. 5. Flame-like structures in fine-sandy and silty beds at Lillsundet 3 km SE of Lansjärv (13 in Fig. 2). The features are interpreted as being seismically induced in connection with the early postglacial faulting in the area. 2.5 cm coin for scale. Photo: R. Lagerbäck 1984.

The landslide scars, in Sweden as well as in Finland, are all stabilized and vegetated. Several slides are radiocarbon dated to be older than 8000 years and some demonstrably moved in direct connection with the local deglaciation, that is, from the period when the faulting occurred (see further below). A causal relation between faulting and landslides seems most likely from the corresponding appearance in both time and space of the two phenomena.

Distortions of the internal structures of different types of Quaternary deposits is another phenomenon interpreted to be related to the faulting. The distortions occur mainly in layered sandy and silty sediments (Fig. 5) but have also been found in glacial till (Lagerbäck 1988b, in manuscript). The distortions include different types of convolution, corrugation, flame-like structures and size-sorting of clasts. These phenomena are interpreted to be due to seismically induced liquefaction and tremor in connection with the faulting.

3 FIELD INVESTIGATIONS

3.1 TRENCHING ACROSS FAULT SCARPS

A complex till-stratigraphy within the area, and the fact that a large portion of the fault complex is situated at, or below, the highest postglacial coastline, theoretically offer ideal conditions for dating of fault movements in relation to different glaciations and the early postglacial land-upheaval.

In connection with this project, excavations across the fault scarps were made at five localities not investigated previously (1, 2, 3, 4 and 6 in Fig. 2). Two previously investigated sites (5 and 7 in Fig. 2), of which one was now reinvestigated (5), are included in the report. For practical and economical reasons, it was necessary to locate the excavations to lightly forested places with roads nearby.

The excavations were made as trenches at right angels to, and crossing, the fault scarps. The excavators theoretically reached depths of 5.5 and 6.5 m. However, in practice it was often not possible to dig very deep into the ground as soils were wet and unstable due to rainy weather during the summer and great quantities of water leaking from the fault zones.

The profiles and sections along the trenches were levelled and recorded by sketches and photographs. The sections shown in Figs. 6, 7, 8, 9, 13, 16 and 21 are simplified and stylized versions of the sketches made in the field. A schematic illustration of the interpreted course of events in connection with faulting and subsequent repose is given at each section. (Note that these sketches are not to be viewed literally!). A restricted number of samples of the bedrock and overburden were collected for later examination and analysis.

At MAINEKJAURE (Figs. 2 and 6) a trench, 54 m long and 5-6 m deep, was excavated across the 7 m high scarp at the south-eastern part of the hill Storsaiviskölen. The trench was located immediately south of, and parallel to, the small road crossing the scarp. The locality is situated well above the highest coastline. The Quaternary stratigraphy was represented by three, or possibly four, different till beds and sporadic intercalating layers of sand and silt.

In the scarp the original stratigraphy, as it appeared on the up-thrown block, was completely destroyed by fault movement and replaced by a structureless rubble of till material enriched in stones and boulders. Large amounts of water were pouring out of the bouldery mass making excavation very problematic as trenchwalls collapsed and the 36 tons excavator sank into the muddy ground on the lower block.

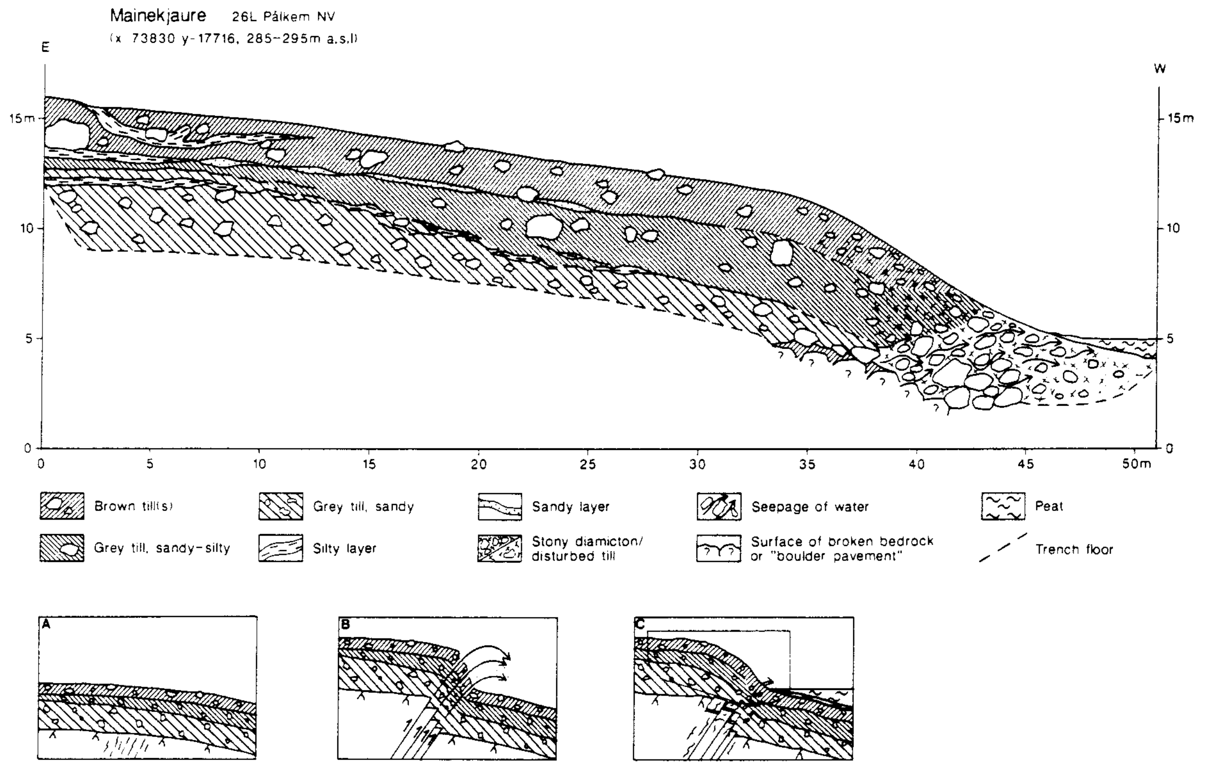


Fig. 6. Trench-section across the fault scarp at Mainekjaure (1 in Fig. 2). Inferred development. A. Previous to faulting. B. Faulting and contemporaneous expulsion of bedrock groundwater resulting in matrix material being washed away. Hypothetically the fault displacement was spread in an existing zone of weakness. C. Present-day conditions. Note that the depth to bedrock is uncertain.

A pavement of big boulders, possibly the surface of broken bedrock, was met with at a depth of about 5 m at the rim of the up-thrown block. The depth of the overburden at the site has been estimated to be about 20 m (Henkel & Wållberg 1987). However, the method they used, refraction shooting, is not adequate for determinations of bedrock surfaces when the bedrock is greatly fractured and chemically weathered (see e.g. Mäjärvberget, p.16 below) and therefore, it cannot be excluded that the boulder pavement represents the bedrock surface.

As the locality is situated above the postglacial coastline there is no possibility to date the fault-movement relative to land-upheaval. The distortions of the glacial stratigraphy however, demonstrate that faulting postdates the deposition of the different till beds, including that deposited by the most recent ice-sheet. It cannot be excluded that the scarp developed beneath a stagnant ice sheet but it is more likely that the site was deglaciated at the time of faulting. The characteristics of the disturbances in the overburden suggests a rapid one-step movement under contemporary expulsion of large quantities of water from the fault zone.

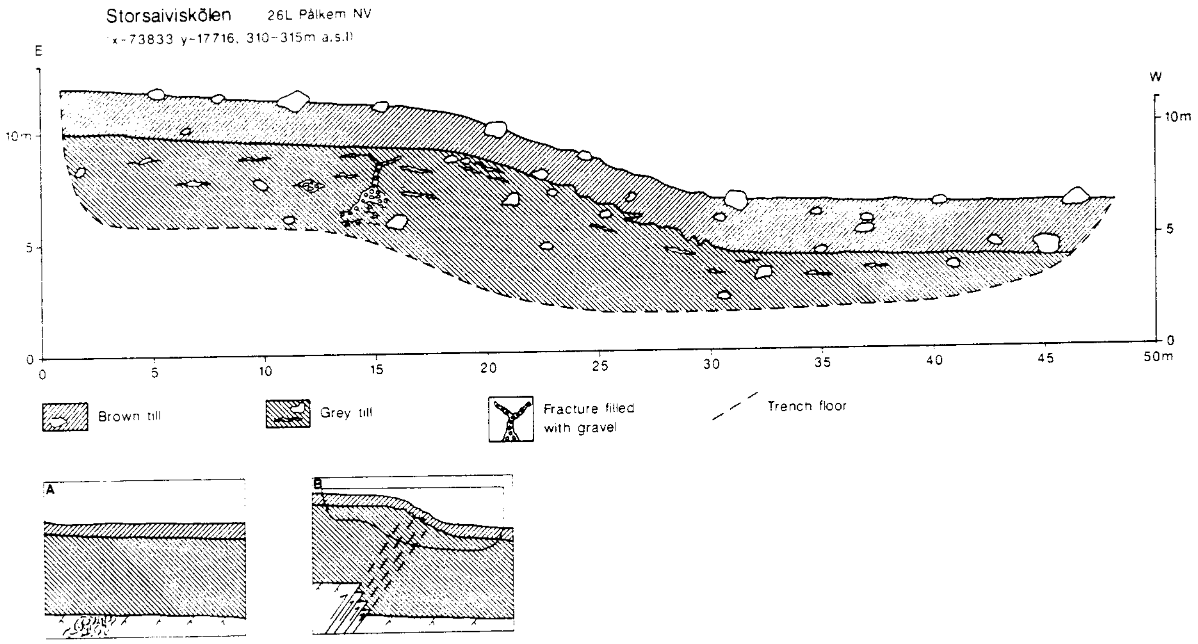


Fig. 7. Trench-section across the fault scarp at the crest of Storsaiviskölen (2 in Fig. 2). A. Previous to faulting. B. Faulting. A thick cover of overburden and/or an existing zone of weakness, in which the displacement was spread, explain the weak distorsions of the Quaternary stratigraphy. Some fractioning of the till and possibly expulsion of water from the fault zone.

At the crest of STORSAIVISKÖLEN (Figs. 2 and 7) about 350 m north of the Mainekjaure trench, a 48 m long and up to 7 m deep trench was excavated across the 5 m high scarp. A minor trench was made close to the major one. Two well-defined till beds (Early- and Mid/Late-Weichselian respectively) were found in the trench. The boundary between the till beds was very distinct and smooth apart from the fault zone, where the contact was gently folded and where wedge-like infillings of the upper till occurred in the lower. With the exception of these modest disturbances, and a vertical fracture, filled with sand and gravel, the section was surprisingly unaffected by the faulting. Although not more than 4-5 m high, the scarp is very distinct, and more drastic disturbances of the interior structures had been expected.

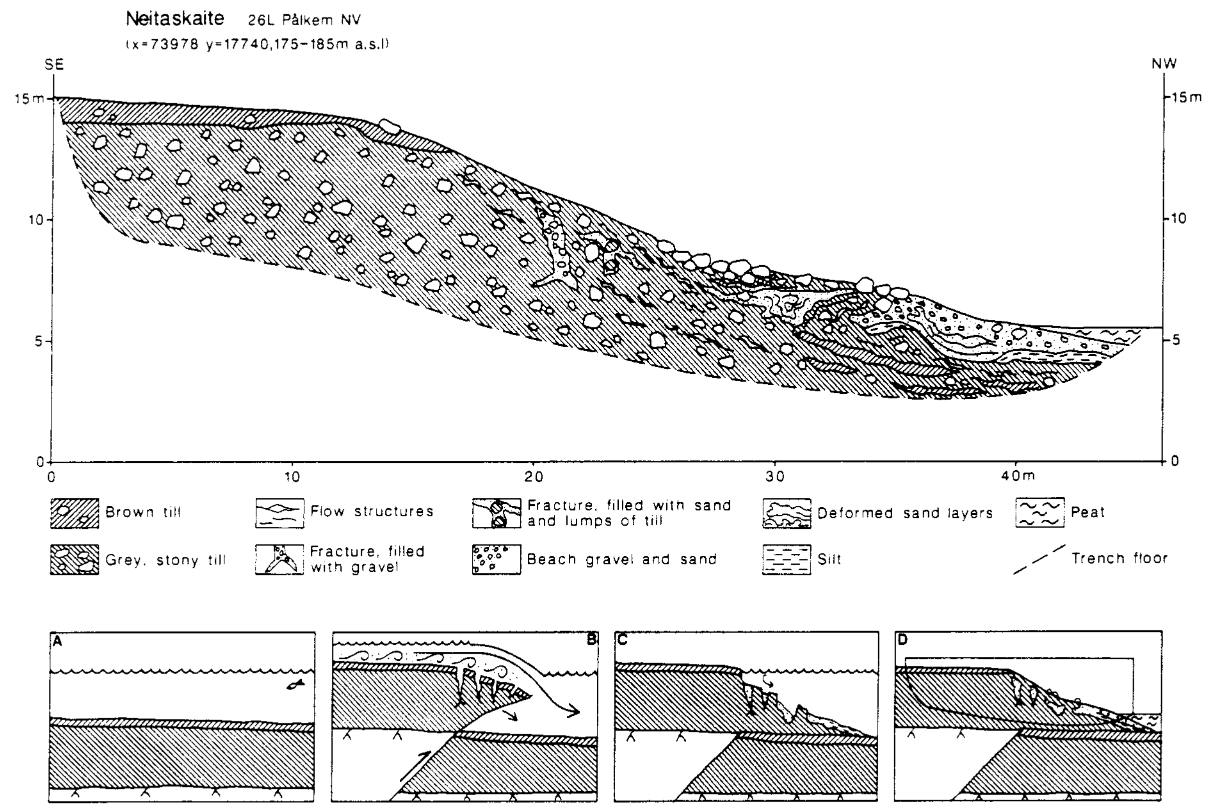


Fig. 8. Trench-section across the fault scarp at Neitaskaite (3 in Fig. 2). Inferred development: A. Previous to faulting. The recently deglaciated ground is covered by shallow water. B. Faulting under contemporaneous collapse of the overburden on the rim of the raised block and rapid discharge of sea water. C. Levelling and stabilization of the scarp by wave abrasion, slumping and flowage of till. The locality is soon raised above sea level and the scarp recieves its present day appearance (D).

At NEITASKAITE (Figs. 2 and 8) a 44 m long and up to 7 m deep trench was excavated across the 10 m high scarp immediately north of the Arctic Circle. The locality is situated at approximately the same level as the highest postglacial coast-line and a minor wave-cut bench, most probably representing the water-table immediately after the faulting, is developed in the lower part of the scarp. Prior to faulting, the post-glacial sea also covered the upthrown block to the east of the westward facing fault, and littoral sediments and wave-washed ground are found here at anomalously high levels.

Two till beds (Early and Middle/Late Weichselian respectively) were identified in the undisturbed parts of the section on the upthrown block. Silt and littoral sand and gravel occurred in the lower parts of the scarp and these sediments were partly integrated in, and deformed by, flow material deriving from the fault-cut and collapsed till beds. The original (pre-faulting) stratigraphy was more or less completely destroyed in the fault zone. The upper till bed was missing and the lower was collapsed and had been subjected to flow.

The relationship between the fault-induced flow material and the waterlaid sediments give evidence for a rapid one-step fault movement which occurred sometime between local deglaci-ation and the upheaval of the locality above the sea. Taking into consideration the very rapid land upheaval at that time, and the site's location close to the highest coastline, it can be concluded that the scarp must have developed within a very short period of time, and probably not more than a few years or decades after local deglaciation.

MOLBERGET (Figs. 2 and 9). This trench, 35 m long and up to 6 m deep, was excavated across a comparatively low fault scarp 2 km SE of Molberget. The site is situated just below the highest coastline and the till on the raised block is largely affected by wave-erosion. Even though the visible fault scarp was not more than 1-2 m high, a 4 m high and vertical bedrock scarp was met with only two metres beneath the ground (Figs. 10 and 11). The bedrock, composed of pegmatites and granodio-ritic granitoids, was excessively fractured and weathered in a wide zone on both sides of the scarp (fig. 12). Two samples of the weathered bedrock were analysed with respect to clay minerals. A sample of the red, clayey saprolite in the very fault zone was dominated by vermiculite and expandable mixed layer minerals. The other sample, from the red, sandy weathering residual of the raised block, consisted of vermiculite, expanding mixed-layer minerals, illite, plagioclase and potassium feldspar.

Three different till beds were present in the section, and they were all cut by the fault. Debris and mud flow material, deriving from the collapsed till beds, covered postglacial fine-grained water-laid sediments on the down-faulted block, demonstrating that faulting occurred after local deglaciation. The ground on the raised block was excessively wave-abraded, and covered by residual till boulders and coarse gravel. On the down-thrown block, situated in a more protected position, fine grained littoral gravel and sand covered the remaining, not eroded deposits, including the fault-induced debris and mud-flow material. The littoral gravel and sand were unaffected by the faulting, making it obvious that no movements have occurred in the fault zone since the site was raised above the sea.

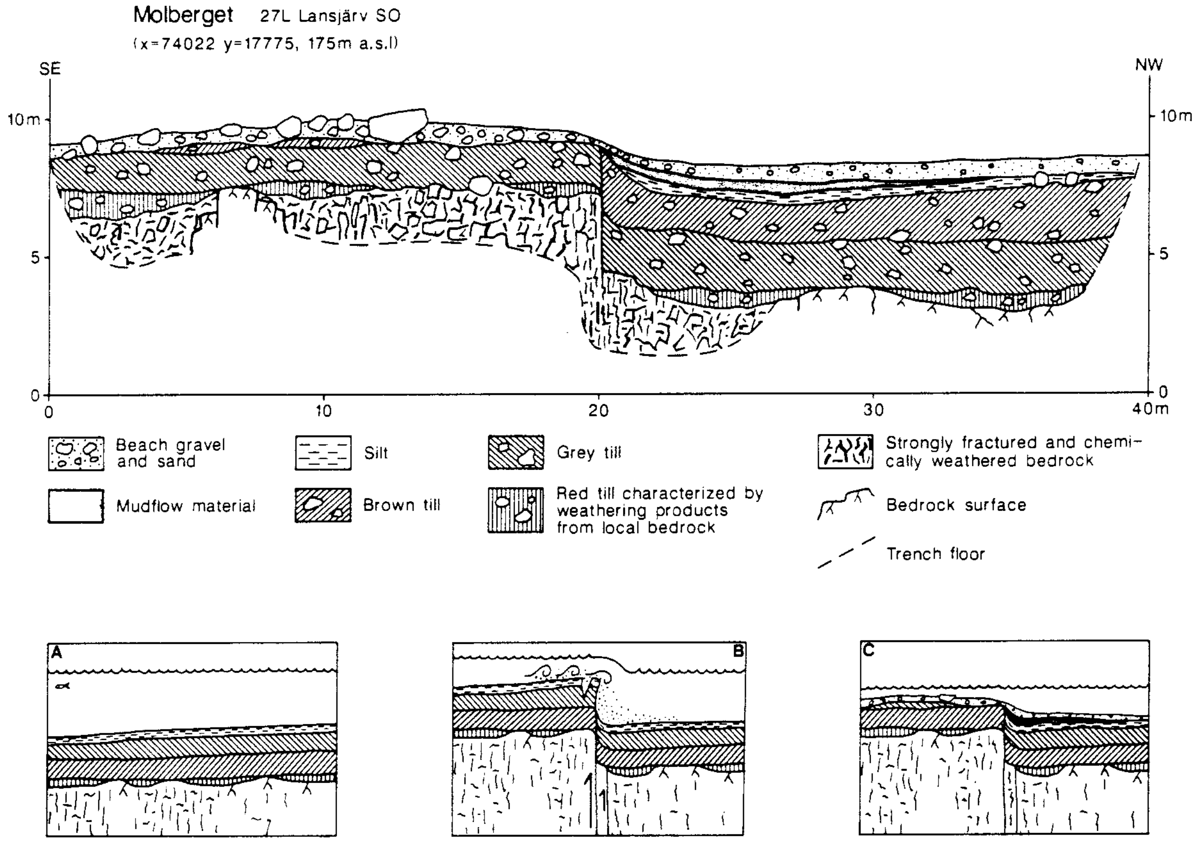


Fig. 9. Trench section across the fault scarp at Molberget (4 in Fig. 2). Inferred development: A. Previous to faulting. The recently deglaciated locality is covered by the postglacial sea, deposition of fairly fine--grained littoral sediments. B. Faulting. Movement occurs in an existing, strongly weathered fracture zone. The fine-grained sediments 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 sand on the lower block during the land upheaval masks the originally more marked fault-scarp.

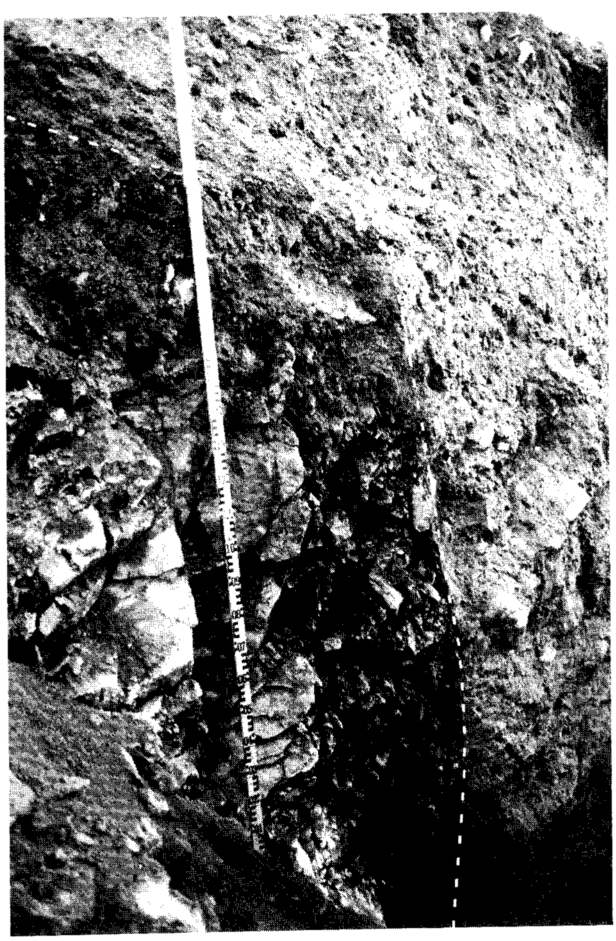


Fig. 10. The strongly fractured edge of the raised bedrock block at Molberget. The contact between bedrock and till is stippled. Photo R. Lagerbäck 1987.

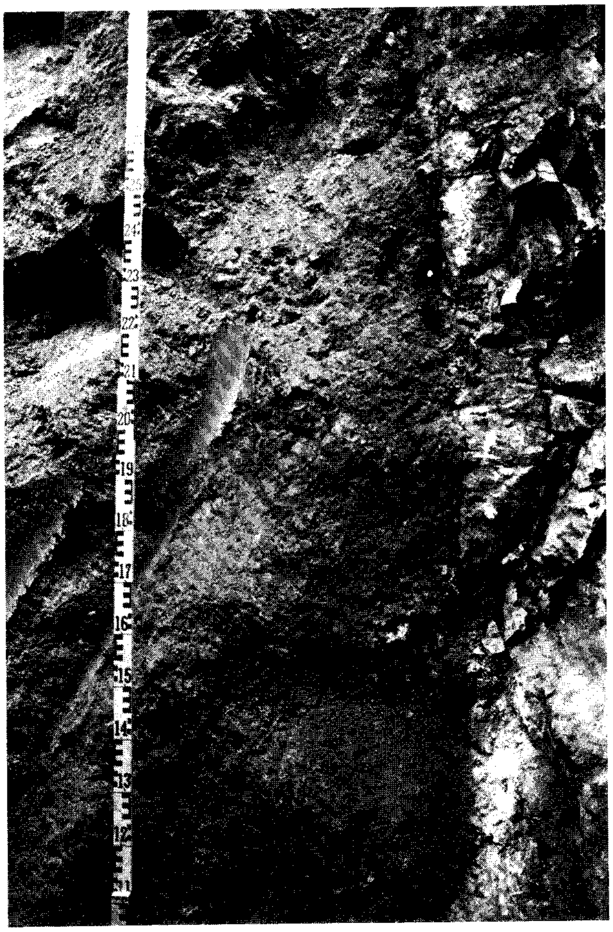


Fig. 11. The sharp, vertical contact between bedrock and till in the fault-zone at Molberget. Photo: R. Lagerbäck 1987.

STUPFORSEN (Figs. 2 and 13). This site, situated just north of Stupforsen 1 km northeast of L. Renberget, has been studied previously (1982, Lagerbäck unpubl.), and was now only partially re-excavated. Two till beds were cut by a well-defined, reverse fault scarp dipping some 45° to the west (Fig. 14). The hanging-wall bedrock, composed of coarse grained Lina granite and pegmatite, was heavily fractured and weathered, similar to that described from Molberget (Fig. 15). The clayey saprolite in the fault zone displayed beautiful, dip-slip slickensides. The clay-minerals in the saprolite were dominated by chlorite, vermiculite and expandable mixed layered minerals. The footwall rock was not reached because of extremely large quantities of water pouring out from the fault zone. A surficial bed of undisturbed littoral gravel demonstrates that no fault movements have occurred after the site was raised above the sea.

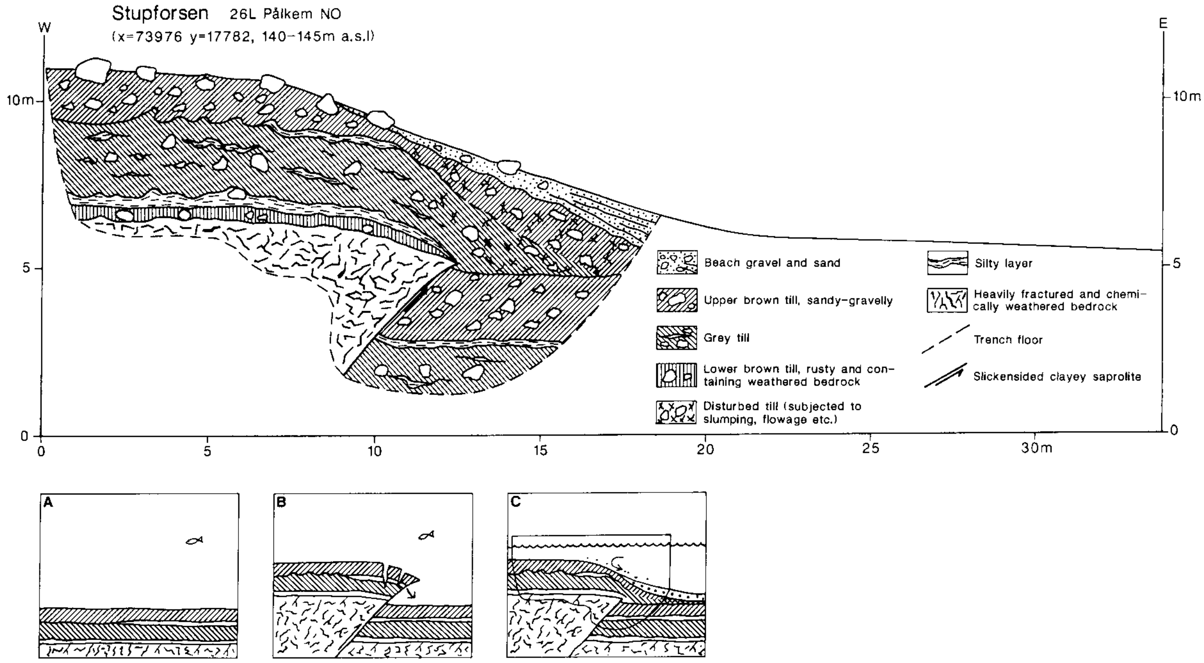


Fig. 13. Trench-section across the fault-scarp at Stupforsen (5 in Fig. 2). Inferred development: A. Previous to faulting. The locality is covered by the postglacial sea. B. Faulting. Fault movement occurs in an existing, strongly fractured and chemically weathered fault zone. The overburden on the edge of the raised block collapses during faulting and slumps and flows to cover the deposits on the lower block. C. During the land up-heaval the raised block is abraded by waves while sand and gravel is deposited on the lower block.

<u>MÄJÄRVBERGET</u> (Figs. 2 and 16). This trench, 68 m long and up to 7 m deep, was excavated across the fault scarp immediately southeast of the hill Mäjärvberget (Fig. 17). The locality is situated at about the same level as the highest coastline and a minor wave-cut bench is developed in the scarp.

Three till units were identified in the trench (Saalian or older, Early and Middle/Late Weichselian) and they were all affected by the fault movement. The bedrock was met with at a depth of between 1.5 and 6 metres but it was not possible to reach the bedrock within the 20 metres nearest to the fault scarp on the foot-wall block. The bedrock 20 m away from the scarp was a continuous and not significantly weathered granite, pinkish in colour, medium grained and possibly belonging to a granite generation older than the Lina Suite (T. Sjöstrand, pers. comm.). The bedrock in the fault zone, which was at least some 15 m wide, was extremely fractured and weathered (Fig. 18). It was composed of Lina granite, pegmatite and biotite gneiss, the latter possibly a metasediment or otherwise a variety of the Haparanda Suite (T. Sjöstrand, pers. comm.).

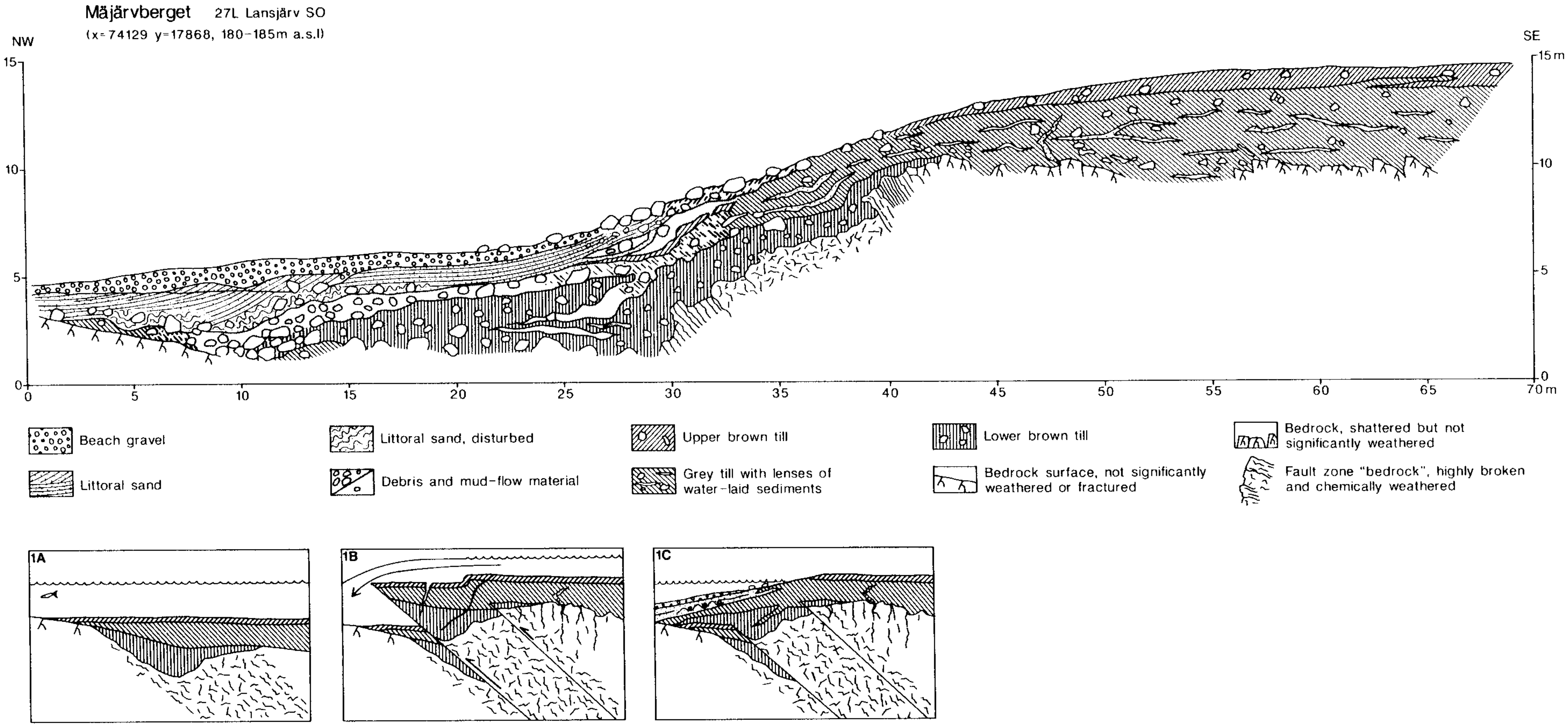


Fig 16. Trench-section across the fault scarp at Mäjärvberget. Inferred development: A. Previous to faulting. The recently deglaciated locality is covered by shallow water. A pocket of pre-Weichselian till occurs in an existing, strongly weathered fracture zone B. Faulting. Fault movement is spread throughout the zone. The bedrock in the raised block becomes fractured and water and sand is extruded through the fractures. The overburden on the rim of the raised block collapses. A minor strike-slip component in fault movement is indicated by the configuration of protruding bedrock. C. Stabilization of the fault scarp by slumping, wave erosion and flowage of till material. The present-day form occurs as soon as the locality is raised above the sea.

Two samples of the weathering products in the fault zone were analysed with regard to clay mineralogy. A clayey sample from the granitic rocks showed illite, expandable mixed layered minerals, potassium feldspar and plagioclase. A more sandy sample from the weathered gneiss showed illite, vermiculite, plagioclase, potassium feldspar and amphibole.

No well defined, single fault plane occurred in the bedrock scarp. Fault displacement was instead more evenly spread within the zone and it was difficult to define the dip of fault movement more precisely. Minor fault planes, fractures, fissility and contacts between different rock units dip some 40^{o}-50^{o} to the southeast, which is judged to be the most likely dip of the near-surface fault movement. A minor dextral, strike-slip movement was indicated by the way the fault-zone bedrock intruded into the lower brown till bed.

The bedrock at the surface of the raised block, composed of a greyish, medium grained, Lina granite, was chemically unweathered but shattered into blocks, somewhat displaced but mainly in primary positions (Fig. 19). Fresh, open fractures were cutting the glacially polished rock indicating violent breakage (Fig. 20). These fractures were generally directed in NNE-SSW, that is, roughly parallel to the fault, and they dipped some 80^{o} to the southeast.

The fracturing of the rock was so extensive that a refraction shooting across the scarp, performed previous to the excavation (profile S 4 in Henkel & Wållberg 1987), failed to indicate the bedrock in the hanging wall.

The Quaternary stratigraphy and the deformational structures related to the faulting were complicated. Breakage and collapse of the till bed, debris flow from the broken till, injection of sand and silt and littoral processes have been interacting in an intricate manner. The interrelationship between the littoral sand at the foot of the scarp, debris flows and boulders which have tumbled down the slope of the scarp, demonstrates that fault movement occurred at the time when the early postglacial sea was still covering the locality. The fact that coarse beach gravel, representing the last stage of wave-activity, has not been affected by any disturbances or interruptions shows that no movements occurred subsequent to that time.

Most probably the postglacial fault movement occurred as a one-step event. However, it cannot be excluded that a part of the fault scarp was developed before the postglacial reactivation of the zone. Two circumstances may support an interpretation implying that faulting also occurred prior to, or during, the Early-Weichselian glaciation. First, the distribution of the lowermost, pre-Weichselian till bed is restricted to the fault zone. This circumstance indicates that this till has been located in a protected position during the Early-Weichselian glaciation. A minor fault scarp, present at that time, could theoretically have served as such a protection. However, an alternative and more likely explanation

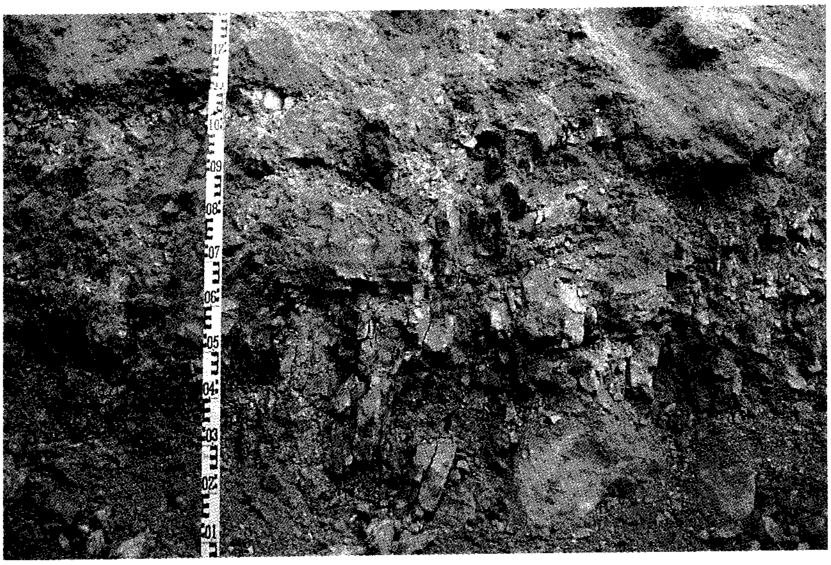


Fig. 12. Strongly fractured and chemically weathered bedrock of the raised block at Molberget. Contact between till and bedrock in the upper part of the photograph.
Photo: R. Lagerbäck 1987.

Fig. 14. The edge of the raised block at Stupforsen. Dip-slip slickensides occur in clayey saprolite on the fault surface. The height of the fault scarp visible on the photograph is about 2.5 m.
Photo: R. Lagerbäck 1987.

Fig. 15. The fractured and chemically weathered bedrock in the hanging wall at Stupforsen. The bedrock was easily cut through by the excavator.
Photo: R. Lagerbäck 1987.

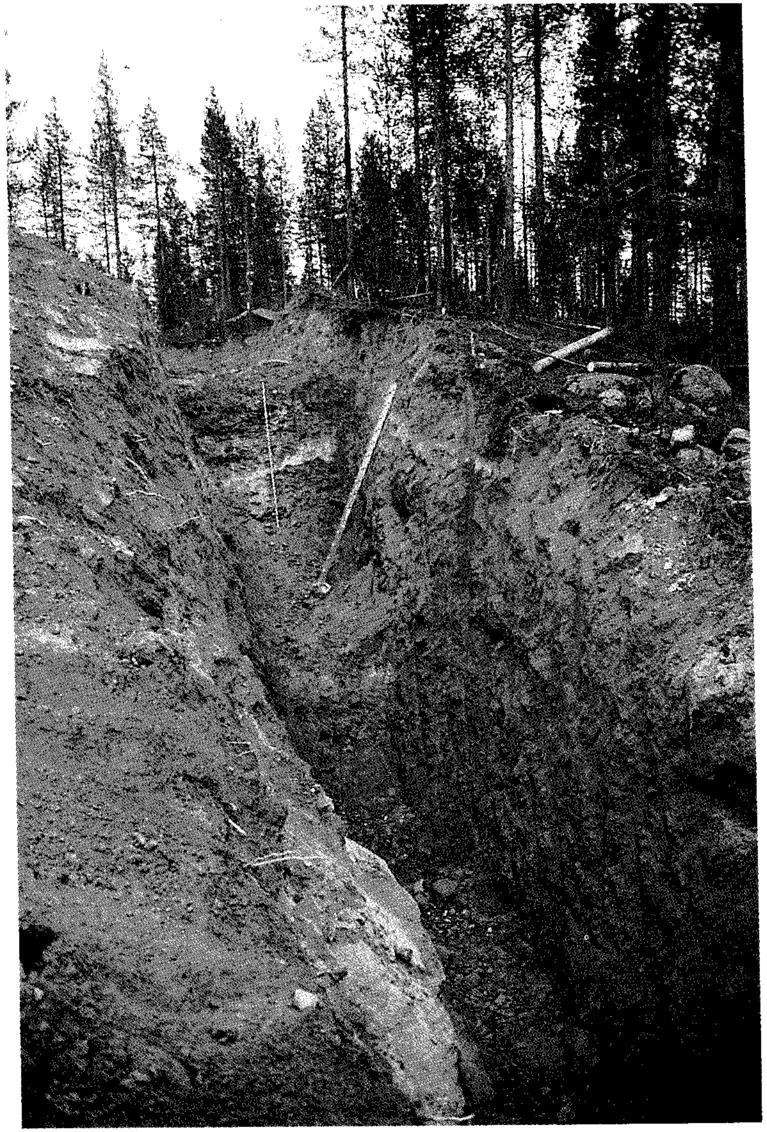


Fig. 17. Part of the trench across the fault scarp at Mäjärvberget. 5 m long ladder for scale. Photo: R. Lagerbäck 1987.

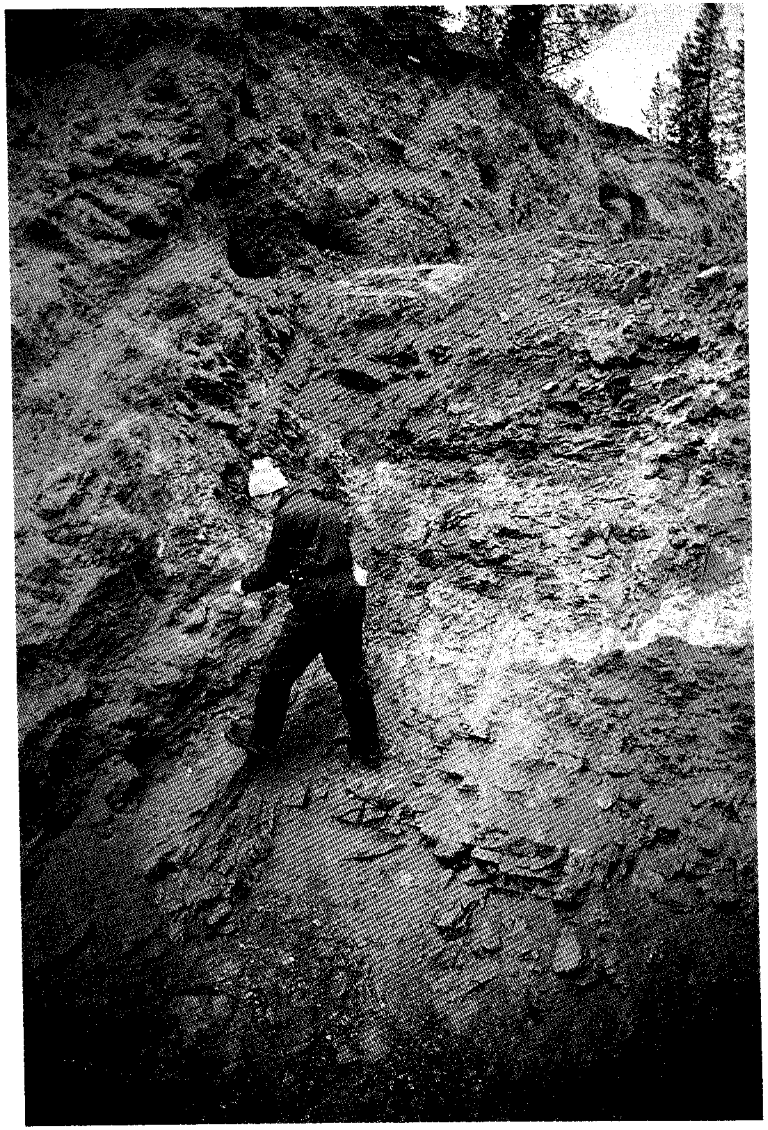


Fig. 18. Part of the strongly fractured and chemically weathered fault zone at Mäjärvberget. Photo: R. Lagerbäck 1987.

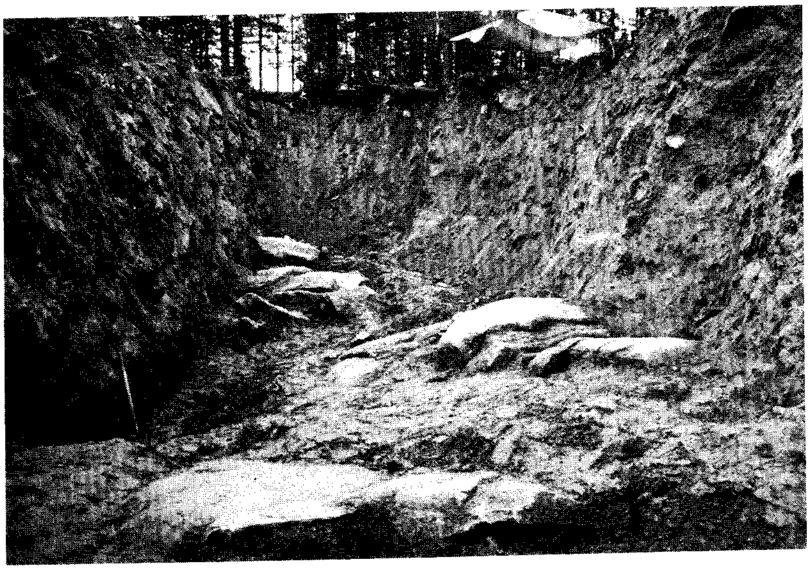


Fig. 19. Part of the trench at Mäjärvberget showing the shattered bedrock surface on the raised block. The thickness of the till-cover is 4-5 m. Photo: R. Lagerbäck 1987.

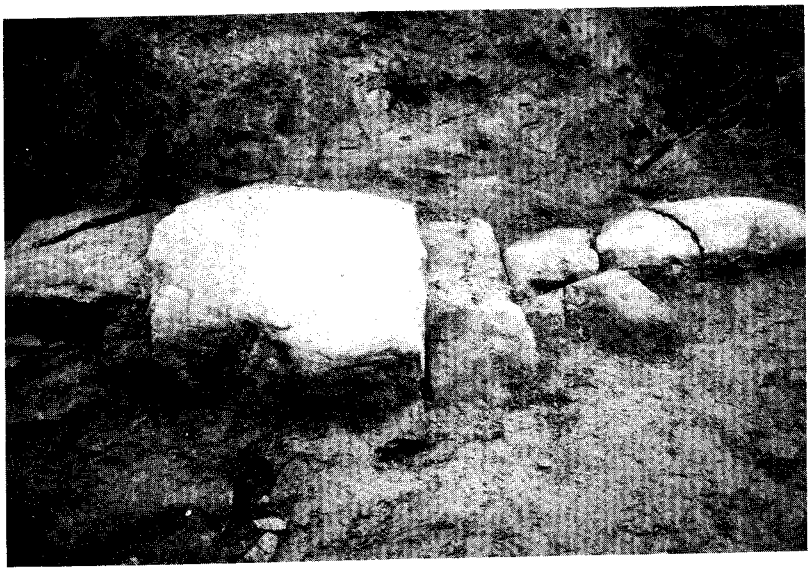


Fig. 20. a. Shattered, glacially polished bedrock at the surface of the raised block at Mäjärvberget. Note exposed part of open fracture in the lower part of the photograph and sand-filled veins emanating from the open fractures to the right. The picture is about 3 m across. Photo: R. Lagerbäck 1987.

Fig. 20 b. Open fractures cutting through the bedrock boss to the right in Fig. 20 a. The rock is very hard and unaffected by chemical weathering. Sand-filled veins emanate from the fractures. Photo: R. Lagerbäck 1987.

is that the probably pre-Quaternary fractured and weathered fault zone was deaply eroded, thus forming a depression in which the pre-Weichselian till was deposited and protected during later stages of glacial activity.

Another circumstance possibly indicative of previous Quaternary activity of the fault is the character of the Early Weichselian till and its relation to bedrock surface on the upthrown block. This till bed is characterized by an extremely high content of sand and silt lenses. This facies of the till is not previously met with in the region and might be hypothetically explained by exceptional meltwater activity in connection with fault zone activity or by water emanating from the fault zone itself. A minor pit dug only some 100 m from the trench, revealed a more normal Early-Weichselian till bed without this unusually high content of water-lain sediments. Besides some drastic exceptions, the sedimentary structures in the till did not seem to be significantly disturbed by the fault induced shattering. These circumstances may support an interpretation of multiple stage Quaternary development of this fault scarp at this particular place.

L. TELMTRÄSKET (Figs. 2 and 21). This locality, situated 700 m NE of the Mäjärvberget-trench, was not investigated in connection with this project but has previously been the subject for thorough investigations concerning stratigraphy, effects of faulting and earthquake impact (Lagerbäck 1988b, in manuscript). The impact of fault movement on the different stratigraphical units clearly dates faulting to an early stage of the postglacial period, shortly after the deglaciation and while the sea still covered the locality.

3.2 PALEOSEISMIC RECORDS

3.2.1 Landslides

Several circumstances indicate that the faulting within the Lansjärv area was associated with strong seismic activity. The most striking phenomena in this context are landslides occurring in the same area as the faults. One of these slides, at ELMABERGET (Figs. 2, 22 and 24) some 15 km to the northeast of Lansjärv, has previously been investigated by excavations (Lagerbäck unpubl.). The landslide scar measures about 300x300 m and approximately some $5\ 10^5\ m^3$ of glacial till was mobilized. Most of the material obviously moved in a liquefied state but big chunks of the more coherent, surficial parts of the overburden were also transported downslope. The slide has been radiocarbon dated using peat formed inside the scar and gives a date older than 8000 years. The landslide is developed in an ordinary sandy till (Fig. 23). This most probably is valid also for the other slides within the region. The fact that these slides are developed in till is remarkable as sandy tills are not expected to slide and as they generally occur in gentle slopes.

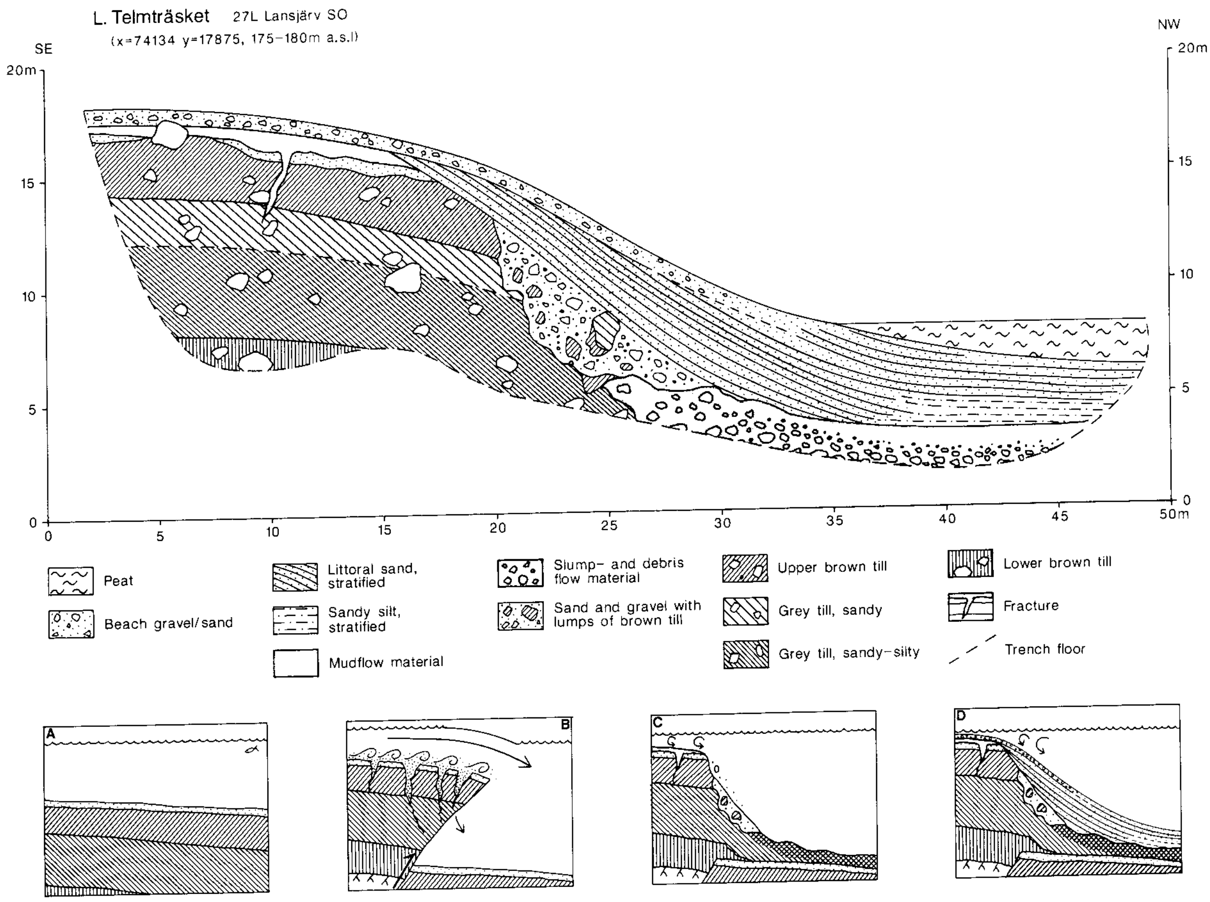


Fig. 21. Trench-section across the fault scarp at L. Telmträsket. Inferred development: A. The recently deglaciated locality is covered by shallow water and a thin cover of littoral sand is deposited B. Faulting, contemporaneous rupturing and collapse of the overburden on the rim of the raised block. Water discharge and mud flowage from the raised block. C. Stabilization of the fault scarp. Lumps of till becomes 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.

The Elmaberget slide was now reinvestigated with respect to stratigraphy and mechanical composition of the deposits involved. Excavations were also made in some peculiar hollows and troughs situated close to the slide and suspected to be genetically related to it. Some of these most probably were created by expulsions of groundwater from the bedrock, or from the overburden in connection with a rise in pore pressure due to seismically induced compaction, while others are interpreted to have formed by subsidence of the ground due to subsurface outflow of liquefied till. A reconnaisance flight over the area revealed a Z-shaped structure, possibly a bedrock

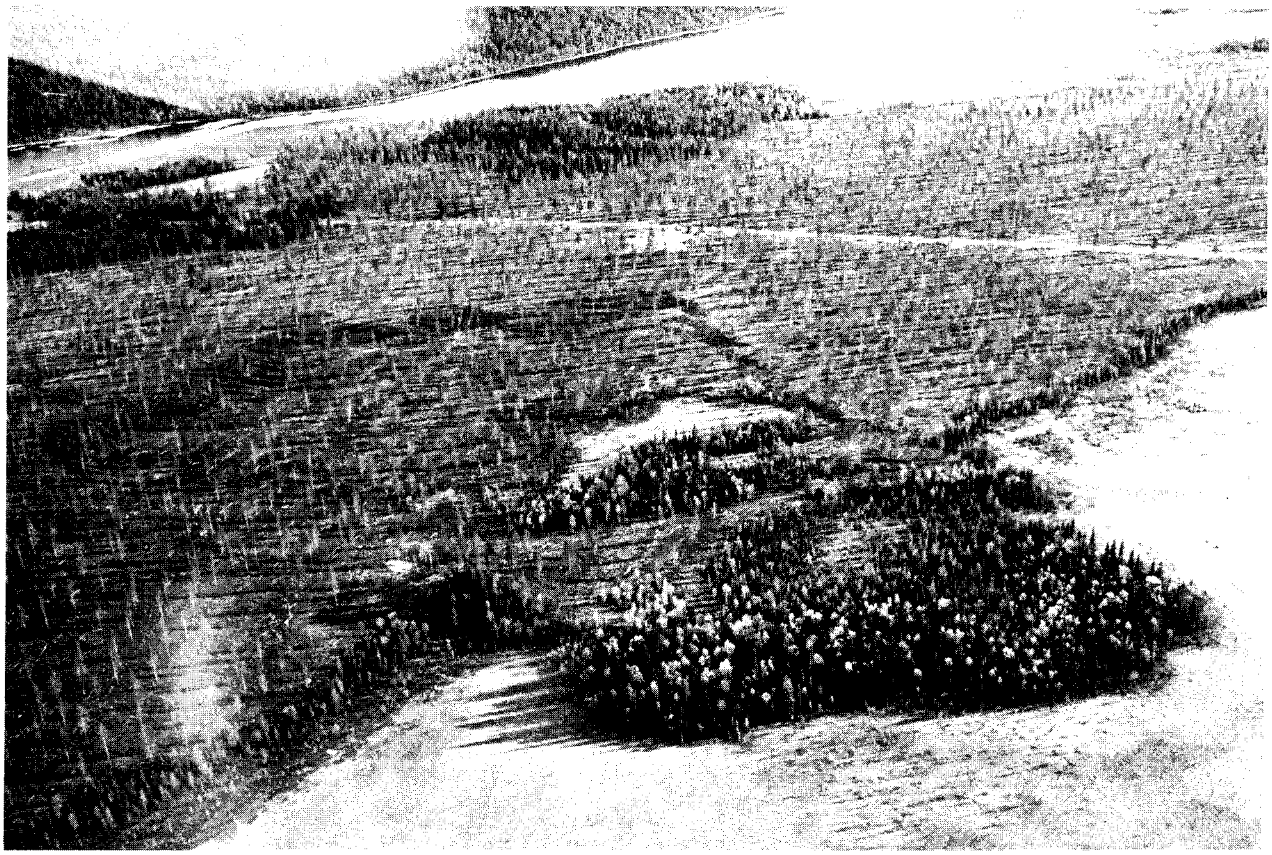


Fig. 22. Landslide in glacial till at Elmaberget (8 in Fig. 2). The landslide developed in a slope with an inclination of only 3-4 degrees. It is radiocarbon dated to an age of more than 8000 years and was probably triggered in close connection to the deglaciation of the area. Photo: R. Lagerbäck 1981. Approved for publication.

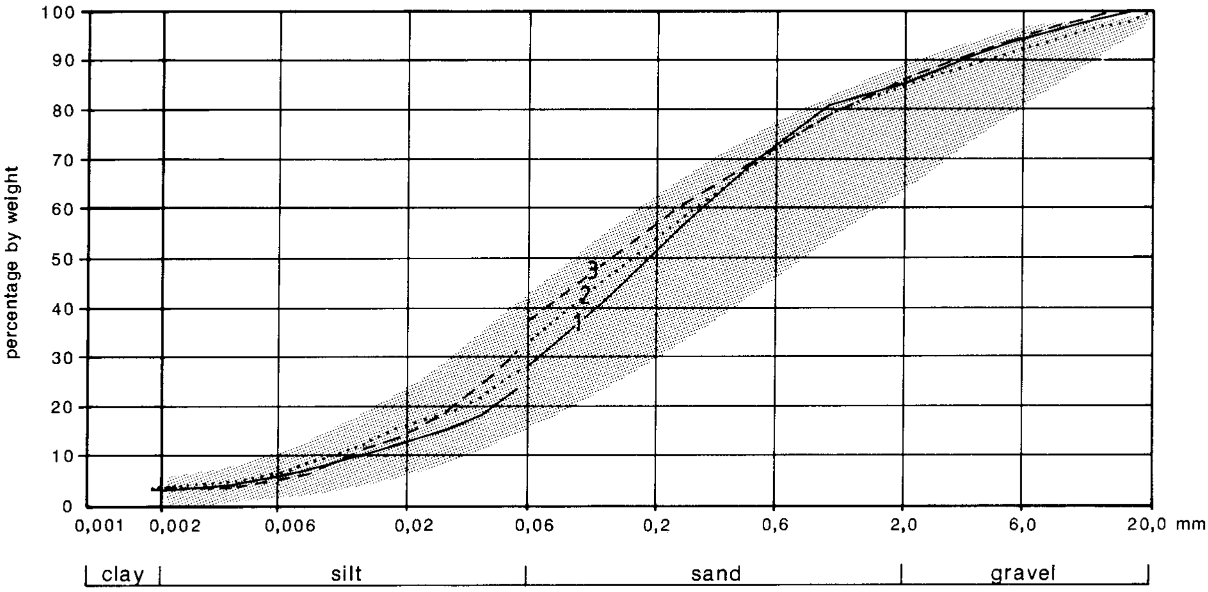


Fig. 23. Grain size distribution of the matrix in till from Repovaara (1) and Elmaberget (2 and 3). Screening shows the variation range of typical sandy tills.

fracture, in the ground close to the slide (fig. 24). This indicates that minor fault movements may have occurred in close connection to the slide. Alternatively the fracture may represent a crack developed in a frozen, upper layer of the overburden.

Fig. 24. Z-shaped fracture (foreground) in the ground close to the landslide scar (background) at Elmaberget (cf. Fig. 22). Several small hollows occur in the till along the structure, probably created by expulsion of ground water. It is not known if the fracture reflects movement in a corresponding bedrock fracture or is linked to the till cover. The locality is situated in the northward extension of the Lansjärv fault scarp system (Fig. 2). Photo: R. Lagerbäck 1987. Approved for publication.

At REPOVAARA (site 9 in Fig. 2), about 25 km north of Lansjärv, two minor pits were dug in connection to a fairly large slide ($\geq 1\ 10^6\ m^3$. This slide was aslo developed in a gentle hillside with an ordinary sandy till (Fig. 23). The distribution of the mobilized material demonstrates that the slide was triggered while remnants of the down-wasting ice-sheet were still present at the place.

3.2.2 Seismites

Seismically induced disturbances of the primary structures of different types of Quaternary deposits is another effect of earthquakes associated with the faulting. Such disturbances are the result of liquefaction and occur in unconsolidated, water saturated frictional soils when affected by seismic acceleration. Disturbances in different types of soils have previously been actively searched for, and have also been found in many places within the Lansjärv area (Lagerbäck 1988b, in manuscript). Deposits, interpreted as being significantly distorted by seismic acceleration, are collectively called here seismites, a term introduced by Seilacher (1969).

In connection with the present project, seismically induced disturbances in waterlain sediments were looked for in two areas; at Ängeså 12 km NNE of Lansjärv and at Slättheden some 50 km to the southwest of Lansjärv.

At ÄNGESÅ, (site 10 in Fig. 2) only a few kilometres from the Lansjärv fault, four trenches were dug to the north of the river and six to the south of it. The sediments met with were postglacial fluvial sand and a clay of uncertain origin. No disturbances of any kind were found. The clay, if deposited when faulting occurred, was most probably too fine-grained and cohesive to liquefy. The fluvial sand on the other hand was of an adequate grain size for liquefaction and, if deposited when faulting occurred, would most probably have demonstrated extensive disturbances. However, at this altitude, about 110 m asl, the age of the sand is most probably less than about 7000 years, that is, at least some 2000 years younger than the regional deglaciation. Thus, the lack of seismic disturbances in the sand is in agreement with the conception that faulting was restricted to a very short period of time in direct connection with the deglaciation of the area.

SLÄTTHEDEN (site 11 in Fig. 2) is a large delta built up more or less to the level of the highest coastline. The purpose of excavating here was to check if seismically induced disturbances of any significance exist at a considerable distance from the fault area. The excavations were carried out in the top-set beds of the marginal parts of the delta. From a mechanical point of view these deposits, composed of sand and coarse silt, were considered favourable for liquefaction and, furthermore, provide good conditions for timing of potential earthquakes relative to deglaciation and land upheaval.

The locality is situated about 25 km to the southwest of the southernmost part of the Lansjärv fault and about 50 km from its center. Four trenches were made. Two of them revealed disturbances of a type very similar to those found earlier in the Lansjärv area, the most typical features being a considerable compaction and a transformation of the original layers into different types of convolutions, "ripples" and "flames" (Figs. 25, 26 and 27). The most surficial layers were not affected by these disturbances.

Fig. 25. Distortions in cross-stratified deltaic sand deposits at Slättheden (site 11 in Fig. 2). The features are interpreted as being caused by earthquake induced liquefaction, dewatering and to some degree load-casting during the build-up of the sequence. The undeformed, upper part of the sequence was deposited subsequent to deformation. Note grading of particle-size in the flame-shaped bulges. The grading is thought to be gravitational and provides evidence for liquefaction during deformation. The picture measures about 1.5 m across. Photo: R. Lagerbäck 1987.

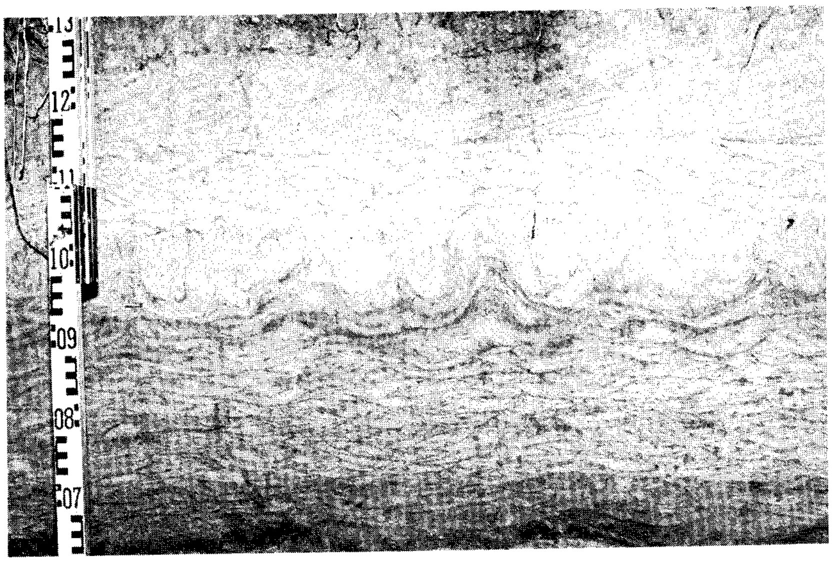


Fig. 26. "Earthquake sheet" close to the sequence shown in Fig. 25. The convolutions, or corrugations, are restricted to a 0.1 m thick bed and represent what was the uppermost, liquefied layer when the earthquake struck the area. Photo: R. Lagerbäck 1987.

Fig. 27. Small scale convolutions and corrugations in silty and fine-sandy layers at Slättheden. The distortions occur at the same stratigraphical level as the features shown in Fig. 25 and 26. Features very similar to the "flames" developed in the darker, silty layer in the middle of the picture are produced experimentally by shaking of sand overlying mud (Dzulynski & Walton 1963, plate XX11B). Scale in cm.
Photo: R. Lagerbäck 1987.

At L. FURUBERGET (site 12 in Fig. 2), some 25 km northwest of Överkalix, phenomena interpreted as seismically induced were come across during reconnaissance for suitable sites for excavation. In a gully, cut by meltwater during the spring of 1987, extensive distortions of the primary sedimentary structures were found in littoral sand (Figs. 28-30). The disturbances seemed to be restricted to a certain stratigraphic level and the uppermost layers were quite unaffected. These circumstances demonstrate that the agents generating the distortions were acting only during a short period, probably at one single occasion, during the early postglacial period and before the locality was raised above the sea.

Fig. 28. Convoluted sandy deposits at L. Furuberget (12 in Fig. 2). The material above the scale is artificial filling. Pseudo-nodules very similar to the one in the center are produced experimentally by simulating earthquake effects on sand overlying mud (Kuenen 1958). Scale in centimetres. Photo: R. Lagerbäck 1987.

Fig. 29. Convolutions and corrugations in slightly inclined, evenly bedded littoral sand at L. Furuberget. The layering in the upper part of the section is undisturbed, demonstrating that the distortion took place before the locality was raised above the sea and the sedimentation ceased. The features occur at the same stratigraphical level as those in Figs 28 and 30. Scale in centimetres. Photo R. Lagerbäck 1987.

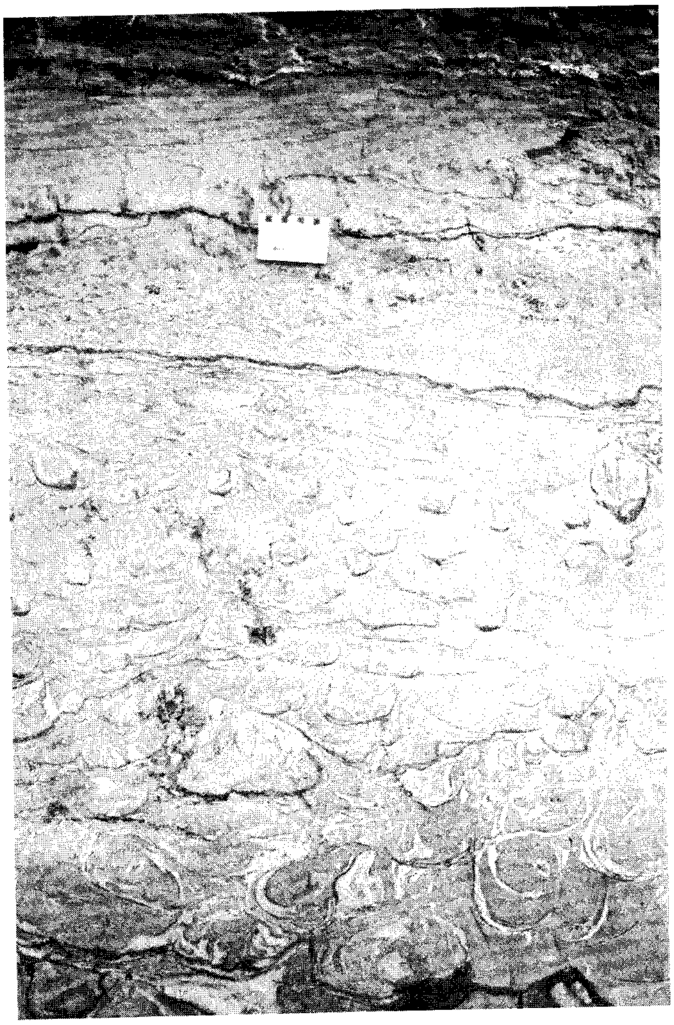


Fig. 30. Strongly corrugated sandy and silty littoral deposits at L. Furuberget. Note that the uppermost part of the picture (above the scale) shows undisturbed layering. The phenomenon is interpreded as being caused by seismically induced liquefaction, compaction and dewatering during the build up of the sequence. Photo: R. Lagerbäck 1987.

4 DISCUSSION

4.1 AGE OF FAULTING

The different stratigraphical units of the Quaternary overburden are the only adequate reference structures for dating the fault movements, visual as scarps in the ground surface. The fact that the scarps cut the till cover, and protrude as morphologically prominent scarps extending over long distances, does not necessarily imply that the faulting occurred postglacially. The reason for this is that the last two ice-sheets in this area were very sluggish and had a generally weak impact on the previous glacial landscape (Lagerbäck & Robertsson 1988, Lagerbäck 1988a). The entire thickness of the till-beds deriving from these two glaciations is often not greater than a metre or less, and morphological features dating from the previous glaciation are often not significantly eroded. Thus, from a morphological point of wiev, the fault scarps in this area might well pre-date the last ice-sheet.

However, a complex stratigraphy, with different till beds together with other stratigraphical units, offer a good potential background for dating of fault movement relative to glaciations and ice-free periods. The fact that the fault scarps are largely situated below the highest coastline means that it is theoretically possible to also date fault movement relative to deglaciation and local land-upheaval. These circumstances make trenching across the scarps a very promising tool in this context. Trenching across fault scarps has succesfully been used for dating of fault movements also in other, tectonically more active, regions of the world, as for instance in Japan (e.g. Ota 1985) and western U.S.A. (e.g. Bonilla et al. 1984 b).

With the exception of the Storsaiviskölen site, (2 in Fig. 2) it is demonstrated that fault movements post-date the deposition of the youngest till bed at all sites investigated in this study. However, the section at the nearby Mainekjaure site demonstrates that the fault-scarp at Storsaiviskölen is also younger than the uppermost till bed.

Furthermore, at Neitaskaite, Molberget, Mäjärvberget and L. Telmträsket it is evident that faulting occurred after local deglaciation, but previous to the rise above the postglacial sea. Taking into consideration the location of these sites close to the highest coastline, the fault scarps must have developed within a very limited time period after local deglaciation. Nothing contradicts that the scarps at Storsaiviskölen, Mainekjaure and Stupforsen are also of the same age, as the stratigraphy at these sites does not allow such precise dating. On the contrary it is of course most likely that these scarps all developed at the same time as shown by their similarity and while together they form a connected fault complex.

At Mäjärvberget sedimentary structures and the appearance of the interface between bedrock and till indicate that the fault may have been active during the deposition of the grey, Early

Weichselian till. However, this is uncertain and the distribution of the different deposits and their relation to the bedrock surface clearly indicates that at least the main part of the fault scarp height developed postglacially.

The stratigraphies at Neitaskaite, Molberget, Mäjärvberget and Telmträsket obviously were cut abrubtly by the fault movement and the scarps were here most probably developed as a one-step event. Nothing, except for what has been said about the section at Mäjärvberget, indicates that the scarps developed by repeated movements. Creeping over a long period of time is definitely ruled out. Also the slickensides at Stupforsen and the bouldery rubble at Mainekjaure, if correctly interpreted, speaks in favour of rapid fault movements. The section at Storsaiviskölen, with very modest deformations of the internal structures, may indicate a less dramatic and, in time, more extended development, but it may be explained just as well by a thick overburden absorbing the displacement and distributing it more homogenously in the ground surface.

To summarize, there is very strong stratigraphical evidence for a rapid fault-movement, most probably a one-step event, shortly after local deglaciation. The occurrence of landslides and seismites, if the causal relationship and interpretation of origin is accepted, also favours the conception of short-lived, co-seismic faulting of great magnitude (see further below). Minor contributions to the fault scarp development during previous glaciations, or ice-free periods, cannot be excluded but there is not much evidence in favour of them.

However, there is no doubt that the fault zones met with at Stupforsen, Molberget and Mäjärvberget pre-date not only the last glaciation but probably also the Quaternary. The possibility that the extensive weathering of the fractured rock should have developed postglacially is excluded and it is thought doubtful that 2-3 million years of cold Quaternary conditions are sufficient for the thorough chemical decomposition of the rock fragments. According to A. Sjödin (Geological Survey of Sweden, pers. comm.) the composition of clay-minerals in the samples from the fault zones, when taking into consideration the local rock-type, indicates that the weathering probably took place independently of atmospheric influence and that it might have occurred at a considerable depth. The relationship between the lowermost till beds and weathered bedrock at Stupforsen, Molberget and Mäjärvberget clearly demonstrates that the fracturing and weathering at least pre-dates the Weichselian and probably also the Saalian glaciations.

Thus, the fault scarps in the Lansjärv area very likely represent an early postglacial reactivation of old, probably pre-Quaternary, fractures. It is also demonstrated by Henkel et al. (1983) that the fault scarps coincide to a high degree with older fracture zones interpreted from aeromagnetic maps.

4.2 FAULT GEOMETRY AND STYLE OF POSTGLACIAL FAULTING, SOME REMARKS

It is beyond the scope of this study to speculate on tectonic style and fault mechanisms but some remarks might be justified. Several attempts to explain the tectonic setting of the area and the relation of the Late Quaternary movements to previous fracture systems have been made. Comprehensive geophysical investigations of the postglacial faults in northern Sweden, including those in the Lansjärv area, have been performed by Henkel et al. (1983). A structural analysis of the postglacial fault-scarp pattern is given by Talbot (1986) and a renewed interpretation of the tectonics within the Lansjärv area has recently been given by Henkel (1988).

Henkel et al. (1983) interprete the postglacial faults as steeply dipping zones involved in block movement tectonism. Talbot (1986) arrives at a different interpretation and concludes that the postglacial fault system involves "gently dipping anastomosing thrusts with N to NE strikes and steep contemporaneous NW-EW-trending sidewalls as well as steep E or ESE dipping reverse faults". The fault system is considered a possible "positive flower structure extruded by transpression along a NE trending master zone of weakness inherited from Proterozoic time" (Talbot 1986).

Inspired by Talbot, Henkel (1988) re-interprets the geophysical data and claims that the postglacial faults belong to a system of gently dipping (near horizontal) thrusts. The seismic refraction profiles performed across the fault scarps (Henkel 1988 fig. 16, Henkel & Wållberg 1987) are said to indicate "shallow dip" and "low angle thrusting" for several or most of the fault branches and scarps. However all fracture-zones are marked as vertical in the figures presented. It is difficult to see in what way these profiles support an interpretation of the faults as gently dipping. Besides, where met with, the fault zone bedrock, is strongly fractured and weathered and therefore not possible to identify as rock by seismic refraction sounding. Therefore, the seismic profiles probably do not reflect the true configuration of the bedrock fault scarp (see e.g. the Mäjärvberget section; Fig. 16 in this paper, and seismic profile S4 in Henkel 1988, fig. 16).

By using "terrain elevation data" (digital 100 m spaced data with an elevation resolution of about 2 m, see Plate 4 i Henkel 1988) Henkel also defines a great number of "suspected post-glacial fault scarps" spread over a large area, (Plate 6 in Henkel 1988) and several "suspected post-glacial shear lenses" associated with the major aeromagnetically indicated shear zones. The "suspected post-glacial fault scarps" are not described and no evidence for a post-glacial age of any of these features is presented. This is valid for example also for the numerous "morphologically indicated, shallow dipping fault zones" indicated by red lines in Henkel (1988, plate 6).

The naturally exposed bedrock outcrops, and those met with in the trenches, give some guidance to fault scarp geometry and the near-surface dip of the postglacially activated fault zones. The bedrock plinths protruding through the till at Ristråskkölen (Fig. 3) are largely shattered and it is difficult to reconstruct the original configuration, but a reverse fault dipping some 40-60° is inferred. At Karhuvaara the fault scarp constitutes a steep cliff (Fig. 4). At Stupforsen (Figs. 13 and 14) the fault is reverse, dips some 45° and displays fresh dip-slip slickensides. Talbot (1986, fig. 13) suggests that strike slip movement occurred along this scarp during the postglacial faulting. At Molberget (Fig. 9) the fault surface is vertical and at Mäjärvberget fault movements are interpreted as occurring along planes dipping some 45°.

Thus, if judging from field evidence it appears more likely that the faults, at least where outcropping, are reverse and dip between the vertical and some 40-50°. Dips of that order also seem reasonable if considering the appearance of the scarps and the deformations of the overburden stratigraphy along the scarps.

Gently dipping faults (a few degrees), as suggested by Talbot (1986) and Henkel (1988) are less likely along most of the scarps for geometrical reasons. It is difficult to see how such gently dipping faults could produce scarps of the type in question. The typical scarp is developed as a very distinct step in the ground surface, with a steep repose angle and a stable configuration for most of its extension. Faults dipping only a few degrees should result in scarps either with more gentle slopes, or, more likely with accumulations of loose deposits pushed to ridges along the fault outcrops. A much more complicated and distorted Quaternary stratigraphy than those recorded, should also be expected in the fault scarp.

4.3 PALEOSEISMICITY

4.3.1 Landslides

The landslides within the Lansjärv area, (Fig. 2) like all the other land slides in Norrbotten (Lagerbäck 1986, in manuscript) and Finland (Kujansuu 1972), are developed in gentle slopes (3-10°) with a considerable cover of glacial till. The tills involved in the sliding have a sandy composition and do not differ from ordinary tills in the region. (Fig. 23). Tills of this composition are not expected to flow under normal conditions, especially not in slopes with a low gradient.

It has been demonstrated that the slides are fossilized and that they all probably developed shortly after, or in direct connection with, local deglaciation, that is, about some 9000 years ago. What anomalous circumstances prevailed during the deglaciation in the Lansjärv area and large parts of the rest of northern Fennoscandia? Kujansuu (1972) suggests that a permafrost table may have occured at some depth in the ground. The permafrost would serve as a slip plane and also prevent the downward percolation of water, thereby forcing a soaking of the till. The southward orientation of most of the Finnish slides, resulting in a fast thawing of the permafrost, is taken as support for this interpretation.

However, Kujansuu (1972) also suggests that earth tremors accompanying the contemporaneous faulting (Kujansuu 1964) may have triggered the landslides and he points to the regional connection between the two phenomena in Finnish Lapland. Also in northern Sweden there is an obvious distributional connection between landslides and fault scarps (Fig. 2 and Lagerbäck 1988b). The correspondance in geographical distribution of the two phenomena is hardly accidental but most likely reflects a causal relationship. The occurrence of permafrost may have had an influence over the distribution of landslides as suggested by Kujansuu. But more important is that a triggering mechanism is a prerequisite for the development. The contemporaneous faulting, associated with strong seismic activity, offers an obvious explanation to the phenomenon.

It is well known that large earthquakes often initiate landslides. Keefer (1984) compiled data from 40 historical world-wide earthquakes and several hundred earthquakes from the U.S.A. in order to study the relations between landslide distribution and seismic parameters. Accepting the causal relationship between faulting, earthquakes and landslides in northern Fennoscandia, and translating Keefers results to this region, it seems that several earthquakes with a magnitude of M 6.5-7.0, or higher, occurred during the deglaciation of the region. In assuming that most of the landslides in eastern Norrbotten were triggered by the faulting in the Lansjärv area we arrive at a magnitude of at least M 6.5-7.0 for this area also .

Magnitudes of this order are also in agreement with the horizontal extension and the displacement of the faults. Inserting the figures of fault length (almost 50 km) and fault displacement of the Lansjärv fault complex (5-10 m, with about 25 m as an extreme) into the diagrams given by Bonilla et al. (1984a), showing relations among earthquake magnitude, surface rupture length and surface fault displacement, indicates that the faulting was accompanied by an earthquake with a magnitude of M 7.0-7.5 or higher.

4.3.2 Seismites

Distortions similar to those found in the Lansjärv area are described from many places and from different environments. They occur not only in unconsolidated sediments but are also found lithified in sedimentary rocks. The features are generally explained in terms of load casting, liquefaction and dewatering, but opinions differ about the conditions and factors responsible. Differences in composition of the beds involved, heterogenities of the sediments, rapid sedimentation, impact of big waves etc. are suggested to initiate the deformational processes. Many authors also stress the importance of earthquakes and seismically induced liquefaction for the development of distortions.

Convoluted and corrugated beds similar to some of those at L. Furuberget and Slättheden are explained by load casting, caused by heterogeneities of the sediments and/or thixotropic behaviour (Davies 1965). The importance of differential loading (density), slumping and water seepage is stressed by e.g. Dionne (1971). Many authors stress the importance of external disturbances acting as triggers of liquefaction and fluidization. Lowe (1975) suggests that a rapid deposition by itself, resulting in consolidation and dewatering of subjacent units, may lead to liquefaction, fluidization and associated distortion of sandy deposits, but also indicates that earthquakes or other disturbauces are probably influential in some instances.

However, features similar to some of those found in the Lansjärv area have also been produced experimentally by vibrating waterlogged sediments at the laboratory. Kuenens (1958) experiments are classical in this context and some of the features found at for instance L. Furuberget are more or less identical with those published by Kuenen. Structures very similar to the small scale deformations at Slättheden (Fig. 27) have been produced experimentally by shaking sand overlying mud (Dzulynski & Walton (1963).

Sims (1973, 1975) claims that earthquakes are critical for the formation of different features found in young lacustrine sediments in California and points to the correspondence of these features and experimentally formed structures. Sims also correlates some of the features with known recent seismic events and stresses the importance of the deformational structures for determination of earthquake recurrence intervals.

In a recent study Aartolahti (1987) describes, and beautifully illustrates, contorted structures in Quaternary glaciofluvial deposits in southern Finland. Aartolahti argues that some kind of shock is probably essential for the causing of at least some of the deformations and suggests local events such as flowage of till, boulders falling from the inland-ice sheet, calving ice boulders falling either into the sediments or into the water above it, gravity-induced faults or fractures in the accumulating sediments etc. Aartolahti excludes earthquakes as a cause of shock by reasoning that "they are rare in Finland and usually weak", According to my opinion it is less likely that the type of events suggested by Aartolahti were sufficient to produce the extensive distortions described while the occurrence of them rather indicates that southern Finland, similar to northern Finland and Sweden, was struck by strong earthquakes in connection with the deglaciation.

The beds described from Slättheden (Figs 25, 26 and 27), L. Furuberget (Figs. 28, 29 and 30), and many other sections in the Lansjärv area (Lagerbäck 1988b, in manuscript) are considered seismites and caused by earthquakes associated with the postglacial faulting. The interpretation of the features as seismically induced is supported by, among others, the following reasons:

- They occur in sediments with a grain size favourable for liquefaction when affected by earthquake vibration (e.g. Lee & Fitton 1969).

- They occur in mainly frictional deposits, of a similar grain-size throughout the sections, not expected to develop load-cast structures if not liquefied.

- They occur in flat-lying or very gently sloping terrain and, thus, provide no reason to expect that slumping or sliding contributed to the deformation.

- They occur in sediments deposited during the early post-glacial period, that is, contemporaueous to the faulting, but have not been found in younger sediments in the area.

- On each site they appear to be developed at a certain stratigraphical level and they are covered by undisturbed sediments. This demonstrates that the phenomenon was syn--depositional, occurred at a certain point of time, and before the sites were raised above the sea when the sedimentation then ceased. The distortions developed in the uppermost, less consolidated strata, which were most sensitive to liquefaction at the time of deformation.

- The features fit perfectly into a pattern of extensive faulting, accompanied by large earthquakes triggering a great number of landslides in the Lansjärv area. The features were found, when actively sought for, in deposits and environments where they were expected according to the theory of early postglacial seismogenic faulting in the Lansjärv area.

5 CONCLUSIONS

Based on the results from the present and previous investigations the following conclusions can be drawn:

- The morphologically expressed fault scarps in the Lansjärv area were formed in connection with co-seismic faulting during, or shortly after, the local deglaciation. There are no indications of fault movement after that time.

- the scarps generally developed as rapid single events but it cannot be excluded that some of them were partially developed prior to, or developed in connection with, an earlier glaciation.

- The different fault-scarp segments in the area most probably developed simultaneously, or at least in close conjunction with each other.

- The postglacial faulting at least partly took place along heavily shattered and chemically weathered (fault-) zones of presumably pre-Quaternary age.

- Extensive fracturing and weathering of the fault zones makes it difficult, or impossible, to use seismic refraction sounding for detailed investigation of bedrock surface and fault scarp geometry.

- The observed bedrock fault scarps and dislocated Quaternary sequences give no support for an interpretation of the faults as very gently dipping thrusts. The faults, when judged from the outcrops, appear to be reverse and dip between the vertical and some 40^{o}.

- Fault movements were mainly dip-slip but a minor strike-slip component is indicated locally.

- The earthquakes associated with the faulting reached magnitudes of at least M 6.5-7.0, they triggered landslides in glacial till and produced extensive deformations of sandy sediments in vast areas.

- Trenching across fault scarps has proved to be a useful method for timing of fault movement in this area.

- An active search for seismically induced deformations has proved fruitful if concentrated to deposits and environments favourable for the development of such structures. The investigations of seismites should be continued in the Lansjärv area in order to elucidate the variation of their appearance in different environments.

- In order to elucidate the significance of paleoseismicity in wider areas the search for seismites should be extended to comprise other and larger parts of Sweden. A systematic study of favourable sediments at strategically located sites would probably contribute to a better understanding of the late- and postglacial seismotectonic evolution of Sweden.

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